AVAILABILITY AND RELIABILITY ANALYSIS OF LARGE WIND TURBINE SYSTEMS IN CHOSEN LOCALIZATIONS IN POLAND

ANALIZA DOSTĘPNOŚCI I NIEZAWODNOŚCI DUŻEJ ELEKTROWNI WIATROWEJ W WYBRANYCH LOKALIZACJACH W POLSCE

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Abstract. *A reliability analysis of wind turbine systems applies to chosen localizations in Poland was inspected. The average availability, capacity factor and energy efficiency of the large wind turbine generator have been analyzed. It is noticed that if a failure rate decreases by modernizing assemblies by removing chosen subassemblies and reconstructing others, an average lifetime of the wind turbine enlarge noticeably. Moreover, it is possible to find, both poor and excellent wind potential on areas classified as not preferable for a wind industry.*

Keywords: *efficiency; reliability analysis; renewable energy; wind energy.*

Streszczenie: *Przeprowadzono analizę niezawodności elektrowni wiatrowych dla wybranych lokalizacji w Polsce. Dla średniorocznych prędkości wiatru przeanalizowano dostępność, współczynnik wykorzystania mocy zainstalowanej i wartość energii. Analizę niezawodności wykonano dla dużej elektrowni wiatrowej. Na podstawie badań ustalono, że istnieje możliwość wydłużenia bezawaryjnej pracy urządzenia wiatrowego poprzez jego rekonstrukcję oraz pokazano, iż na obszarach o potencjalnie niekorzystnych warunkach wiatrowych istnieje możliwość zrealizowania przedsięwzięcia aeroenergetycznego.*

Słowa kluczowe: *efektywność; analiza niezawodności; odnawialne źródła energii; energia wiatrowa.*

1. Introduction

Wind energy, achieving approximately 2 [%] of a global electricity production, is already the world's leading green technology among sources of renewable energy, ahead in terms of market share. The development of a wind energy sector is not only a chance to acquire energy by methods of human and environmental friendly, but also need to meet EU obligations. Although wind power is deal with caution by a traditional energy sector, a retreat from ambitious targets for a share of renewables in meeting energy needs is not possible. Moreover, being a technology developing faster than traditional energy technologies and other renewable energy sources, it is a leading and prospective way of struggle against a global greenhouse effect. In terms of investment, wind energy is competitive with other technologies for an electricity production from the renewable sources. In terms of exploitation, wind energy characterizes by low operating costs. Potential of renewable resources, held by Poland, in excess fills needs for national implementation of EU obligations, and it is at cost no more expensive than in other European countries. Technical potential of wind energy in Poland, associated with spatial distribution of open areas, reaches 1 400 [GW/year], which indicates a possibility of substantial amounts of electricity produced by a wind. The potential of wind energy can be seen in terms of a theoretical accessibility, a technical potential, potential of environmental constraints and an economically viable capacity. Large, modern onshore or offshore wind turbines of an annual failure rate of 0.5-3 are continuously improving in reliability in order to keep an unscheduled maintenance visits need as rarely as possible. Despite of the fact that modern onshore wind turbines achieve availability up to 97 [%], a higher availability of wind turbine still requires additional maintenance work. A reliable and efficient energy provision is associated with development of conceptions and organization procedures and with an optimization of an arrangement, a system design and trials. The high reliability ensures a high degree of operating and personal safety, a high availability of system, a low maintenance necessity and a low cost production downtime resulting in development on areas of a wind energy technology. It is essential for a wind power industry to identify factors that influence on a reliability of wind turbines in order to face the economic challenges of offshore installations especially, because of a high wind power harvesting, limited access time of a failure recovery and maintenance breaks at level of one or below per year.

2. Intermittency of wind turbines output

There are numbers of factors affecting on amount of energy produced by wind turbines including maintainability, reliability, availability and safety. Modern wind turbine are fairly not shut off for a maintenance or repairs very often but dispatchability that is ability of a wind turbine to be turned on as quickly as possible to a desired level of output, is a very important attribute. Similar to other type of a green energy, the wind turbine is not dispatchable and furthermore must be stopped for a scheduled and unscheduled maintenance. The study of a large

wind turbine processing is limited to analysis of assessment and evaluation purposes. Exergy efficiencies of a wind turbine E82 system were examined according to a wind speed in two localizations A and B characterized with a different surface roughness, a wind energy condition and a structure of resources. Both localizations placed in south-west part of Poland characterize with insufficient wind conditions according to a macro scale wind potential of Poland [4].

When considering a reliability of wind turbines, it can be regarded in two ways. A reliability factor $\square(t)$ is dependent primarily on a construction of a wind turbine. A capacity factor CF takes into account additional working conditions such as turbine locations, logistics and a maintenance. The capacity factor of the wind turbine is the ratio of the actual energy generated in a specified period to the theoretical maximum possible. In other way, the capacity factor for the wind turbine represents the ratio of average power produced by the turbine over a year to its rated power capacity. All wind turbines have capacity factors that indicate an amount of energy gained from an individual turbine in a particular place. The air flowing with the wind has some kinetic energy so availability of the wind is a kinetic energy it possesses:

$$ke_1 = \frac{V_r^2}{2} \quad (1)$$

where ke_1 is exergy of kinetic energy and form of mechanical energy that is able to convert to work entirely [5]. A wind speed value V_r can be approximated for different heights by Hellmann's equation that recalculates average values of the wind speed at the lower level to the wind speed at the upper level. A wind speed dependence of heights above ground level is non-linear but simplified Hellmann's equation gives practically good enough results:

$$V_r = V_{ref..} \left[\frac{H}{H_{ref.}} \right]^\mu \quad (2)$$

where V_r [m/s] is the calculated wind speed on analyzed heights, V_{ref} [m/s] is the wind speed at a reference height. H [m] and $H_{ref.}$ [m] are local and references heights, respectively. Used in practice approximation values for the Hellmann exponent depend on localization in regions with a stratification stability (Table 1).

Table 1. Values for the Hellmann exponent

Stability	Open water surface	Flat open coast	Urban area
Unstable	0.06	0.11	0.27
Neutral	0.10	0.16	0.34
Stable	0.27	0.40	0.60

The efficiency of the wind turbine is usually characterized by its power coefficient (a dimensionless energy conversion ratio) as given below:

$$C_p = \frac{P_a}{0.5\rho\pi R^2 V_r^3} \quad (3)$$

where C_p is a power performance of the wind turbine, P_a [W] is an electricity produced by the wind turbine, $\rho = 1.225[\text{kg}/\text{m}^3]$ is an air density, R [m] is a maximum rotor radius. The wind turbine stands out various C_p values depending on the wind speed. To determine an available power it is necessarily to know an amount of the air passing through the rotor of the wind turbine per time, that is a mass flow rate $\dot{m}$:

$$\dot{m} = \rho \pi R^2 V_r \quad (4)$$

A maximum power available to the wind turbine P [W] is given as below:

$$\text{Available power} = P = \dot{m} k e_1 \quad (5)$$

An active power at a generator output P_a [W] is given:

$$P_a = C_p P \quad (6)$$

Every wind turbine can failure, but when an appliance is often unavailable due to breakdowns it results in the lower reliability of the system. The reliability factor is to be determined by the individual reliability of subsystems or elements. If each component exhibits the constant failure rate λ , the reliability $R(t)$ for the component will be in a form of exponential $(-\lambda t)$ and the reliability $R(t)$ for the system is given:

$$R(t) = \exp(-\sum \lambda_i t) \quad (7)$$

The value of the reliability decreases subsequently with time and reaches value of zero for a long time or for the high failure rate [3]. Mean time between failures measured in hours as average time that a device functions until addle, is given:

$$\text{MTBF} = \frac{1}{\lambda} \quad (8)$$

MTBF ratings are predicted based on a manufacturer experience or by analyzing known factors such as a raw data supplied by exploiters. Calculation is under assumption that systems fix after failures and service is to be conducted immediately after assembly breakdown.

3. Results and discussions

The capacity factor CF and an available active power at generator output have been calculated for the E82 wind turbine generator. The calculated performance parameters for average values of the wind speed for periods of time in the localization A and the theoretical power output are stored (Table 2). The average wind speed at a hub height is 3.17 [m/s] and the annual calculated electricity exported to a grid ought to be 558 498 [kWh] (Table 3). Typical values for the wind power plant capacity factor range from 20 to 40 [%]. The lower end of the range is representative of technologies installed in average wind regimes while the higher end of the range represents modern wind turbines installed in good wind

conditions. Achieved results of CF on 2,13 [%] of up to date the wind turbine indicate the localization A as not supposed to be properly selected or point on modification of a concept of energy production by the wind turbine. Decreasing a cut-in speed could be essential to increase an energy generation and could cause a wider use of the wind turbine, especially in Poland with insufficient windy conditions and a low annual average wind speed below 5 [m/s] on 10 [m] above a ground level, generally.

Table 2. Calculated performance parameters of E82 wind turbine in localization A

Month	V_r	ke_l	$\dot{m}$	C_p	P_a
January	3,65	6,66	23 613	0,36	56 782
February	3,96	7,84	25 618	0,40	79 744
March	3,96	7,84	25 618	0,40	79 744
April	3,50	6,13	22 642	0,34	47 707
May	2,89	4,18	18 696	0,27	21 315
June	2,59	3,35	16 755	0,22	12 476
July	2,59	3,35	16 755	0,22	12 476
August	2,28	2,60	14 750	0,17	6 326
September	2,59	3,35	16 755	0,22	12 476
October	3,20	5,12	20 702	0,31	33 070
November	3,20	5,12	20 702	0,31	33 070
December	3,65	6,66	23 613	0,36	56 782

Table 3. Typical and calculated values for wind turbine performance parameters of E82 in localization A

Power system parameters	Typical values range		Actual
	from	to	
Airfoil losses	1 [%]	10 [%]	10 [%]
Miscellaneous losses	3 [%]	6 [%]	6 [%]
Availability	93 [%]	98 [%]	97 [%]
Capacity factor	20 [%]	40 [%]	2,13 [%]
Electricity exported to grid			558,498 [MWh]

It is possible to find other theoretical location B in the same macro scale region of the wind energy potential. The calculated performance parameters average values of the wind speed for periods of time in the localization B and the theoretical power output are stored (Table 4). The annual average wind speeds in the localizations A and B are 3.17 [m/s] and 19.14 [m/s], respectively. The capacity factors for selected localizations are 2.13 [%] and 55,4 [%] respectively. During a winter season, the wind speed is higher and increases the capacity factor for the selected localization. This shows that the capacity factor is highly dependent on the

wind speed. Maximum, useful energy produced in year is found at 559 [MWh] and 14 564 [MWh], respectively. Although, modern wind turbines achieve a quite high availability of about 95 [%] to 99 [%] [2], quite a number of faults cause unscheduled downtimes up to several per year, resulting in high maintenance efforts, production losses and bearing extra costs.

Table 4. Calculated performance parameters average values of the E82 wind turbine in the localization B

Month	V_r	ke_l	$\dot{m}$	C_p	P_a
January	24,35	296,46	157 526	0,07	3 171 801
February	24,05	289,20	155 585	0,07	3 179 540
March	21,76	236,75	140 771	0,09	3 132 291
April	17,96	161,28	116 188	0,16	3 059 024
May	15,83	125,29	102 408	0,23	2 928 654
June	15,07	113,55	97 492	0,26	2 839 749
July	14,91	111,15	96 456	0,26	2 817 689
August	14,15	100,11	91 540	0,29	2 696 552
September	16,74	140,11	108 295	0,20	3 003 117
October	20,39	207,88	131 908	0,11	3 101 277
November	21,46	230,27	138 830	0,10	3 124 003
December	23,28	270,98	150 604	0,08	3 175 750

An actual seasonal performance useful energy is less because of internal and external causes of failures affecting subassemblies and components of the wind turbine. The reliability of the wind turbines depends on reliability of subassemblies: an electrical system, an electronic control, sensors, an hydraulic system, a yaw system, a rotor hub, a mechanical brake, rotor blades, a generator, a gearbox, a support and a housing, a drive train. Depend on the turbine representation, the annual failure rates for the different models of the large wind turbines change from 2,4 to 3,5 [failures turbine⁻¹ year⁻¹] [7], so the average failure rates of the whole wind turbine system are found to be from $2,74 \cdot 10^{-4}$ [h⁻¹] up to $3,99 \cdot 10^{-4}$ [h⁻¹]. Mean time between failures is found to be from 3 650 [h] to 2 500 [h], respectively (Fig. 1). It has been estimated that the system reliability factor will become zero at 17 000 [h] and 12 000 [h], respectively.

It was found that by removing 5 [%] of all defects of the wind turbine system with the failure rates at $2,74 \cdot 10^{-4}$ [h⁻¹], the failure rate would be reduced which would result in the improvement of MTBF from 3 650 [h] to 3 850 [h] and the increasing of the lifetime of the wind turbine system to 18 000 [h]. Removing number of defects could be realized by improving quality of subassemblies, by a periodical maintenance regime or by removing defective subassemblies with the low reliability factor and by reconstructing device. The increasing reliability factor in some type of the assembly was achieved by eliminating a gearbox (the average

annual failure rates 0.12 [2]) from the construction of the wind turbine and altering the generator.

Fig. 1 Reliability factor of large wind turbine with existing boundary failures

4. Conclusion

To obtain a maximum power possible in polish weather conditions it is important for wind turbines to start working at the lowest possible wind speed. When optimizing operation, the wind turbine should not be assumed to seek maximum reliability of all components, as it may be uneconomic and not significantly affect overall reliability of sophisticated devices. The essential difficulty is to find elements of selected reliable but not in isolation from their position in the whole system. Increasing of the failure rate for the components with the considerable values of the failure rate, even if it is less than percentage reduction of failures for other components results in an enhancement of the failure rate.

It is possible to find a proper place for the wind industry that are marked in macro scale of potential of the wind as not preferable for the wind turbine erection.

5. References

- [1] Cengel YA, Boles MA.: Thermodynamics an engineering approach. McGraw-Hill Science/Engineering/Math. NY. 2005.
- [2] Hahn B., Durstewitz M., Rohrig K.: Reliability of wind turbines, experiences of 15 years with 1,500 WTs, Wind Energy. Springer, Berlin, 2007.
- [3] Iniyar S, Suganthi L, Jagadeesan TR.: Critical analysis of wind farms for sustainable generation. Solar Energy Vol. 64, Nos 4–6, pp. 141–149, Elsevier Sci Ltd, Exeter, 1998.

- [4] Lorenc H.: Atlas klimatu Polski, IMGW, Warszawa, 2005.
- [5] Ozgenera O., Ozgener L.: Exergy and reliability analysis of wind turbine systems: A case study. *Renewable and Sustainable Energy Reviews* 11, 1811–1826, 2007.
- [6] Pytel K.: Ekologia, ekonomia i edukacja wobec wyzwań odnawialnych źródeł energii. Wykorzystanie energii wiatru - aspekt technologiczny i ekologiczny, Divoir, Kraków, 2010.
- [7] Spinato F., Tavner P.J., van Bussel G.J.W., Koutoulakos E.: Reliability of wind turbine subassemblies. *IET Renew. Power Gener.*, Vol. 3, Iss. 4, pp. 1–15, 2009.

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