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UNCERTAINTY OF EXTREME WIND ESTIMATION AND ON SITE WIND TURBINES CLASSIFICATION

Abstract: The correct prediction of the maximum wind speed as well as wind turbulence intensity that are expected to occur on a large time interval and consecutively the definition of the wind turbine class that is to be installed in a given wind farm site is of crucial importance to the wind farm development. The maximum wind speed is defined as extreme wind or reference wind speed by the standard IEC 61400–1. A turbine designed for a wind turbine class with a reference wind speed and estimated turbulence intensity, is designed to withstand climates for which the extreme ten minutes average wind speed with a recurrence period of future 50 years at turbine hub height is lower than or equal to reference wind speed for the specific site. This paper is dealing with uncertainty analyses of different methodologies for estimating the extreme wind as well as turbulence intensity from available experimental datasets and uses it to guide the wind turbine class definition. Obtained results from datasets based on two and three years measurement period respectively have been compared and perform cost-benefit analysis related to uncertainty of calculated extreme wind and turbulence intensity, crucial for definition of required period for efficient site characteristics measurement campaign. Uncertainty assessment as well as methodology of extreme wind calculation is based on statistical tools from General Extreme Value theory. Furthermore, from the given climatology data at the mast location, and digital terrain data, it is presented how wind turbine class can be estimated at different wind turbines locations inside the wind farm using Computational Fluid Dynamics technique coupled with General Extreme Value theory.

Key words: *Wind Energy, Extreme Wind, Wind Turbulence Intensity*

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1. INTRODUCTION

For wind turbine design, as for any large structure, safety considerations are confronted to costs of over-design. To ensure structural integrity the wind turbines are designed to withstand extreme winds as well as extreme and fatigue loadings produced by ambient turbulence and of turbulence pertinent to the interior of the wind farm.

In this paper we assess the uncertainty in estimation of extreme wind speed – the fifty-year wind u_{50}, which is the wind speed exceeded on average once in period of fifty years. Extreme wind conditions are defined in terms of this value in documents such as the standard elaborated by the International Electro-technical Commission IEC 61400–1 [1] and is accepted in the wind energy community. To meet our task we choose measurement duration length of a typical campaign for collection of climatology data for a given wind farm site, which is between two to three years. Estimates are then made with the data gathered during the first two year period and compared with the estimate from three years measurement to assess the uncertainty. We think that this comparison is crucial since the length of dataset used to fit the statistical distribution is shorter in practical case than what best practices require (at least ten years of data). Therefore uncertainty estimation in practical situations like present one is of great importance.

Extreme winds are defined by fitting the extreme values to a statistical distribution appropriate for the extreme event distribution. From the cumulative probability for the given recurrence interval estimates of values such as u_{50} are produced. It is generally accepted that the Gumbel distribution is suitable for distribution of extreme winds, so it is chosen for this work. What is outside the scope of the present article, are the other choices for a statistical distribution, such as different distribution types beside Gumbel (type I) within Generalized Extreme Value Theory (GEV), Peaks over Threshold Method with Generalized Pareto Distribution which enables enrichment of dataset available for statistical model fitting, relative to Annual Maximum Method that we use here, and they can be found elsewhere in the literature [3].

What influences the wind turbine besides extreme ambient wind is ambient turbulence and wind farm interior turbulence both defined in terms of standard deviation of wind speed fluctuations. Fatigue loads that originate from the ambient as well as from the wind farm internal flow conditions are combined in fatigue models.

In the following sections uncertainty analysis of extreme wind estimation is conducted, while performing evaluation of fifty year wind at the specific site (Dobric, Municipality Svrljig, East Serbia). Short summary of the used method is included. In the subsequent sections a model for IEC classification of wind turbines is given and classification of the wind turbines is shown for the Dobric site, with examination of outcome caused by changes in the new edition of the IEC standard [1].

2. Estimation of Extreme Wind Speeds

For our statistical method the distribution of the maximum wind speeds is described using the cumulative distribution function of the Gumbel distribution:

$$F(U) = \exp(\exp(-\alpha\,(U-\beta))) \tag{1}$$

The probability weighted moment procedure is applied to obtain the coefficients a and b. First one finds

$$b_1 = \frac{1}{N}\sum_{i=1}^{N}\frac{i-1}{N-1}U_i^{\max} \tag{2}$$

Then one may find coefficients α and β,

$$\alpha = \frac{\ln 2}{2b_1 - \langle U^{\max}\rangle} \tag{3}$$

$$\beta = \langle U^{\max}\rangle - \frac{\gamma}{\alpha} \tag{4}$$

The value of the Euler-Mascheroni constant is $\gamma \approx 0.5772$. $\langle U^{\max}\rangle$ is the mean of $U_i^{\max}$.

The coefficient values obtained by this method won't differ too much from the values obtained by least square regression method; however it has been proved that this method gives less bias and variance on the parameter estimates, and is efficient for samples of small size.

Recurrence interval T is defined as

$$T = 1/\left(1 - F(U_T)\right) \tag{5}$$

The fifty-year wind speed is obtained from the cumulative probability for the given recurrence interval T=50, with the following expression

$$U_T = -\alpha^{-1}\ln\ln\frac{T}{T-1} + \beta \tag{6}$$

What could be taken as a major criticism of Annual Maximum Method is that it considers a single maximum in each year. It therefore ignores all other extreme events that may have occurred.

This methodology is used for the assessment of maximum fifty year wind-speed, from experimental dataset collected by present group of authors. Wind speed datasets, pertinent to altitude of 50 m from ground level, are collected during the period from April 2010 to July 2013 at Dobric (Svrljig municipality) in Eastern Serbia. Observed data are processed using WaSP Climate Analyst, a program from WaSP bundle, developed by Riso Laboratory ands (Denmark) [4].

Fig. 1 (left) shows observed extreme wind speed at Dobric. It represents a polar map where both direction and wind-speed are visible.

Highlighted are two events, each maximum in own epoch (observational year). Selection of a single maximum from each epoch belongs to Annual Maximum

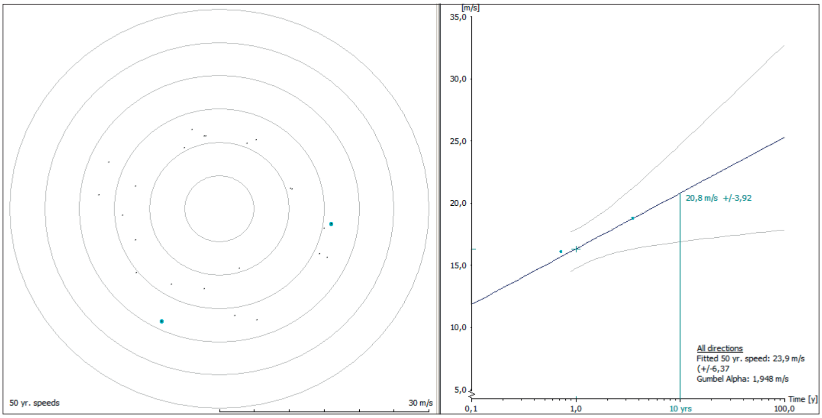

Figure 1. Annual extremes (left) and maximum wind speed as a function of return period (right). Two years of data.

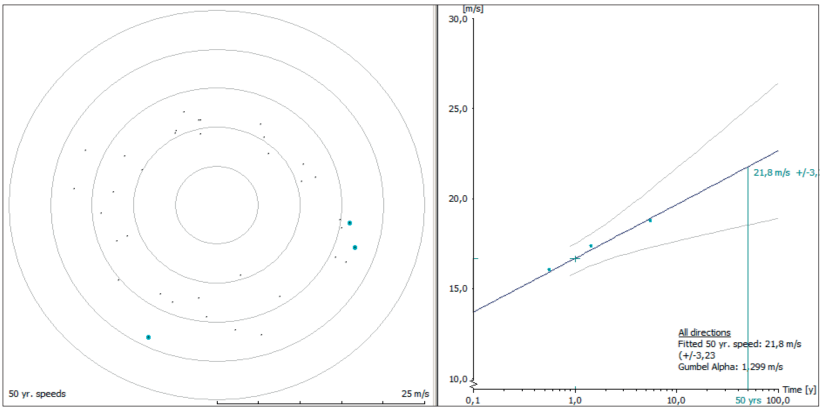

Figure 2. Annual extremes (left) and maximum wind speed as a function of return period (right).Three years of data.

Method. Using presented methodology, WaSP uses selected two annual extremes to Gumbel distribution, calculating parameters presented in previous section. Using cumulative distribution function for Gumbel distribution, WaSP is able to produce a graph, showing maximum wind-speed for a given return period in years (Fig. 1 right). What is noted is a linear scaling of extreme wind speeds with return years; which is a consequence of used distribution function. Uncertainty ranges are demarked using gray lines in the plot. Fitted fifty-year wind speed extracted from this plot is 23.9 m/s.

Fig 2 shows fitted fifty-year wind speed extracted from this plot is 21.8 m/s. The relative difference is around nine percent.

3. MODEL FOR IEC CLASSIFICATION OF WIND TURBINES

In this chapter the suitable IEC class for the designed wind farm is given. Measured wind climatology into the wind farm micro-area is transferred to each hub position of wind turbine, and then the parameters V_{ref}, I_{ref} (mean value and standard deviation) are computed for the transferred climatology. The reference velocity, an extreme wind with a recurrence period of 50 years, is computed by Gumbel fitting the annual peaks of recorded wind speed with the method of the maximum likelihood. Three years of measurements are used to perform a Gumbel fitting. The I_{ref}, is given as mean turbulence intensity for 15 m/s bin, its standard deviation is also computed for the same samples. For IEC classification, two methodologies have been applied:

– In the case of classification of wind turbines according to the second edition of the standards [1] a characteristic turbulent intensity is required (84th percentile, mean plus the standard deviation for a normal distribution).

– In the case of classification according to the third edition [1], it is verified that the standard deviation of the longitudinal component from the normal turbulence model σ_1 of the wind velocity at hub height is greater or equal to the estimated 90th percentile of the effective turbulence standard deviation (accounting for both ambient and wake turbulence):

$$\sigma_1(V_{hub}) \geq I_{ref} V_{hub} \tag{7}$$

where:

$\sigma_1(V_{hub})$ – standard deviation of the longitudinal component of the wind velocity;
V_{hub} – wind velocity at the hub height
I_{ref} – effective turbulence intensity

The verification is performed between 60% of the rated wind velocity V_r and the cut-out wind velocity at hub height V_{out}.

The effective turbulence I_{eff} is defined in the IEC standards as weighted average of turbulence intensity to the power of *m*, being *m* the Wöhler exponent. For the IEC classification m is considered to equal 10, number valid to verify the glass fiber of the blades, the most fragile component of the wind turbine. The effective turbulence is therefore that turbulence intensity that would produce fatigue damage after the same number of cycles of a failure caused by the actual turbulence wind rose.

$$I_{eff}(V_{hub}) = \left[\int_0^{2\pi} p(\theta, V_{hub}) \cdot I^m(\theta, V_{hub}) d\theta \right]^{\frac{1}{m}} \quad (8)$$

where:

m – Wöhler exponent;
θ – wind direction;
p – frequency of occurrence;
I – representative value (90th percentile) of the turbulent intensity of the wind;
V_{hub} – wind velocity at the hub height.

The turbulence intensity I accounts for the presence of the neighboring turbines with the version of the Frandsen model[2] as proposed in the Amendment 1 (2010) of the 3rd edition of the IEC standards 61400–1 (2005) [1].

The integral defining I_{eff} is therefore discretized in a set of wind directional sectors. Using the subscript *„s"* for sector-wise properties, *NS* number of directional sectors:

$$I_{eff} \cong \left[p_s(V_{hub}) \cdot I_s^m(V_{hub}) \right]^{\frac{1}{m}} \quad (9)$$

For the general sector *„s"* I_s is the representative value of the turbulence intensity, accounting for wake induced turbulence by N_s neighboring turbines in the sector *„s",* in the diameter of $d_i \leq 10$, where d_i is the distance, normalized by rotor diameter, to neighboring wind turbine *„i":*

$$I_s = \sigma_{eff\_s}(\theta_s, V_{hub}) / V_{hub} \quad (10)$$

where:

$$\sigma_{eff\_s}(\theta_s, V_{hub}) = \left[(1 - N_s p_{ws}) \cdot \sigma_{r\_s}^m(\theta_s, V_{hub}) + p_{ws} \sum_{i=1}^{N_s} \sigma_{T\_s}^m(d_i) \right]^{\frac{1}{m}} \quad (11)$$

where:

N_s – neighboring turbines within sector „s";
p_{ws} – probability to be under wake for a given sector;
σ_{r_s} – representative value of ambient turbulence intensity for sector „s";
σ_{T_s} – representative value of turbulence intensity in wake condition.

In the case of non-uniform wind direction distribution, p_{ws} may be adjusted by a factor equal to the ratio of the actual probability of the wind direction in the direction of the neighboring turbines and the probability associated with uniform wind direction distribution ($p_{ws} = 0.06$).

The turbulence intensity under wake condition σ_{T_s} is modeled with the following expression:

$$\sigma_{T\_s}(d_i) = \sqrt{\frac{V_{hub}^2}{(1.5 + 0.8d_i\sqrt{C_T})^2} + \sigma_{r\_s}^2(\theta_s, V_{hub})} \tag{12}$$

where:

C_T – thrust coefficient of i-th wind turbine generating the wake;

4. IEC CLASSIFICATION OF WIND TURBINES FOR SITE DOBRICH

Here we apply presented procedure to wind turbine classification at Dobric wind farm site. Fig. 3 shows contour map of terrain elevation and the wind farm layout. Fig. 4 shows average wind velocity, which are transferred values to turbine hub height. Turbulence intensity contour map is given in Fig. 5.

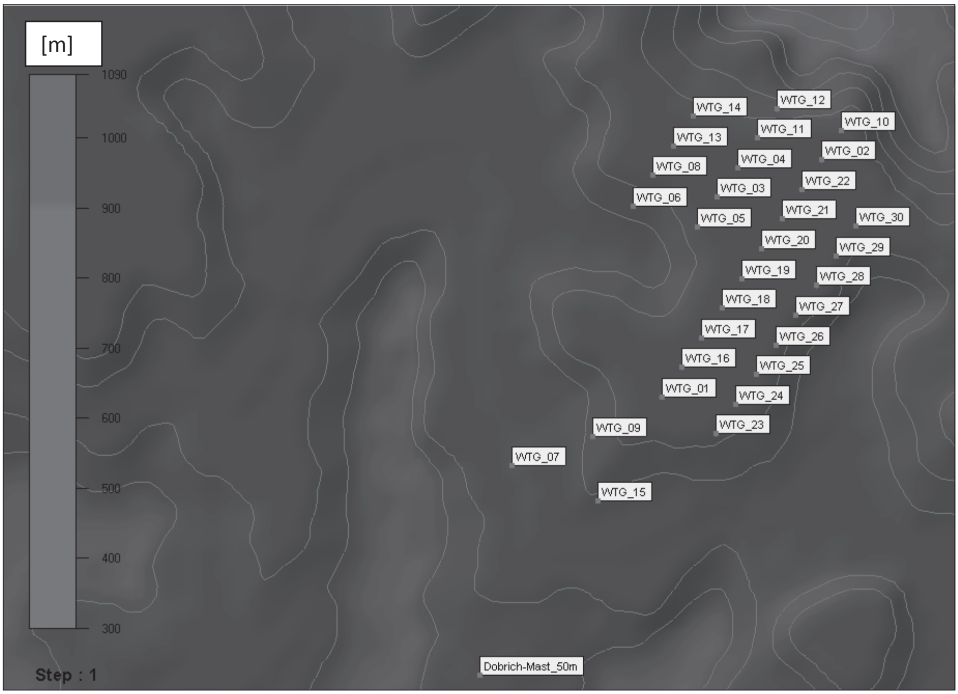

Figure 3.Orography model (terrain height a.s.l. given in mters) and wind turbine locations (WTG) of Dobric Wind Farm

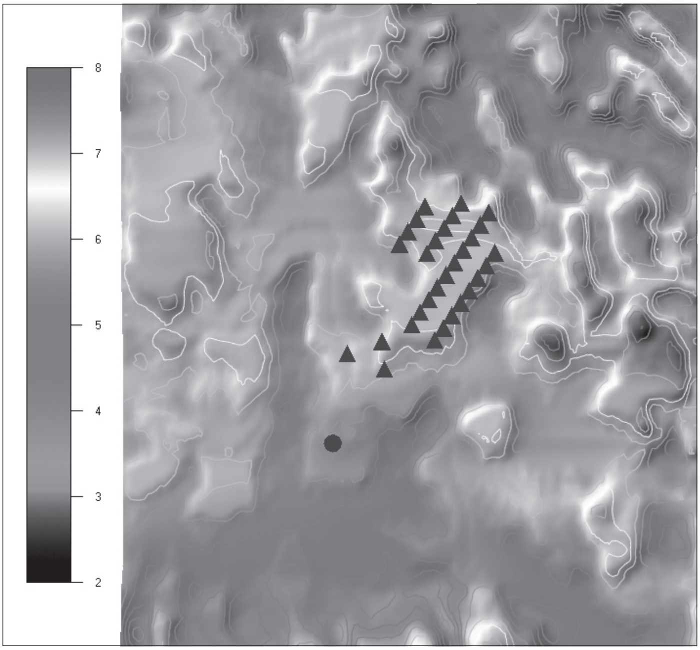

Figure 4.Average wind velocity (m/s) at hub height.

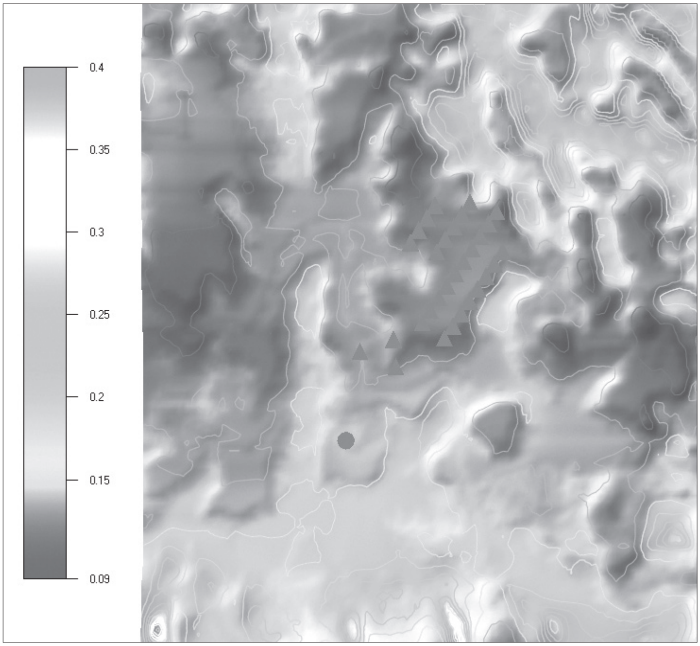

Figure 5.Turbulence intensity (-) at hub height.

Table 1 shows criteria for wind turbine classification as given in [1]. Results of classification pertinent to second and third edition of the standard are shown in Table 2 and Table 3. Differences are visible in these two tables since majority of wind turbine under new criteria now fall into special or 'S' class. This class requires that special considerations have to be taken into account by turbine manufacturer related to turbulence intensity at wind farm site.

Table 1. Wind turbine classification by IEC 61400–1:2005 3rd Edition

Wind turbine class	I	II	III	S
Vref (m/s)	50	42.5	37.5	Values specified by the designer
A I_{ref} (-)	0.16			
B I_{ref} (-)	0.14			
C I_{ref} (-)	0.12			

Table 2. IEC classification parameters (IEC 61400–1 2nd edition)

name	V_{ref}	V_{aver}	I_{ref}	s (I_{ref})	$I_{V=15}$	WTG class
	(m/s)	(m/s)	(-)	(-)	(-)	(-)
WTG_01	30.86	6.47	0.107	0.030	0.137	IIIB
WTG_02	39.66	6.58	0.099	0.029	0.128	IIB
WTG_03	31.17	6.64	0.100	0.030	0.129	IIIB
WTG_04	33.97	6.58	0.108	0.030	0.138	IIIB
WTG_05	31.60	6.78	0.096	0.028	0.124	IIIB
WTG_06	31.00	6.30	0.108	0.029	0.137	IIIB
WTG_07	28.01	6.36	0.101	0.036	0.138	IIIB
WTG_08	31.67	6.74	0.101	0.029	0.130	IIIB
WTG_09	30.65	6.50	0.091	0.033	0.124	IIIB
WTG_10	41.59	6.98	0.079	0.029	0.107	IIB
WTG_11	38.81	6.66	0.099	0.027	0.127	IIB
WTG_12	35.70	6.35	0.111	0.028	0.139	IIIB
WTG_13	32.04	6.59	0.104	0.028	0.133	IIIB
WTG_14	32.47	6.65	0.105	0.027	0.133	IIIB
WTG_15	29.34	6.38	0.098	0.035	0.133	IIIB
WTG_16	31.65	6.34	0.104	0.030	0.134	IIIB
WTG_17	32.03	6.35	0.103	0.028	0.131	IIIB
WTG_18	32.30	6.33	0.102	0.028	0.130	IIIB
WTG_19	33.58	6.36	0.102	0.032	0.134	IIIB
WTG_20	34.76	6.49	0.100	0.031	0.132	IIIB
WTG_21	37.40	6.49	0.105	0.030	0.135	IIIB
WTG_22	37.69	6.59	0.095	0.031	0.126	IIB
WTG_23	34.26	6.81	0.083	0.033	0.117	IIIB
WTG_24	32.38	6.59	0.101	0.032	0.133	IIIB
WTG_25	33.90	6.51	0.102	0.033	0.134	IIIB
WTG_26	36.02	6.49	0.101	0.031	0.132	IIIB
WTG_27	40.14	6.31	0.102	0.031	0.133	IIB
WTG_28	38.65	6.34	0.102	0.029	0.132	IIB
WTG_29	40.84	6.46	0.094	0.030	0.124	IIB
WTG_30	41.66	6.45	0.100	0.032	0.131	IIB

Table 3. IEC classification parameters (IEC 61400–1 3rd edition)

name	V_{ref}	V_{aver}	I_{ref}	$\sigma(I_{ref})$	$I_{V=15}$	WTG class
	(m/s)	(m/s)	(-)	(-)	(-)	(-)
WTG_01	30.86	6.47	0.107	0.030	0.145	S
WTG_02	39.66	6.58	0.099	0.029	0.136	S
WTG_03	31.17	6.64	0.100	0.030	0.138	S
WTG_04	33.97	6.58	0.108	0.030	0.146	S
WTG_05	31.60	6.78	0.096	0.028	0.132	S
WTG_06	31.00	6.30	0.108	0.029	0.145	S
WTG_07	28.01	6.36	0.101	0.036	0.148	S
WTG_08	31.67	6.74	0.101	0.029	0.138	IIIA
WTG_09	30.65	6.50	0.091	0.033	0.134	S
WTG_10	41.59	6.98	0.079	0.029	0.115	IIA
WTG_11	38.81	6.66	0.099	0.027	0.134	S
WTG_12	35.70	6.35	0.111	0.028	0.147	S
WTG_13	32.04	6.59	0.104	0.028	0.140	S
WTG_14	32.47	6.65	0.105	0.027	0.140	IIIA
WTG_15	29.34	6.38	0.098	0.035	0.142	IIIA
WTG_16	31.65	6.34	0.104	0.030	0.143	S
WTG_17	32.03	6.35	0.103	0.028	0.139	S
WTG_18	32.30	6.33	0.102	0.028	0.138	S
WTG_19	33.58	6.36	0.102	0.032	0.143	S
WTG_20	34.76	6.49	0.100	0.031	0.140	S
WTG_21	37.40	6.49	0.105	0.030	0.143	S
WTG_22	37.69	6.59	0.095	0.031	0.135	S
WTG_23	34.26	6.81	0.083	0.033	0.126	S
WTG_24	32.38	6.59	0.101	0.032	0.142	S
WTG_25	33.90	6.51	0.102	0.033	0.143	S
WTG_26	36.02	6.49	0.101	0.031	0.141	S
WTG_27	40.14	6.31	0.102	0.031	0.141	S
WTG_28	38.65	6.34	0.102	0.029	0.140	S
WTG_29	40.84	6.46	0.094	0.030	0.133	S
WTG_30	41.66	6.45	0.100	0.032	0.140	S

5. CONCLUSIONS

The usual climatology measurement campaign for a given wind farm site lasts between two to three years so there is a tendency for higher uncertainty in prediction of extreme wind speeds that are usually represented by a Gumbell distribution, as it requires data collected for more than ten years. We have shown that the difference in extreme wind speed u_{50} from climatology data differ approximately

10 percent for the Dobric site case, when decision is made to create extreme wind estimates based on two or three year of data respectively.

To produce estimates of wind turbine classes by current methodology it is necessary to transfer the referent values of wind speed, turbulence intensity and standard deviation to the hub height at the position of each individual wind turbine. Further, we have seen that novel (3^{rd}) edition of IEC standard for classification of wind turbines [1] has more rigorous classification guidelines. By contrast to calculation for Dobric site done according to the 2^{nd} edition, wind turbine classes differ significantly when done according to guidelines of latest edition of the IEC standard, as majority of wind turbines in our example now belong to special (‘S’) class.

Under such circumstances it is required that special turbines are ordered from the manufacturer that take into account specific considerations of climatology conditions in design, mostly when flexural and torsion rigidity are in question.

Lastly, it has to be noticed that these considerations are principally associated with turbulence characteristics of the wind farm site.

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NEIZVESNOST PROCENE EKSTREMNE BRZINE VETRA I KLASIFIKACIJA VETRO TURBINA ZAVISNO OD LOKACIJE

Sažetak: Ispravno predviđanje maksimalne brzine vetra, kao i intenziteta turbulencije vetra koji se očekuje u budućem vremenskom intervalu, kao i određivanje klasa vetroturbina koje trebaju da se instaliraju na određenoj lokaciji su od presudnog značaja za izgradnju vetroelektrana.

Maksimalna brzina vetra se definiše kao ekstremna brzina vetra ili referentna brzine vetra prema standardu IEC 61400–1. Turbina projektovane klase sa odgovarajućom referentnom brzinom vetra i intenzitetom turbulencije je tako projektovana da klimatski

uslovi definisani prema očekivanoj ekstremnoj desetominutnoj brzini vetra u periodu za narednih 50 godina na visini centra rotora, bude niža ili jednaka referentnoj brzini vetra za određenu lokaciju.

U radu su date analize nesigurnosti različitih metodologija za procenu ekstremne brzine vetra, kao i intenziteta turbulencije na osnovu dostupnih eksperimentalnih setova podataka koji su korišćeni i za određivanje klasa turbina.

Dobijeni rezultati iz skupova podataka na osnovu dve i tri godine merenja su poređeni s obzirom na procenu neizvesnosti određivanja ekstremne brzine vetra i inetnziteta turbulencije kao i ekonomske opravdanosti potrebnog perioda merenja.

Procena neizvesnosti, kao i metodologija određivanja ekstremne brzine vetra je urađena statističkim alatima opšte teorije ekstremnih vrednosti.

Osim toga, na osnovu raspoloživih podataka klimatologije za jednu određenu lokaciju, i digitalnog modela terena, predstavljena je metodologija određivanja klasa turbina na različitim lokacijama unutar vetroparka korišćenjem numeričke mehanike fluida u kombinaciji sa opštom teorijom ekstremnih vrednosti.

Ključne reči: *Energija vetra, ekstremna brzina vetra, intenzitet turbulencije vetra*