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Impact of wind turbines reliability models on the power generation system reliability

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Abstract. In this paper we describe the methodology of determining the reliability indices for power generating subsystem. We analyse then influence of the considered wind power plant reliability modelling on system reliability. The proposed reliability model of wind power plant is two-state model as compromise between calculation time and accuracy. We have found an empirical relationship between the power system reliability index LOLE (Loss of Load Expectation) and reserve capacity margin for a given wind share. This allowed us to estimate the required minimal reserve capacity margin for a given level of power system security and for a known structure of system installed capacity.

1 Introduction

The growing share of renewable energy in the Polish Electric Power System is a new challenge for the previously used measures of power system reliability, the methods of their determination and reliability models. Generation reliability (adequacy) assessment is used to evaluate short-term and long-term risks in generation capacity planning [1-3]. In this context, when variable renewable energy sources (VRES) such as wind generation are integrated into power grids, it is important to investigate their effect on the system reliability [4]. A simple method of risk assessment for generation subsystem (being a part of power system), which is based on the margin of generating capacity (reserve capacity margin – RCM), is no longer sufficient. This is the reason why this paper presents an attempt to estimate the influence of the existing and newly build wind turbines' capacity on evaluation of power system reliability. The influence of used wind turbine reliability model on power system reliability calculation results is also considered. As a basis for reliability calculation the IEEE RTS-79 test system [5-6] with additional wind turbines is used.

2 Methodology of determining the reliability indices for power generation systems

Reliability (adequacy) of power generating subsystem can be considered as a question of the overtopping the stochastic process of available generating capacity $P(t)$ by a stochastic

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process of power demand $Z(t)$ [2-3]. Model of generating subsystem reliability is therefore a generation shortage (deficiency) stochastic process $D(t)$, defined as [2-3]:

$$D(t) = \begin{cases} Z(t) - P(t) : Z(t) > P(t) \\ 0 \qquad\qquad : Z(t) \le P(t) \end{cases}. \tag{1}$$

The stochastic process $D(t)$ parameters are the quantitative characteristics of power generating reliability (adequacy) – reliability indices. In practice power system reliability is evaluated basing on the probability that the system is capable (or not) to cover the specific demand by comparing the probabilistic distribution of the load and the distribution of system ability to generate power (available capacity), usually represented by cumulative outage probability table (COPT) [1, 6] or cumulative distribution function (CDF) [2-3].

Calculation of COPT or CDF of generating available capacity is based on the accepted reliability models of generating units. They may be two-state or multi-state models [2-4, 7-10]:

A. **Two-state model**. Each generating unit in the system may with probability p_i (i = 1, ..., n) be in up-state (capable to work) or with the probability $q_i = 1 - p_i$ can be in down state (disable). Generating capacity (rated capacity) of the unit is equal P_i. This model is the most appropriate in the case of thermal power plants (conventional and nuclear).

B. **Multi-state model**. Each generating unit in the system, besides the two above-mentioned states, can be in states of partial availability, characterized by the generating capacity lower than the rated capacity. Generating capacity of the unit is in this case a random variable, which can achieve $l_{si} + 1$ different values.

Different techniques have been used to model wind generation and integrate them to evaluate the reliability of wind-integrated power systems [7-10].

3 The power system generation capacity and load models

The IEEE RTS-79 [5-6] was considered as a base case for the calculation. The IEEE RTS consists of 32 generating units with total generation capacity of 3405 MW and total peak load of 2850 MW. Generating units' reliability data is given in [5-6]. Test system was enhanced by adding 2 MW wind turbines. Considered cases are listed in Table 1.

Table 1. Considered cases of the wind generation share.

No.	Wind generation share, %	Number of 2 MW wind turbine units	Wind turbines capacity, MW	System capacity, MW
0	0.00	0	0	3405
1	1.96	34	68	3473
2	5.02	90	180	3585
3	8.00	148	296	3701
4	11.99	232	464	3869
5	14.98	300	600	4005
6	20.01	426	852	4257
7	24.98	567	1134	4539
8	30.01	730	1460	4865

For reliability calculation we need also the load model – we used an annual load series of IEEE RTS [5]. Load duration curve is shown in Fig. 1. The mean load for this curve is equal to 0.709 of peak demand P_d and the annual demanded energy A can be calculated as:

$$A = 8.760 \cdot 0.709 \cdot P_d = 6.211 \cdot P_d, \quad \text{GWh} \tag{2}$$

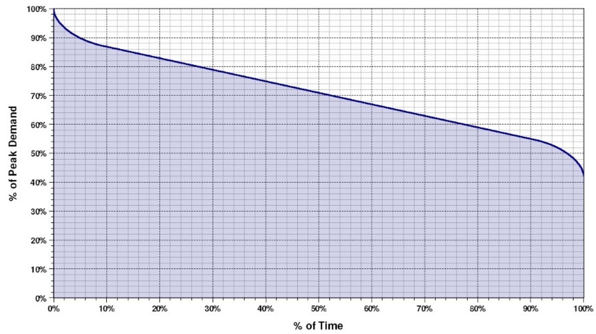

Fig. 1. Annual Load Duration Curve.

4 Impact of wind turbines reliability model on power system reliability

To analyse the impact of wind turbine model on generation reliability calculation we have considered 8 different cases of wind turbines reliability representation, as shown in Table 2 and Table 3. In this calculation the case 6 of wind generation share (see table 1), where wind share in system generation capacity is equal 20.01%, was taken as an example. In that case the RTS-79 capacity was enhanced by wind turbines of total capacity 852 MW what makes total system capacity 4257 MW. Probabilities in Table 3 were obtained [10] by the most commonly used approach of combining wind variability and turbine output power curve [8-9].

Table 2. Wind generation share realization and turbine reliability representation cases.

Case name	Single wind turbine capacity P_w, MW	Number of wind units	Wind turbine reliability representation model, as in Table 3
A	2	426	5 states model
B	2	426	3 states model
C	2	426	2 states model
D	4	213	
E	12	71	
F	71	12	
G	142	6	
H	426	2	

The resulting CDFs of available generating capacity are shown in Fig. 2. As we see, the aggregation of wind units causes significant error. For low range of power demand the cumulative probability of generating capacity is higher. It means that worse representation leads to underestimation of power system reliability. We can see it on generation reliability calculation results, shown in Table 4. This calculation was done using own computer program GRA (Generation Reliability Assessment) described in [3]. LOLE, which is the expected number of hours during a given time period (year) in which a system is unable to meet its total demand [1, 3, 9], was chosen as reliability index.

Table 3. Wind turbine reliability representation models.

State No *i*	**2 states model**		**3 states model**		**5 states model**	
	p_i	P_i, MW	p_i	P_i, MW	p_i	P_i, MW
0	0.8	0.0	0.691	0.0	0.582	0.0
1	0.2	$P_w = 2.0$	0.218	1.0	0.199	0.5
2	-	-	0.091	$P_w = 2.0$	0.100	1.0
3	-	-	-	-	0.075	1.5
4	-	-	-	-	0.044	$P_w = 2.0$

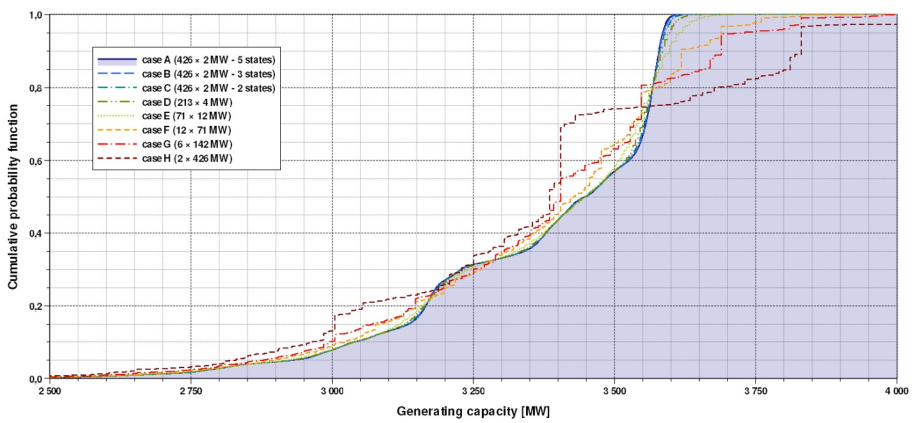

Fig. 2. CDF of available generating capacity for different wind generation representation models.

Table 4. LOLE calculation results for different wind generation representation models.

P_d, MW	2450	2550	2650	2750	2850	2950	3050
***A*, TWh**	15.22	15.84	16.46	17.08	17.70	18.32	18.94
Case name	**LOLE (Loss of Load Expectation), hrs/year**						
A	0.272	0.702	1.636	3.621	7.682	15.38	28.76
B	0.273	0.703	1.638	3.626	7.690	15.39	28.78
C	0.274	0.706	1.644	3.638	7.712	15.43	28.83
D	0.278	0.714	1.661	3.672	7.774	15.52	28.99
E	0.295	0.746	1.730	3.807	8.017	15.91	29.62
F	0.415	0.992	2.234	4.791	9.753	18.73	34.27
G	0.552	1.284	2.820	5.920	11.71	21.96	39.70
H	0.951	2.130	4.547	9.296	17.68	31.98	56.32

The results in case A seems to be the most accurate (real number of wind units and multi-stage wind unit reliability model), so we assuming case A as reference. The LOLE relative error (δLOLE) can be determined using formula:

$$\delta\mathrm{LOLE} = (\mathrm{LOLE} - \mathrm{LOLE}_{\mathrm{A}}) / \mathrm{LOLE}_{\mathrm{A}} \tag{3}$$

Mean relative LOLE errors are as follows: case B – 0.13%; case C – 0.45%, case D – 1.39%, case E – 5.13%, case F – 32.6%, case G – 64.3% and 158.8% for case H. The wind turbine reliability model has no significant influence on system reliability calculation results, when the number of considered units is sufficient. However the aggregating wind units, by replacing many smaller by one bigger, cause considerable errors.

5 Impact of wind generation share on power system reliability

The CDFs of generating available capacity were calculated for 9 different wind generation shares (listed in table 1). As a wind generation representation the 2 MW wind turbine reliability model with 2 states (table 2, case D) was used. The Capacity Credit (CC) was calculated using the results CDFs of available generating capacity. Capacity Credit express how much of the power generated in thermal power plants can be replaced by the power generated by wind tines. The following formula was used [4, 11]:

$$\mathrm{CC} = (P_{s\mathrm{EW}} - P_{\mathrm{S}}) / P_{\mathrm{EW}} \tag{4}$$

where: $P_{s\mathrm{EW}}$ – total power system capability to cover the load in the case when additional wind turbines are installed, MW; P_{s} – the total power system capability, when the additional wind turbines are not taken into account, MW; P_{EW} – maximum generating capacity of additional wind turbines, MW.

The power system ability to cover the load in both cases: including and excluding the additional generating capacity of wind turbines are calculated for the same level of system reliability. The assumed LOLPs (Loss of peak Load Probability – another often used generation reliability index, defined as the probability of encountering event in which a system is unable to meet its peak demand during a given time period [1, 3, 7-10]) level is equal to 0.015. The calculation of reliability for different peak load values, and for different wind generation shares were preformed. The calculated Capacity Credit values are shown in Table 5. Part of the generation reliability calculation results is presented in Table 6.

Table 5. Results of capacity credit (CC) calculations.

Wind share, %	P_{EW}, MW	P_{S}, MW	$P_{s\mathrm{EW}}$, MW	Capacity Credit (CC)
0.00	0	2559	-	-
1.96	68		2575	0.235
5.02	180		2559	0.222
8.00	296		2623	0.216
11.99	464		2655	0.207
14.98	600		2683	0.207
20.01	852		2731	0.202
24.98	1134		2787	0.201
30.01	1460		2851	0.200

Table 6. Part of the system reliability calculation results.

Wind share %										
Wind share %	***P**$_d$***, MW**	2400	2500	2600	2700	2800	2900	3000	3100	3200
	L**$_d$, MW**	1702	1773	1844	1915	1987	2057	2128	2198	2269
	***A*, TWh**	14.9	15.5	16.2	16.8	17.4	18.0	18.6	19.3	19.9
0.00	RCM, %	41.9	36.2	31.0	26.1	21.6	17.4	-	-	-
	LOLPs	0.00	0.01	0.02	0.04	0.06	0.11			
	LOLE, hrs/y	0.98	2.22	4.86	10.1	19.9	36.7			
	LOEE, MWh	93.3	232	540	1193	2515	5002			
5.02	RCM, %	49.3	43.4	37.9	32.8	28.0	23.6	-	-	-
	LOLPs	0.00	0.01	0.02	0.04	0.05	0.10			
	LOLE, hrs/y	0.69	1.61	3.58	7.59	15.3	28.9			
	LOEE, MWh	63.7	164	390	877	1884	3829			
11.99	RCM, %	61.2	54.8	48.8	43.3	38.1	33.4	-	-	-
	LOLPs	0.00	0.01	0.01	0.02	0.04	0.07			
	LOLE, hrs/y	0.38	0.96	2.18	4.77	9.96	19.5			
	LOEE, MWh	34.1	92.5	229	533	1177	2475			
20.01	RCM, %	-	70.2	63.7	57.7	52.0	46.8	41.9	-	-
	LOLPs		0.00	0.01	0.01	0.03	0.05	0.08		
	LOLE, hrs/y		0.45	1.09	2.46	5.32	11.0	21.2		
	LOEE, MWh		40.3	107	262	602	1320	2745		
30.01	RCM, %	-	-	87.1	80.2	73.7	67.7	62.2	56.9	52.0
	LOLPs			0.00	0.01	0.01	0.02	0.04	0.07	0.12
	LOLE, hrs/y			0.33	0.82	1.89	4.13	8.69	17.0	31.5
	LOEE, MWh			29.4	79.7	198	463	1027	2168	4313

P_d – annual peak load; L_d – average load; A – annual energy; RCM – reserve capacity margin, calculated as the ratio of the difference between the maximum generation capacity and peak load to the peak load; LOLPs, LOLE, LOEE (Loss of Energy Expectation, defined as the expected energy that the system is unable to serve during a given period) – system reliability indices

The calculated LOLE values for different values of wind generation share (WGS) and different values of RCM are shown in Fig. 3. Based on the results of reliability calculation the regression analysis of relationship between LOLE, RCM and WGS was performed. The coefficient of determination R^2 was used as a criterion of the quality of the estimates [12]. The higher the coefficient of determination, the better the fit of the model to the data analyzed. It is assumed that values below 0.9 mean poor fit of the model to the data.

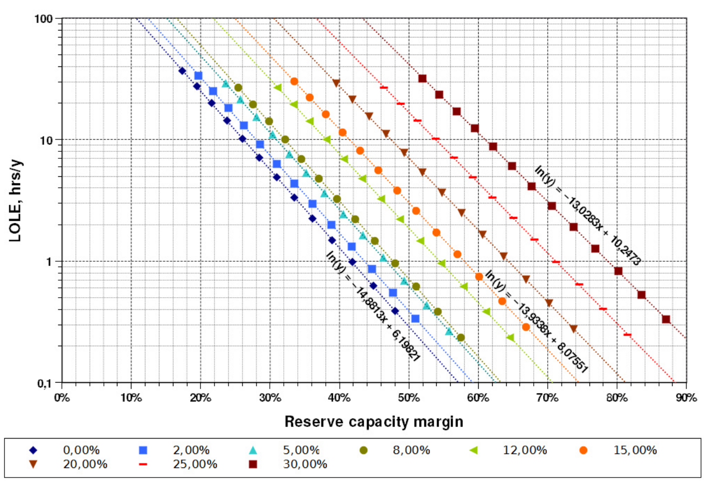

Fig. 3. Calculated LOLE values and RCM relationships for different wind generation shares (0–30%).

The value of LOLE = f(WGS, RCM) can be estimated using the following formulas:

$$\mathrm{LOLE_{est}} = 311 \cdot e^{(16.31\mathrm{WGS} - 14.07\mathrm{RCM})}\ \text{, hrs/y} \tag{5}$$

or

$$\mathrm{LOLE_{est}} = 491 \cdot e^{(5.87 \cdot \mathrm{WGS}^2 + 11.74 \cdot \mathrm{WGS} - 14.87\mathrm{RCM} + 6.16 \cdot \mathrm{WGS} \cdot \mathrm{RCM})}. \tag{6}$$

The coefficient of determination R² is equal 96.19% for formula (5) and 99.98% for formula (6). That's mean a good fit of estimation to the data.

Transforming formula (6), the required minimal reserve capacity margin as a function of the desired LOLE value and a given wind generation share can be calculated as:

$$\mathrm{RCM} \geq \frac{5.87 \cdot \mathrm{WGS}^2 + 11{,}74 \cdot \mathrm{WGS} + 6.196 - \ln(\mathrm{LOLE})}{14.87 - 6.16 \cdot \mathrm{WGS}} \cdot 100\% . \tag{7}$$

This relationship between the wind generation share and the required minimal reserve capacity margin is shown in Fig. 4. The dotted area indicates that for a given wind generation share and a given reserve capacity margin LOLE is greater than 3 hrs/year. Assuming this LOLE value as the threshold limit, the dotted area can be interpreted as a risk area for power generation subsystem.

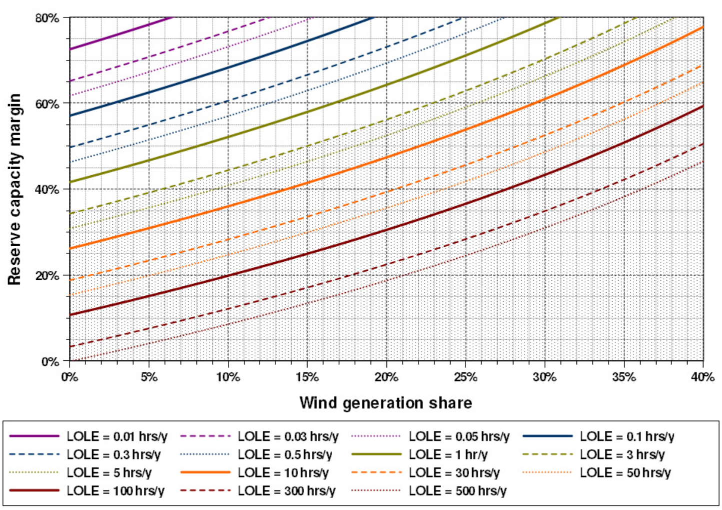

Fig. 4. The relationship between the wind generation share and the required minimal reserve capacity margin for different LOLE values.

6 Conclusions

The growing share of wind generation demands a different approach to the previously used rapid methods of assessment of the power generation subsystem reliability. The specificity of wind power plants requires the appropriate modelling of theirs reliability. The aggregation of generation units, involving the replacement of a number of small generating units with one bigger, results in underestimating the power system reliability. However, if the number of modelled units is sufficient, the taken into account unit reliability model (two-state or multi-state) has no significant impact on the system reliability calculation results. However, the more accurate wind units representation, the longer system reliability calculation time is. A kind of compromise can be modelling the wind power plants using small two-state units. As a measure of reliability (adequacy) of power system the loss of load expectation LOLE was taken. For a given generating capacity structure of the power system LOLE is exponentially dependent on the reserve capacity margin. The empirical relationship between the LOLE and reserve capacity margin for a given wind share was found in this paper. This relationship allowed us to estimate the required minimal reserve capacity margin for a given level of power system security, defined by a desired LOLE value and for known structure of power generation subsystem. When the maximum acceptable LOLE value equal 3 hrs/y is taken, then in case of the absence of wind power plants in the system the required minimal reserve capacity margin will be about 34%. In case, when the wind share is 10%, the expected minimal reserve capacity margin increase to about 44%, with the 20% wind share reserve capacity margin should not be less than 57% and for the 30% share wind power plants the required reserve capacity margin is about 70%. These calculations were made assuming the availability of wind power plants equal 0.2. This is a typical value for modern wind power plants in Poland, so the analysis can also be applied to the Polish Power System.

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