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RELIABILITY OF ELECTRIC POWER GENERATION IN POWER SYSTEMS WITH THERMAL AND WIND POWER PLANTS

M. VALDMA*, M. KEEL, H. TAMMOJA, K. KILK

Department of Electrical Power Engineering
Tallinn University of Technology
5 Ehitajate Rd., 19086 Tallinn, Estonia

The principles of evaluation of the reliability of electric power generation in a power system including thermal and wind power plants are considered in this paper. Besides classical probabilistic models the use of uncertain probabilistic and fuzzy probabilistic models of reliability is recommended. Generation of electric power at wind power plants is treated as a non-stationary stochastic process controllable only to down. The paper presents numerical examples.

Introduction

Reliability is a fundamental requirement put to the power systems and their subsystems. Different probabilistic models [1, 2] are used for evaluation of the reliability of power systems. Yet the probabilistic models are not sufficiently general for reliability evaluation. In a power system the failures take place relatively seldom, and the failure-repair cycle changes in very large limits. The questions when a failure occurs and how long it will take to repair are rather uncertain or fuzzy events than probabilistic cases. Therefore also the perspectives of using the uncertain and fuzzy models for evaluation of the power system reliability [3] are studied.

In this paper we will introduce the probability, uncertain probability and fuzzy probability models of reliability and their applications for the analysis of electric power generation reliability. The paper is based on reliability studies of oil shale power plants and units.

The output power of wind power plants is treated as a non-stationary random process. Their reliability from the classical point of view is very low. Some special characteristics are used for describing the availabilities of wind power plants.

* Corresponding author: e-mail address *mati.valdma@ttu.ee*

Probabilistic models

The reliability is regarded as the ability of a system to perform its required function under stated conditions during a given period of time [1]. In the strict conception the reliability is a probability that the system is operating without failures in the time period *t*. Let us look at the main probabilistic characteristics of reliability [2–5].

Reliability function $p(t)$ is a function which expresses the probability that the system will operate without failure in the period *t:*

$$p(t) = P\left\{\tilde{T} < t\right\}, \tag{1}$$

where $\tilde{T}$ – period without failures, continuous random variable;
P – symbol of probability.

The function $p(t)$ decreases if *t* increases, $p(t) = 1$ if $t = 0$.

Non-reliability function or failure probability function $q(t)$ is a function which expresses the probability that a failure will happen in the period *t*:

$$q(t) = 1 - p(t) \tag{2}$$

Distribution function of time without failure $F(t)$:

$$F(t) = P\left\{\tilde{T} < t\right\} = q(t). \tag{3}$$

Density function of time without failures $f(t)$:

$$f(t) = \frac{\partial F(t)}{\partial t} = \frac{\partial q(t)}{\partial t}. \tag{4}$$

If intensity of failures is constant, the reliability function is the exponential function:

$$p(t) = e^{-\lambda t}, \tag{5}$$

and

$$f(t) = \lambda e^{-\lambda t}, \tag{6}$$

where λ – intensity of failures.

The exponential reliability function $p(t)$ and distribution function $F(t)$ of a power unit are shown in Fig. 1.

On the basis of density function we can evaluate the expectation, variance and standard deviation of the period without failures.

Expected period without failure $\overline{t}$:

$$\overline{t} = \int_0^\infty t \cdot f(t)dt. \tag{7}$$

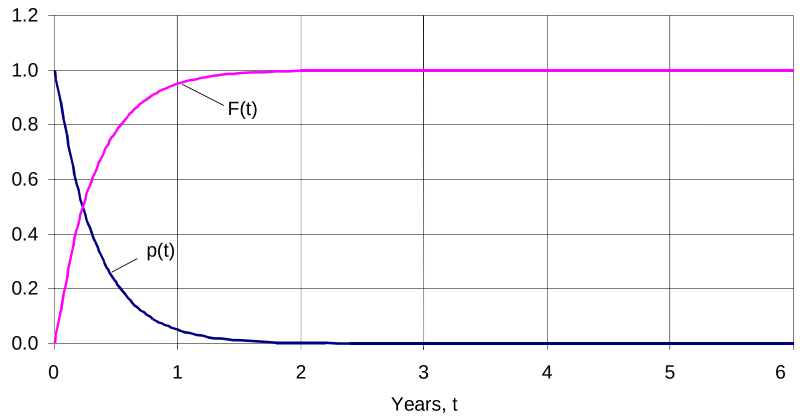

Fig. 1. Reliability function *p(t)* and distribution function *F(t)* of power unit, $\lambda = 3$.

Variance of period without failures, which measures the dispersion of values away from the expected time to failure:

$$D_t = E(t-\bar{t})^2 = \int_0^{\infty} (t-\bar{t})^2 f(t)dt \quad (8)$$

Standard deviation of period without failures:

$$\sigma_t = \sqrt{D_t} \quad (9)$$

In practice the reliability evaluation takes place on the basis of expected failure rate and expected repair rate, or on the basis of mean time to failure and a mean time to repair. According to that the following probabilities [2] are determined:

1) Unavailability (forced outage rate) of object *q*

$$q = FOR = 1 - p = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \quad (10)$$

2) Availability of object *p*

$$p = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \quad (11)$$

where λ – expected failure rate;
μ – expected repair rate;
m – mean time to failure, $m = 1/\lambda$;
r – mean time to repair, $r = 1/\mu$.

Here the probabilities *p* and *q* are the corresponding probabilities at some distant time in the future.

Statistical indicators of reliability for power units are often changing within great limits and confidence limits of probabilities are ordinarily very large. This indicates the need to consider uncertain and fuzzy factors in the reliability modeling.

Uncertain probabilistic models

Uncertain probabilistic models are the probabilistic models, the parameters of which are given by crisp intervals and the values of parameters are uncertainties in those intervals.

If the value of intensity λ is not given exactly, the intensity of failures must be described as an uncertain variable in the crisp interval. Then the reliability function is an uncertain probabilistic function:

$$p(t,\lambda_2(t)) \le p(t) \le p(t,\lambda_3(t)) \tag{10}$$

If λ_2 and λ_3 are constants, we have

$$e^{-\lambda_2 t} \le p(t) \le e^{-\lambda_3 t} \tag{11}$$

The exponential reliability function $p(t)$ and distribution function $F(t)$ of a power unit in the uncertain form are shown in Fig. 2. The intensity of failures is given by intervals:

$$2 \le \lambda \le 3.5 . \tag{12}$$

The other characteristics and indicators of reliability in the uncertain probabilistic form can be analogically described.

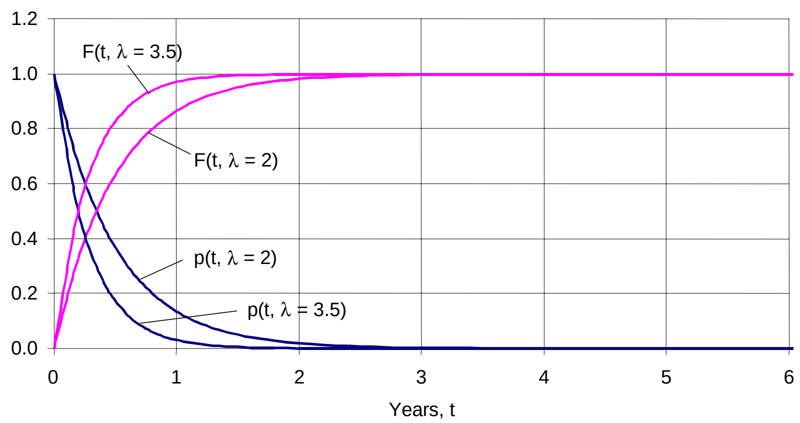

Fig. 2. Reliability function $p(t)$ and distribution function $F(t)$ of a power unit in the uncertain form, $\lambda_2 = 3.5$ and $\lambda_3 = 2$.

Fuzzy probabilistic models

Actually the limits of reliability characteristics are not given exactly. In reality the intervals of reliability characteristics values are fuzzy zones. Consequently we must use the fuzzy probabilistic models of reliability.

The fuzzy probabilistic models are the probabilistic models whose parameters are given by fuzzy intervals.

A fuzzy zone $\tilde{A}$ is defined in *U* as a set of ordered pairs [5]:

$$\tilde{A} = \left\langle (x, \mu_A(x) \middle| x \in U \right\rangle , \tag{13}$$

where $\mu_A(x)$ is called the membership function, which indicates the degree of that *x* belongs to $\tilde{A}$. The membership function takes values [0, 1] and is defined so that $\mu_A(x) = 1$ if x is a member of $\tilde{A}$ and 0 otherwise. At that, if $0 < \mu(x) < 1$, the *x* may be the member of $\tilde{A}$. *U* is the given crisp set. The application of fuzzy systems in reliability analysis is nowadays expanding.

A typical membership function of intensity λ is shown in Fig. 3.

Figure 4 shows the exponential reliability function *p(t)* and distribution function *F(t)* of a power unit in the fuzzy form if the membership function is $\mu(\lambda)$.

The other indicators of reliability may be presented in the fuzzy probabilistic form in an analogical way.

Fig. 3. Membership function $\mu(\lambda)$.

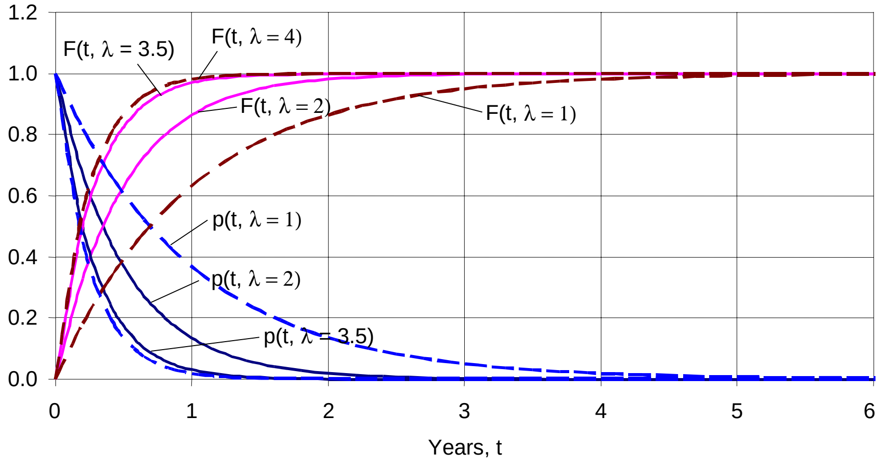

Fig. 4. The reliability function *p*(*t*) and distribution function *F*(*t*) of a power unit in the fuzzy form: $\lambda_1 = 4.0$, $\lambda_2 = 3.5$, $\lambda_3 = 2.0$ and $\lambda_4 = 1.0$.

Reliability of power units

The models described above were used for reliability analysis of oil shale power plants in the Estonian power system in the years 2000–2005. Power units have two boilers per unit. Capacity of a unit with two boilers is 200 MW, and with one boiler – 100 MW.

The uncertainty intervals of reliability indicators for boilers, turbine, generator and for the whole unit are presented in Table 1.

Table 1 shows that reliability indicators of the unit are changing within rather great intervals. Therefore the limits of intervals are inaccurate.

The probabilistic models of reliability for power system generation in the uncertain probabilistic form are shown in Figures 5 and 6.

Table 1. **Intervals of reliability indicators of oil shale power units 200 MW (λ – expected failure rate; μ – expected repair rate, *m* – mean time to failure, $m = 1/\lambda$; *r* – mean time to repair, $r = 1/\mu$)**

	Boiler	Turbine	Generator	Power unit
λ	1.40–4.67	1.0–1.5	0.14–0.29	7.71–10.86
μ	73–250	102–190	79–584	138–252
r	0.0046–0.0137	0.0052–0.0098	0.0017–0.0127	0.0040–0.0072
m	0.2143–0.4286	0.7–1.0	1.75–7.00	0.0921–0.1296
p	0.9494–0.9936	0.9863–0.9939	0.9977–0.9993	0.94055–0.96765
q	0.0064–0.0506	0.0061–0.0137	0.0007–0.0023	0.03235–0.05945

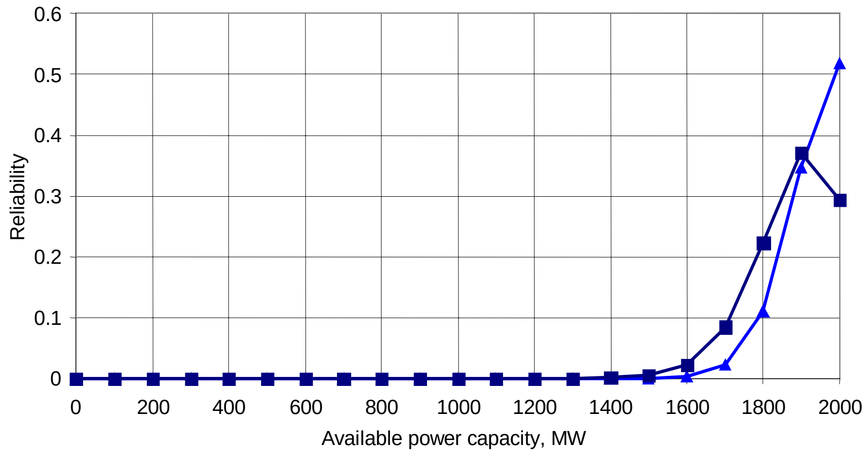

Fig. 5. Uncertain probabilistic model of reliability for a ten-unit electric power system generation.

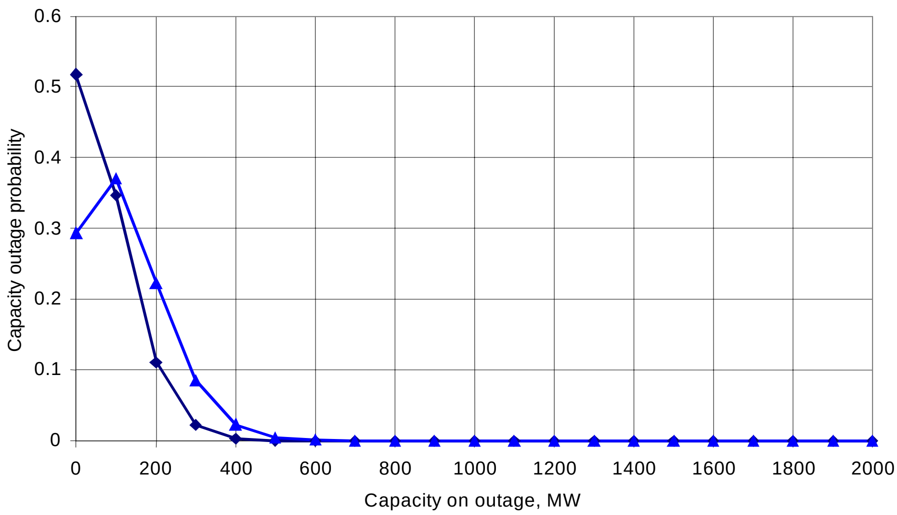

Fig. 6. Zone of uncertainty for probability of capacity outage for a ten-unit power system.

If we consider the inexactness of confidence limits, it would be expedient to present the information about reliabilities and probabilities of failures in the fuzzy probabilistic form.

The information about unit's reliability in the uncertain probabilistic and fuzzy probabilistic forms is presented in Table 2.

The fuzzy probabilistic models of reliability for power system generation in the fuzzy probabilistic form are shown in Figures 7 and 8.

Table 2. **Fuzzy intervals for reliability indicators**

	Fuzzy essential points			
	μ = 0	μ = 1	μ = 1	μ = 0
λ	1.57	2.86	7.71	10.86
r	0.0039	0.0040	0.0072	0.0090
m	0.0921	0.1296	0.3500	0.6364
p	0.9406	0.9676	0.9818	0.9938
q	0.0062	0.0182	0.0324	0.0594

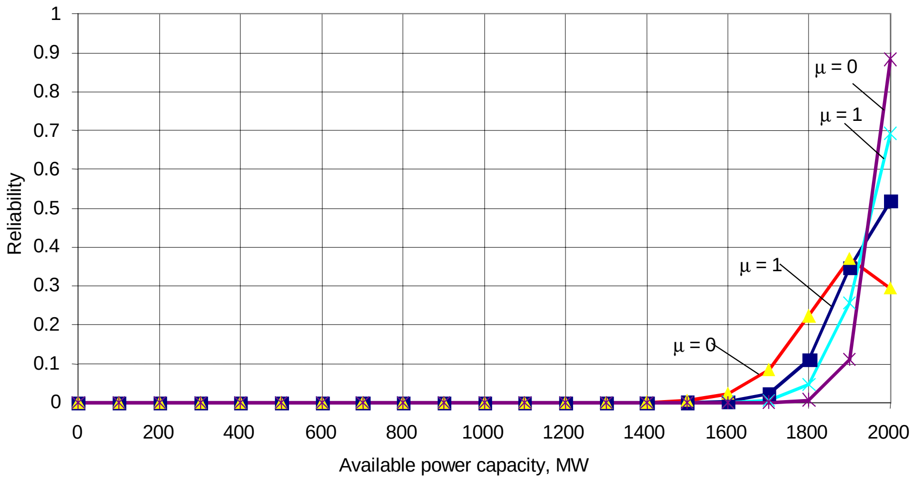

Fig. 7. Fuzzy probabilistic model of reliability for a ten-unit electric power system generation.

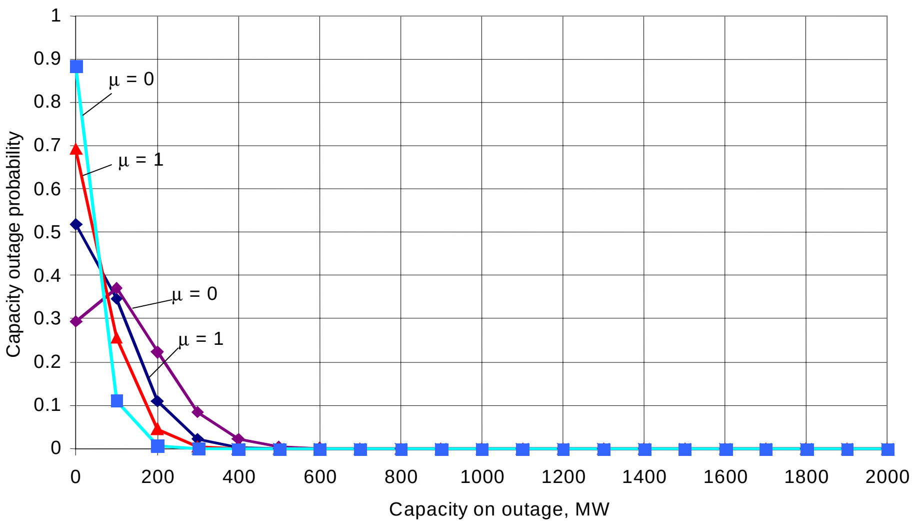

Fig. 8. Fuzzy probabilistic functions of capacity outage for a ten-unit power system.

The fuzzy probabilistic models enable to use exact probabilistic, uncertain probabilistic and fuzzy probabilistic information for describing the reliability characteristics and indicators of units.

Reliability of wind generators

The usage of wind power plants shows an increasing tendency. With that the problems of wind power plants' reliability and their effect on power system operation are becoming extremely relevant.

Wind speed and power output of wind power plants are random processes. The functions of autocorrelation of wind power show large variations. In [6] the data about short-term power fluctuations of wind power plants is presented. Wind power is controllable only to down and may change every second. Therefore the traditional reliability indicators are not very suitable for wind power plants.

In the case of wind power plants, both the value of power output and the duration of this value are random variables. For approximate description the loads of wind power plants, two-dimensional distribution functions may be recommended:

$$F_{WP}(P(t),\tau(t)) = G\left(\tilde{P}(t) < P(t)\right) \cap (\tilde{\tau}(t) < \tau)\} \qquad (14)$$

where G – probability;

F_{WP} – distribution function of wind power;

$P(t)$ – value of wind power;

$\tau(t)$ – duration of wind power value;

$\tilde{P}(t), \tilde{\tau}(t)$ – random variables.

On the basis of function (14) practical models may be derived for describing and making the prognosis for power outputs of wind power plants.

Figure 9 shows the distribution of wind speed duration at Pakri Wind Park (Estonia), and Figure 10 – the distribution diagram of output power duration for Pakri Wind Park. For comparison the same diagram and distribution function for wind power plants in Denmark is presented in Fig. 11.

The diagrams and distribution functions in Figures 10 and 11 are very similar.

For comparison in Fig. 12 are shown the monthly generation factors *K* of Pakri Wind Park and wind power plants of Denmark. The monthly generation factor is:

$$K = \frac{\overline{P}}{P_{\max}},$$

where $\overline{P}$ – average power output in month;

$P_{\max}$ – peak generation in month.

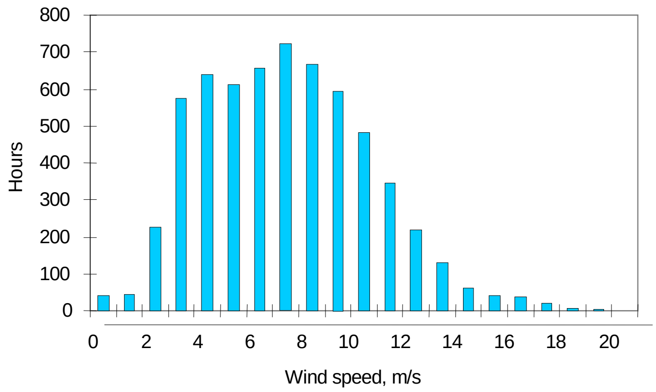

Fig. 9. Distribution diagram of wind speed duration in Pakri Wind Park (IV, 2005 – XII, 2005).

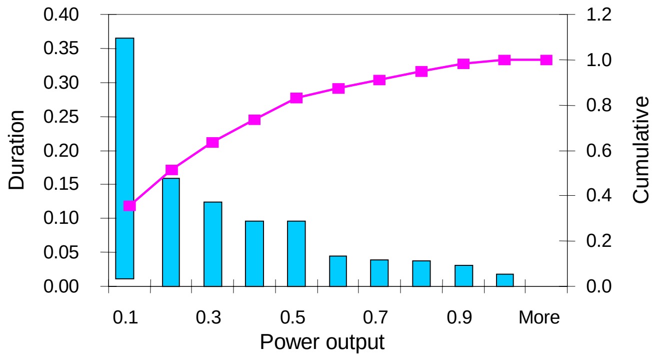

Fig. 10. The distribution diagram and distribution function of power output duration for Pakri Wind Park (2006).

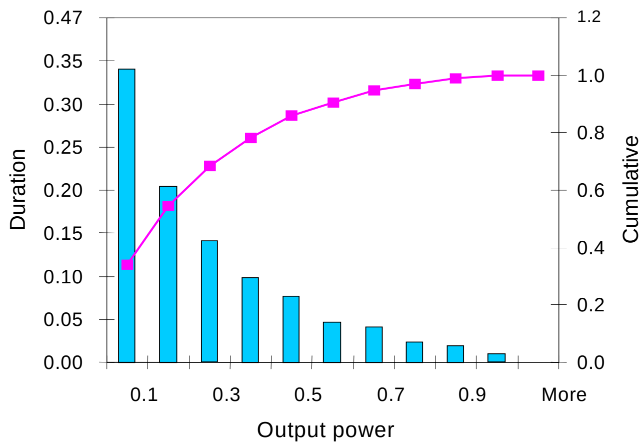

Fig. 11. The distribution diagram and distribution function of power output for wind power plants of Denmark (2006) [7].

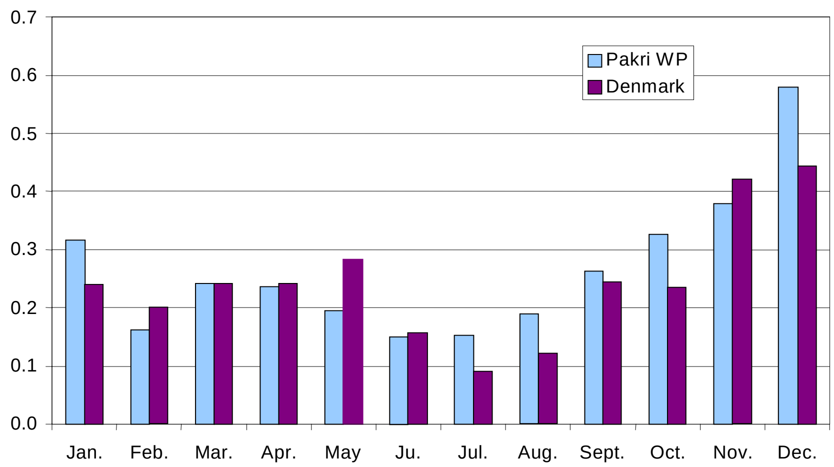

Fig. 12. Monthly generation factors changing in a year for Pakri Wind Park and wind power of Denmark

The average values of monthly generation factors of Pakri Wind Park and wind power plants of Denmark are 0.27 and 0.24.

Conclusions

1. The use of uncertain probabilistic and fuzzy probabilistic models is a suitable method for the analysis and control of power system reliability, since they are more general and more complete than traditional probabilistic models of reliability.
2. Power generation at wind power plants is a random process. Two-dimensioned distribution functions of power values and power durations can be used for modeling and making prognosis of wind power generation.
3. Uncertain and fuzzy models have also a prospect for modeling wind power generation.

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