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Stochastic Modeling of a DFIG Wind Turbine in Matpower

YULY D. BAY, ALEKSEY A. SUVOROV, ALEXANDR S. GUSEV, IGOR A. RAZZHIVIN, AND ALISHER B. ASKAROV
School of Energy and Power Engineering, Tomsk Polytechnic University, 634050 Tomsk, Russia

Corresponding author: Yuly D. Bay (nodius@tpu.ru)

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ABSTRACT One of the main trends in the electric power industry is the use of green energy – renewable energy sources (RES), especially wind power generation. The penetration of large wind turbine (WT) power capacity leads to changes in the topology and characteristics of electric power systems (EPS), which can cause an increase the likelihood of emergency processes and a decrease in the steady-state and transient EPS stability. The issue arises in ensuring the EPS stability with RES units, especially in the case of large disturbances. The main way to solve this issue is mathematical modeling. However, almost all the main currently used software programs are based on deterministic methods for calculating EPS processes, which are not able to consider all possible state uncertainties. To reliably determine all possible states of the system in which it can be, it is necessary to determine in a non-deterministic form how the values in the nodes and branches will be distributed. The peculiarity of this paper is associated with the use of a set of approaches to increase the accuracy of the results obtained: the approximation method in combination with two goodness-of-fit criteria for wind; the SIBD method, which generates the required probability density without loss of density values; and the controlled discretization of input variables. This paper assumes the formation of a WT stochastic model to study the impact of RES on stability in a non-deterministic form using the example of IEEE standard bus systems in the Matpower program.

INDEX TERMS Wind turbine, wind speed time series, probability density function, cumulative distribution function, power system stability, numerical simulation.

I. INTRODUCTION

Currently, due to the environmental challenges associated with the use of fossil fuels as the main energy sources for power production, wind energy has become the most promising alternative among renewable energy sources (RES). This is due to the rapid development of generation and distribution technologies, power conversion, and new policies that encourage the use of new generation technologies in electric power systems (EPS).

According to the International Renewable Energy Agency (IRENA) analysts, the RES penetration, as well as electrification and increased energy efficiency, will provide more than 90% of the greenhouse gas emissions reduction needed to achieve the Paris Agreement aim. According to the IRENA forecasts, wind power generation will provide more than a third of the world's electricity demand by 2050.

It is worth noting the risks associated with an inaccurate knowledge of the probability distribution function (PDF) describing these sources [1]. The stochastic nature of the generated power can adversely affect the EPS stability, excessively decrease the total system inertia, which can also lead to unforeseen accidents (Fig. 1). The calculation of electricity consumption is not only the basis for studying the entire EPS, but also a criterion for the steady-state and transient stability assessment [2].

To study this issue, in order to minimize the possible difference between the required and generated power, the consideration of the RES penetration must be carried out in a non-deterministic form, as well as it is necessary to find the full probabilistic characteristics. The main issue is that obtaining probabilistic characteristics by standard statistical methods does not have a comprehensive solution [3].

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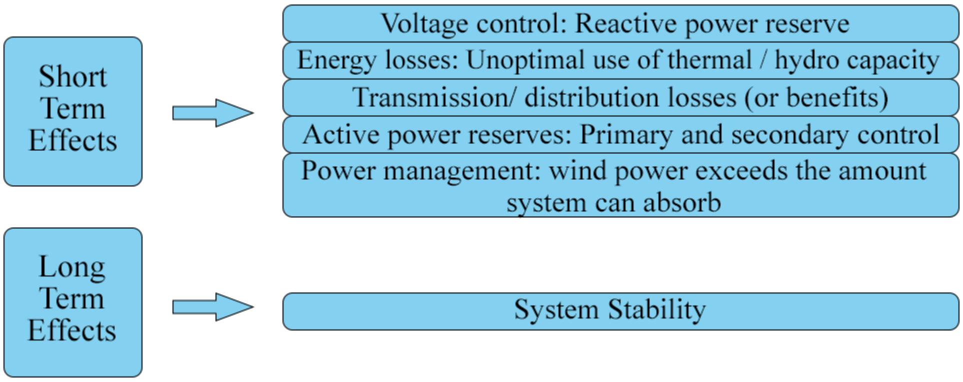


FIGURE 1. Impact of wind power generation on power system operation.

Unlike conventional generating units (synchronous generators), the output characteristics of RES depend on the geographic features of the area where the units are installed, the season and the average wind speed [4].

Based on the results of the existing scientific works analysis, several options for modeling wind turbines can be noted. The first one is a deterministic modeling of wind generation units and the study of the steady-state and transient processes [5]. In addition, a number of works consider which wind laws can be applied to the modeling of wind turbines during approximating full-scale measurements using the goodness-of-fit criteria [6]. Moreover, the current methods for reliable approximation of the probability distribution laws based on the available wind time series and the goodness-of-fit criteria are studied. The difference from previous literature sources is that no limitations on the types of laws are used in Ref. [7]. There are results of modeling the impact of wind turbines on the EPS stability in a non-deterministic form, when the input characteristic of the wind turbine (WT) is a predetermined probability distribution law, and the initial EPS load power is set randomly, using the Monte Carlo method [8]. However, more and more often, a full-fledged version of calculations is used with a specific, full-scale example of the wind law, and an assessment of the goodness-of-fit criteria [9]. Finally, the modifications of Monte Carlo algorithm using the economic component of the RES penetration are developed. The modeling of the most common uncertainties (such as load demand, electricity price, RES generation), as well as possible variants of the modified Monte Carlo methods, and other methods of stochastic EPS modeling have been described in detail in Ref. [10].

Most of the power system modeling programs currently use deterministic methods and are unspecialized for stochastic EPS modeling. To obtain probabilistic characteristics, single calculations or a number of calculations are used with a randomly set of wind turbine power and its probabilistic characteristics, respectively. In addition, there are various scientific works aimed at the assessment of the wind probabilistic characteristics and their accuracy, as well as the correct formation of the WT power curve using different power functions (linear, quadratic, etc.). However, there are practically no, or extremely rare, works devoted to a complete and comprehensive analysis of the full probabilistic characteristics of the EPS parameters, including wind turbines, based on the full and reliable probabilistic characteristics of the initial generation and load data.

To solve this issue, it was decided to form an algorithm for a unified calculation process, which includes the use of justified WT probabilistic data, in conjunction with the probabilistic data of the EPS load and generation. This approach allows to carry out non-deterministic calculations of steady-state EPS operation. The most relevant software package for the implementation of such approach is the Matlab Matpower, which is used in this paper, due to the ease of monitoring and changing of any data involved in the calculation process, and the existing base of IEEE test systems. Moreover, the relationship of this subroutine to the Matlab program allows to implement a proposed algorithm and a calculation of any complexity. To do this, it is required to create an appropriate model and probabilistic characteristics of a wind turbine generator that can work in this program based on real wind time series data using approximation methods and goodness-of-fit criteria. In this regard, the following requirements are imposed on the developed WT model:

- the use of complete and reliable WT data, obtained by wind time series approximation;
- the use of controlled EPS arguments discretization to take into account the data of rare repeatability;
- the possibility of stochastic EPS calculating and obtaining reliable probabilistic characteristics of the system parameters on the entire data interval of the probability density formation, in accordance with the selection of interval boundaries of input and output data (SIBD) method.

For high-quality modeling of EPS with RES, it is necessary to use wind turbine generator models with the possibility of taking into account stochastic changes. Considering the features of well-known EPS modeling programs (Eurostag, PSS® E, etc.) when using macros, Matlab was chosen to study the issue, which has the ability to program all the required functions. Several of previous works have already studied the possibility of obtaining the probabilistic characteristics of the steady-state using the proposed SIBD method in Matpower [11], [12].

Matpower is a special package of Matlab® M-files, using to calculate power flow (PF) and optimal power flow (OPF) tasks [13]. Its main feature, in comparison with Simulink and Simscape Electrical, is that Matpower allows to quickly solve large-scale power systems. In this paper the nonlinear AC model with corresponding options will be used, the solution of which will be carried out using the 'NR' method – Newton's method [14], since it provides the fastest system solution, all other things being equal.

II. PROBLEM STATEMENT FOR DFIG MODELING

Throughout the development and implementation of wind turbines, the use of various types of generators has been studied – fixed speed cage or wound-rotor induction generators, variable speed doubly-fed induction generators (DFIG) and permanent-magnet generators (PMG). The most state-of-the-art WTs are Type-3 (with DFIG) and Type-4 (with gearless PMG) wind turbine generators. This paper focuses on the application of DFIGs, since they are gaining wide acceptance in the power industry among the different types of WTs, which is due to several reasons. The main reason can be considered the ability to flexibly vary its operating speed to gain optimum WT power generation. This is achieved by supplying the rotor circuit with real and reactive power from the back-to-back converter, as shown in Fig. 2. The converter circuit makes it possible to both produce and consume reactive power, which is not possible for fixed speed induction generators. Consequently, DFIGs do not cause the same voltage instability issues as the latter [15].

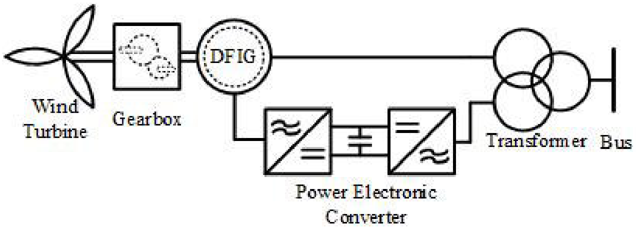


FIGURE 2. **Standard configuration of a DFIG turbine.**

After determining the DFIG power factor, the nodes associated with wind power installation location is considered as time-varying *P-Q* nodes with active power as a function of wind speed and reactive power as a function of active power and voltage at generator terminals. If the generator voltage has been set in advance, and the reactive power of the wind turbine is adjustable, the nodes will be considered as *P-V* nodes, changing over time series. In practice, these two types of node models are interchangeable. For modeling in Matpower, it is also possible to model DFIGs as *P-Q* or *P-V* nodes, depending on the objectives of the study [16].

In the case of modeling a DFIG as a *P-Q* node, it is assumed that the wind turbine is operating in the power factor control mode, i.e. the initial value of reactive power is equal to zero. In the case of modeling a DFIG as a *P-V* node (voltage control mode) – the reactive power limits are applied. For dispatchable generators it is required to define 'type' = 2 (*P-V*) in Matpower, and set the generator data. For non-dispatchable generators (such as wind power), it is required to set node as 'type' = 1 (*P-Q*) and define the power injected as negative load.

Currently, one of the main trends in the EPS with RES development and management is to keep a given voltage level in the network nodes. According to this, the wind turbine generator will be set as a *P-V* node, in order to be able to set the required voltage, including in a probabilistic form. The logic of the experimental studies consists in the wind turbine probabilistic analysis, which requires the use of the wind turbine generator as a controlled unit, while the *P-Q* type simulation is better suited for deterministic use of the EPS with RES calculation and analysis.

III. THE WIND SPEED PROBABILITY DISTRIBUTION APPROXIMATION

The wind turbine power capacity highly depends on the turbine type used in the wind farm and geographical location. The accuracy of wind power generation forecasting can be achieved by taking into account all possible factors that may affect the final capacity [17]. The wind speed on the area varies randomly, and its change in a certain region over a certain period of time can be represented by various PDF. The selection of a suitable probability distribution law to describe the actual wind speed distribution is one of the most important tasks for the accuracy of forecasting, studying and modeling.

The most commonly used distribution is the two-parameter Weibull distribution [18], which can be described by Eq. (1). It is a versatile PDF, is simple to use, and is found to be accurate for most of the wind characteristics encountered in nature [19]. However, Weibull distribution is not suitable for certain wind regimes.

$$PDF(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where k and c are the shape and scale factor of the Weibull PDF, respectively.

The selection of the distribution law depends on many factors, including the features of specific task. To determine the calculated wind speed, the main requirement is a reliable coincidence of empirical and theoretical distributions in the high values region. The wind speed distribution has also been described in the literature using several other PDFs, which include lognormal, beta, and gamma distributions. A detailed review of different PDFs for wind speed modeling and techniques for estimation of their parameters is given in Ref. [20]. Subsequently, the approximation of the wind speed distribution by the Weibull and Weibull-Goodrich law has become one of the most widely used. Along with this law, the normal distribution law is often used for theoretical alignment, but a large sample size is required for reliable estimation of the distribution parameters.

The wind is stochastic in nature. To deal with wind speed, it is necessary to describe its behavior by a probability density function. The distribution that is used to describe wind speed affects the estimate of the wind energy potential due to the cubic dependence between wind speed and power, consequently, even a small change in wind speed can lead to a significant change in power. For this reason, the chosen distribution should fit well with the measured wind speed data.

The wind speed data used in this paper will be extracted using a graphical method and an appropriate check will be carried out using the Pearson and Kolmogorov goodness-of-fit criteria [21]. For the experimental studies, a sample of wind time series data with an unknown cumulative distribution function (CDF) was taken (Fig. 3).

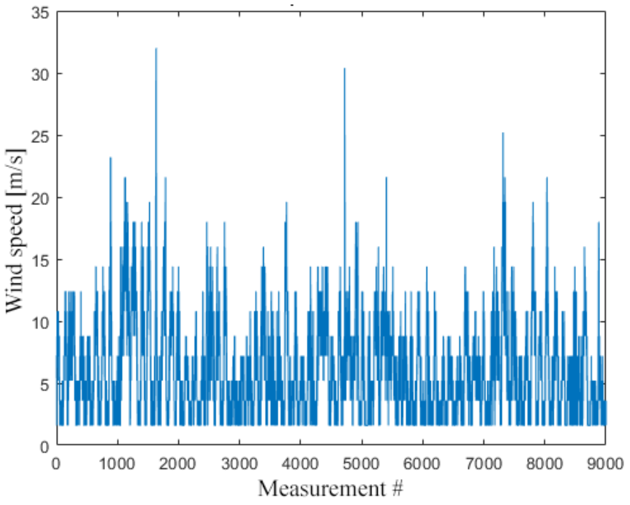


FIGURE 3. Wind time series data.

The sample size is 9000 measurements. Based on the information provided, preliminary conclusions can be drawn about the frequency of the wind values, the both maximum observed and average values.

Before starting the process of finding a suitable CDF and validating it against the goodness-of-fit criteria, the wind input data needs to be processed. To do this, the unique values that occur in the wind time series were extracted, as well as the number of occurrences of each unique wind speed value was found. After this, the total number of measurements, the cumulative frequency and density of the distribution at the last step were obtained (Fig. 4). This procedure is performed using a script that computes the distribution parameters from the wind time series, programming in Matlab by Robin Roche [22]. In this case, the Weibull law was accepted.

Further, the Weibull parameters through the linearize distributions using the polynomial curve fitting function were extracted [23]. The results are shown in Fig. 5. The parameters for constructing the model were following: k = 1.4028 and c = 5.2612, respectively (Fig. 6).

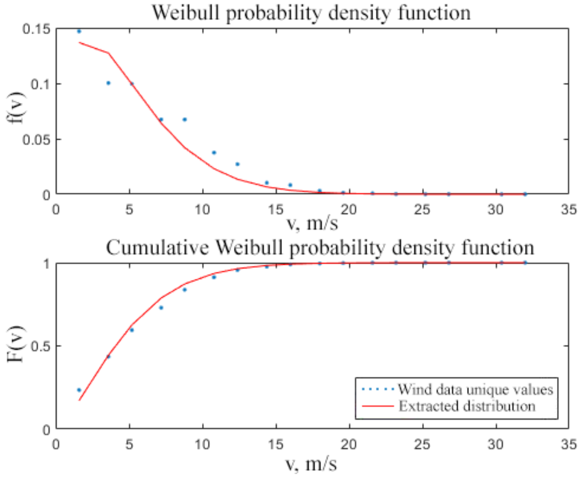


FIGURE 4. Extracted probabilistic characteristics.

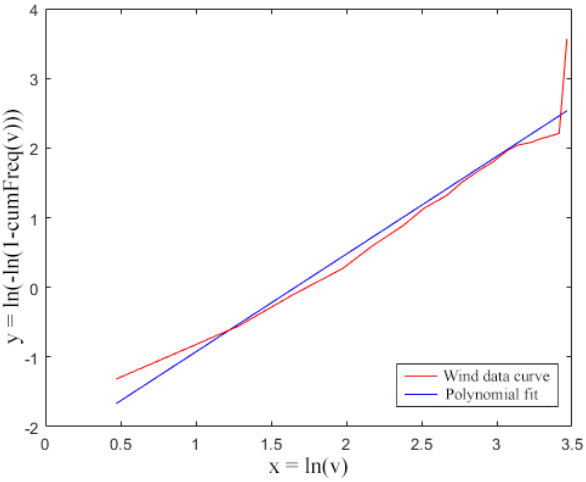


FIGURE 5. Polynomial curve fitting function.

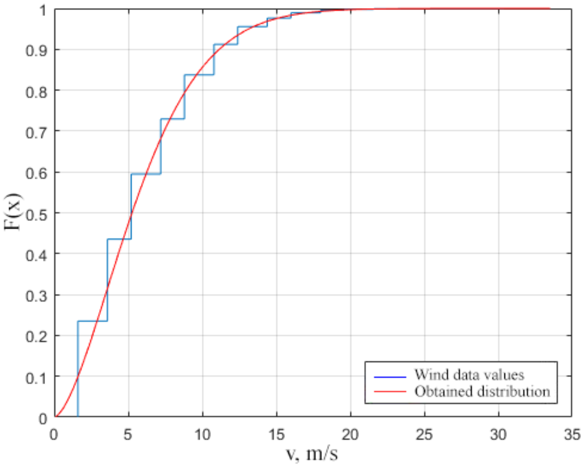
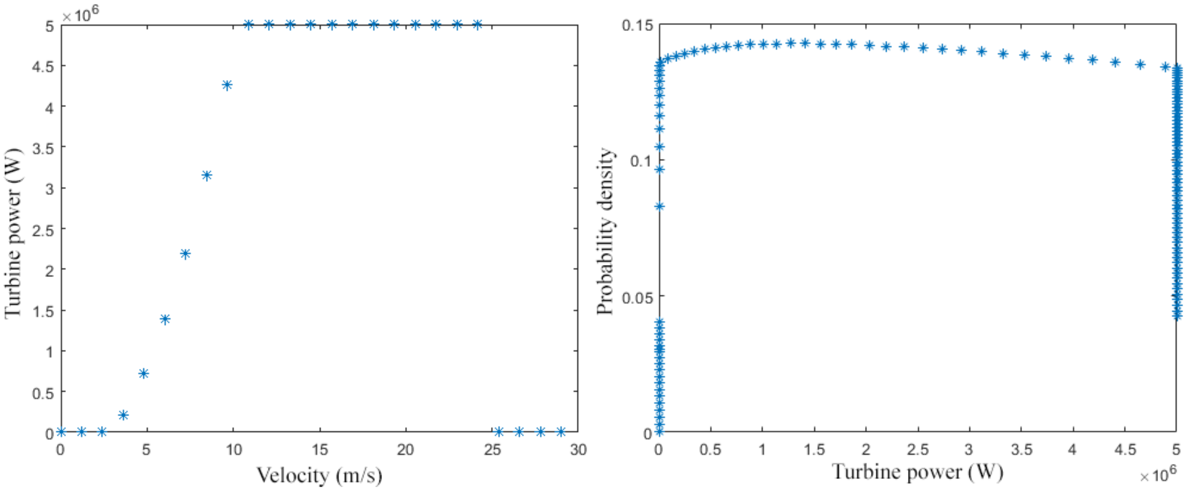


FIGURE 6. Obtained wind data CDF.



(a) ***(b)***

FIGURE 7. **Wind turbine power curve characteristics.**

The suitability of the chosen theoretical distribution for describing the empirical probability of a given meteorological argument is verified using the goodness-of-fit criteria (Table 1):

TABLE 1. **Goodness-of-fit testing results.**

Goodness-of-fit criteria	Fitted distribution	Critical significance level	Chi-squared test	Critical value
Kolmogorov	Weibull	0.962	-	-
Pearson	Weibull	-	502.400	537.808

According to the goodness-of-fit tests, by applying both criteria (with a given 5% significance level), the selected theoretical distribution function can be reliably used for indirect calculations.

IV. WIND TURBINE POWER CURVE MODELING

The power curve of a wind turbine represents the relationship between the input wind speed and the output mechanical power, and is an important characteristic of the turbine. With the growth of wind power generation, WTs are installed in various climatic conditions, both onshore and offshore, as well as in difficult landscapes, which leads to a significant deviation of these curves from the guaranteed values. Accurate power curve models can play an important role in improving the wind generation performance. Possible models of the wind turbine power curve can be found in Ref. [24].

In this paper, to test the general structure of the algorithm of finding the steady-state probabilistic characteristics with RES, it is sufficient to use a simplified model [25]. The generated power of a wind turbine is determined using its speed and power curve as in Eq. (2).

$$P_i^w = \begin{cases} 0 & if\ v \le v_{in}\, or\, v \ge v_{out} \\ \dfrac{v^2 - v_{in}^2}{v_{rated}^2 - v_{in}^2} P_{i,r}^w & if\ v_{in} \le v \le v_{rated} \\ P_{i,r}^w & else \end{cases} \tag{2}$$

where $P_{i,r}^w$ is a rated power of wind turbine installed in node i, P_i^w is a generated power of wind turbine in node i, v_{out} is a cut-out speed, v_{in} is a cut-in speed and v_{rated} is a rated speed of the wind turbine.

For experimental studies, the NREL 5.0 MW Baseline Wind Turbine was selected (Table 2) [26].

TABLE 2. **Parameters of DFIG.**

Parameter	Quantity	Values
Cut-in speed	m/s	3
Rated wind speed	m/s	10.4
Cut-out speed	m/s	25
Rotor radius	m	126
Rated power	MW	5
Hub height	m	90

According to the data in Table 2, taking into account the Eq. (2), it is possible to form a WT power curve and the corresponding probability density (Figs. 7a and 7b). To simplify the model, the electrical and mechanical losses can be ignored. In the case of studying transient stability, the used models of the generator, gearbox, and converter can have a major impact on the results accuracy, especially during the disturbances near the RES location.

V. EXPERIMENTAL RESULTS

The computational algorithm was tested on the IEEE 14-bus system model (Fig. 8). It is part of the American power grid (Midwestern US), as of February 1962. The system has 14 buses, 5 generators, and 11 loads. The basic power of the system is 100 MVA. Detailed information is provided in the technical documentation [27].

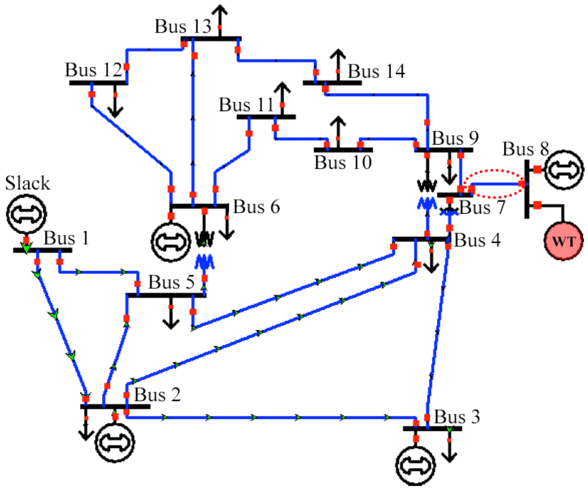


FIGURE 8. IEEE 14-bus system.

Active power and voltage level of the generators, active and reactive power of the loads are set according to predetermined expected value (EV) and standard deviation (SD), and all non-deterministic vectors are calculated with respect to the inverse normal and uniform CDF distribution as in Eq. (3).

$$\begin{cases} f_{1n}(n_1),\ f_{1q}(q_1),\ \ldots,\ f_{in}(n_i),\ f_{iq}(q_i), \\ f_{g1n}(n_{g1}),\ f_{g1u}(u_{g1}),\ \ldots,\ f_{gkn}(n_{gi}),\ f_{gku}(u_{gi}), \\ c_{1n}(n_1),\ c_{1q}(q_1),\ \ldots,\ c_{in}(n_i),\ c_{iq}(q_i), \\ c_{g1n}(n_{g1}),\ c_{g1u}(u_{g1}),\ \ldots,\ c_{gkn}(n_{gi}),\ c_{gku}(u_{gi}); \end{cases} \tag{3}$$

At this stage, the initial WT probabilistic data was also set in the calculation program.

After that, the quantile orders of the source data were selected, which will be adhered to, from the range from 0 to 1 ($0, \ldots, p_1 \ldots, p_j \ldots, 1$) with a uniform step. The preparation of quantiles and quantile orders of the variable mode values is necessary for solving the main problem, since this allows using of probabilistically determined data.

If there is no dependence between the parameters in the nodes, the system can be simplified as in Eq. (4) (for the zero quantile order).

$$\begin{cases} n_{10} = f_{1n}^{-1}(0), q_{10} = f_{1q}^{-1}(0), \\ n_{i0} = f_{i1n}^{-1}(0), q_{i0} = f_{iq}^{-1}(0), \\ n_{g10} = f_{g1n}^{-1}(0), u_{g10} = f_{g1u}^{-1}(0), \\ n_{gk0} = f_{gkn}^{-1}(0), u_{gk0} = f_{gku}^{-1}(0); \end{cases} \tag{4}$$

The solution is formed for all quantile variants of a given order for the case of independent components at network nodes. If necessary, this dependence can be taken into account by adding a correlation coefficient. Further, the PDF of the values from the zero-order random value (RV) quantiles can be formed as in Eq. (5).

$$\begin{cases} c_{1n}(n_{10}),\ c_{1q}(q_{10}),\ \ldots,\ c_{in}(n_{i0}),\ c_{iq}(q_{i0}), \\ c_{g1n}(n_{g10}),\ c_{g1u}(u_{g10}),\ \ldots,\ c_{gkn}(n_{gk0}),\ c_{gku}(u_{gk0}); \end{cases} \tag{5}$$

The probabilistic data is generated for all quantile orders. The produced data is used to calculate the steady-state of the EPS. In parallel, the multiplied values of the probabilistic characteristic quantiles are calculated for each individual steady-state with probabilistically determined initial data as in Eq. (6).

$$\begin{cases} c_{1n}(n_{10}) \cdot c_{1q}(q_{10}),\ \ldots,\ c_{in}(n_{i0}) \cdot c_{iq}(q_{i0}), \\ c_{g1n}(n_{g10}) \cdot\ c_{g1u}(u_{g10}),\ \ldots,\ c_{gkn}(n_{gk0}) \cdot\ c_{gku}(u_{gk0}); \end{cases} \tag{6}$$

A flow chart of solving the power flow with the proposed model is determined in Fig. 9.

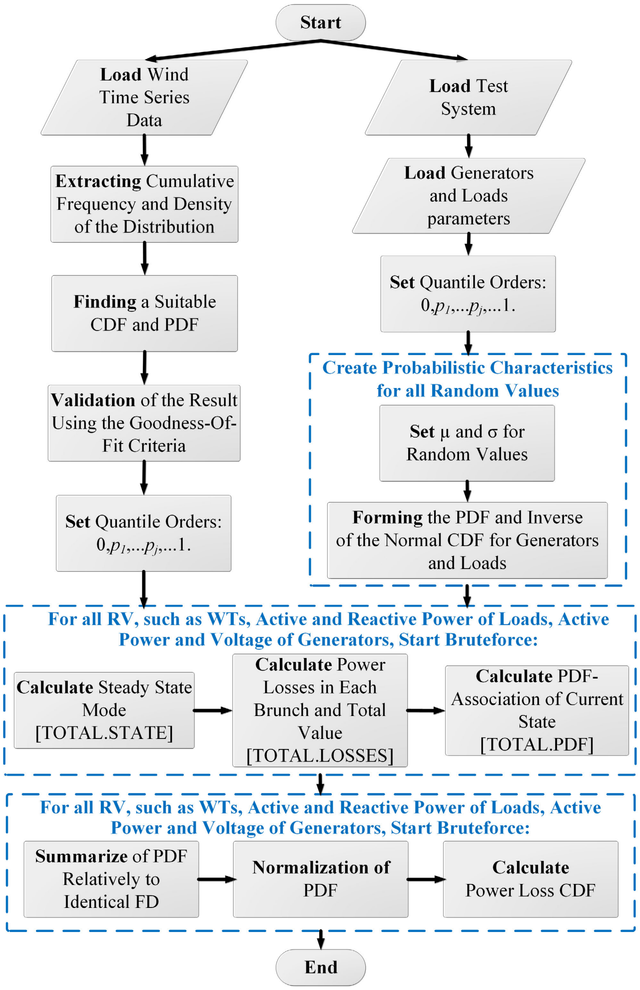


FIGURE 9. Flow chart of solving the power flow with the proposed WT model.

After the calculations performed using all quantile orders in their various combinations, all possible values of operating parameters in the nodes and branches, as well as

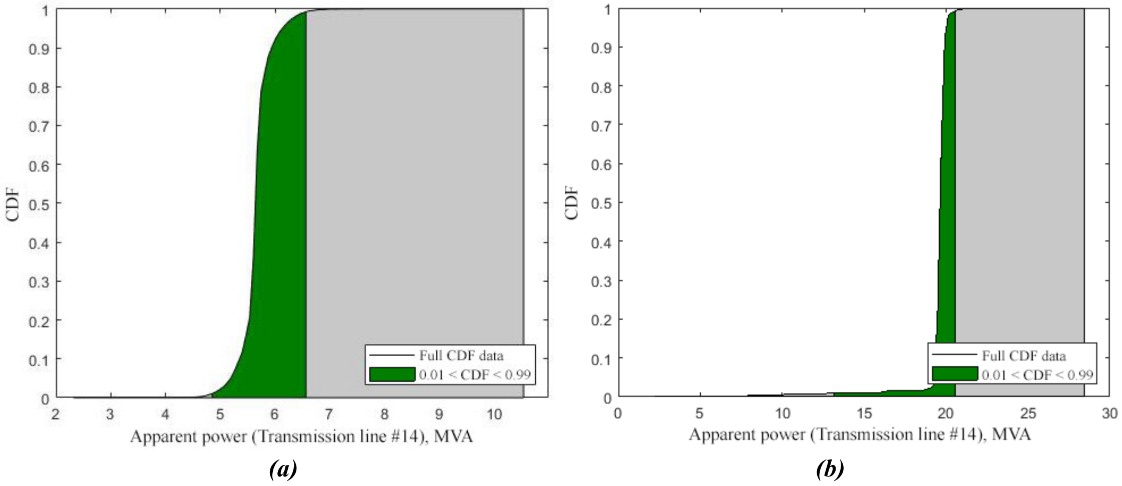


FIGURE 10. CDF of power losses in branch 14.

multiplied values of the probabilistic characteristic quantiles were obtained. Further, for the selected investigated value, separate arrays are taken, that contain data on all possible functional dependency (FD) values and the corresponding PDF. According to the obtained FD, a separate series of uniformly distributed values is formed. With a given delta, the multiplicative PDF is summed when the corresponding FD value is equal to the value from the series. This is carried out for each FD value from the series. At the end of the calculation, the PDF is normalized.

The output probabilistic characteristics were taken from the previous research, where the steady-state was calculated in a non-deterministic form. According to the results, the largest power losses were obtained in branches 1, 2 and 14. Since the slack bus of the system is located near the branches 1 and 2, a more distant node 8 (branch 14) were considered for experimental studies.

The planned penetrated capacity of RES is 5, 10, 20 and 50 MVA. With an increase in the penetrated WT capacity, the wind farm will be considered with the same probabilistic characteristics as a single unit. Within each iteration of the steady-state calculation, a wind turbine generator with *P-V* settings will be added to node 8. After that, the calculation of power losses and EPS parameters was made. Further, the calculation and normalization of CDF and PDF parameters were preformed. A little less than half a million steady-state calculations were performed for each individual installed WT capacity.

For greater clarity, Figure 10 shows the density of the apparent power loss in branch 14 without WT (Fig. 10a) and with 50 MVA WT (Fig. 10b).

According to the results obtained, with 50 MVA penetration, the total power loss in the branch 14 can increase by about 2.5 times (Table 3). Within the obtained distribution limits, the values that are beyond 0.99 of CDF have the largest spread with the minimum occurrence probability. According to the main CDF logic, the power loss with a 99% probability will not exceed the value at 20.59 MVA, which is 78.30% of the maximum. In the case of the wind turbine generators absence, the FD with 99% probability will not exceed 53.93% of its value in 6.56 MVA. The study of CDF in some cases will contribute to the power losses analysis and determine the maximum possible losses with a minimum occurrence probability in the future.

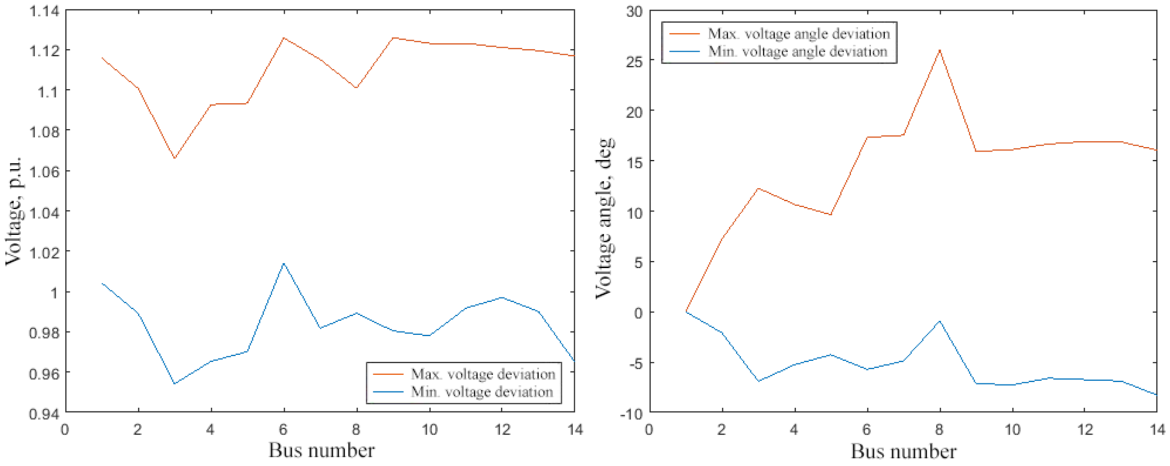
In addition, with an increase of WT power, a shift of the expected value and a decrease in the probability of the power losses can be observed. The analysis of repeatability of certain WT power values will make it possible to assess the impact of the power CDF on the steady-state stability. Table 3 summarizes all the data obtained during the different WT capacities penetration. It can be determined that when the WT penetration level increases, the maximum apparent power loss and power losses percentage also increase, but their assessment requires additional study of all the obtained probabilistic characteristics.

As a result, the calculated operating parameters in the nodes and branches were also obtained. Figure 11 shows the minimum and maximum possible fluctuations of the voltage value (Fig. 11a) and voltage angle (Fig. 11b) for the case of 50 MVA penetration for each bus, which were found together with the main calculations.

In accordance with the logic of the calculation method, there is no practical problem with the adaptation of the algorithm to large-scale EPS. The experimental studies on the example of the IEEE 57-bus system with and without wind power penetration were also carried out. The WT capacity was equal to 20 and 50 MVA, the studies were conducted in order to compare the tendency of changes in the probabilistic power losses characteristics. The general calculation process corresponds to Fig. 9. Test case system is not modified, it has 7 generators, 57 buses and 42 loads [28]. The basic power of the system is 100 MVA. Preliminarily, the calculation of the steady-state EPS operation without RES was carried out. According to the results, the maximum possible power loss can occur in branches 1, 8 and 15. An example of the initial power loss probabilistic characteristic is shown in Fig. 12a.

TABLE 3. Power losses results for IEEE 14-bus system.

The penetration level of wind power, MVA	Branch #	Minimal Apparent power loss, MVA	Maximal Apparent power loss, MVA	Power losses (CDF > 0.99), MVA	Power losses percentage, %
—	1	0.3617	23.336	5.342	23.24
	2	0.203	11.035	5.168	47.71
	14	0.217	10.534	6.563	53.93
5	1	0.3614	36.67	4.899	13.49
	2	0.2524	12.37	4.594	37.91
	14	2.183	13.15	7.301	66.57
10	1	0.3614	36.67	5.202	14.33
	2	0.2524	12.37	4.998	41.25
	14	2.183	13.59	8.459	74.16
20	1	0.3614	36.67	5.807	15.99
	2	0.2524	12.37	5.604	46.25
	14	2.183	16.77	10.94	75.00
50	1	0.3614	36.67	8.227	22.66
	2	0.2524	12.37	8.028	66.25
	14	2.183	28.48	20.59	78.30



(a) *(b)*

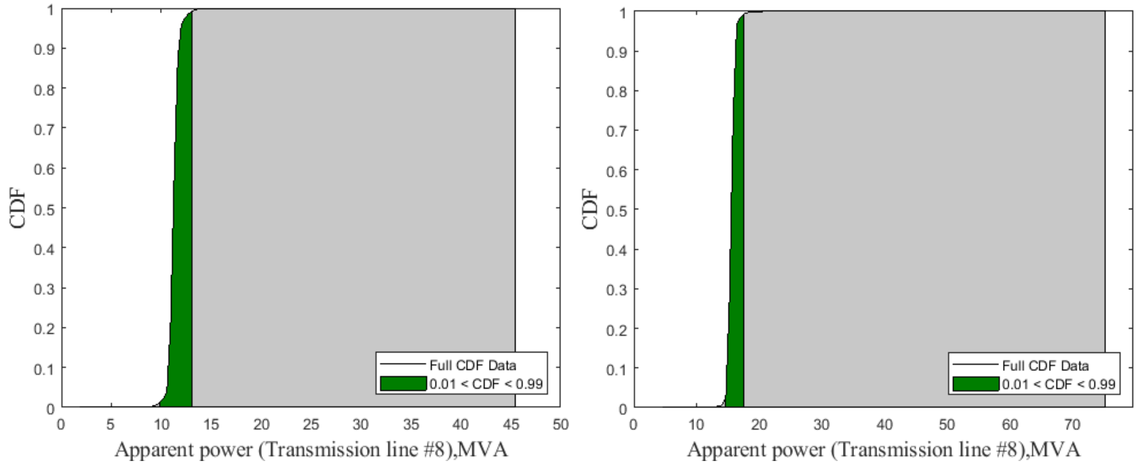
FIGURE 11. The minimum and maximum possible fluctuations of the voltage value and voltage angle.

The WTs were penetrated in node 9, which related to branch 8, because as in the previous experiment, the studies are focused on probabilistic characteristics at a distant nodes. According to the results obtained, the total power loss can increase by 1.5 times, and, as in the previous experiment, there is a change in the probability characteristic intensity and a shift in the EV (Fig. 12b).

Despite the general similarity of the experiments, in this case for the studied branch a decrease in the power loss percentage can be observed, which may indicate a decrease in a particular branch loss (Table 4). However, depending on the branch under study, the effect of power penetration is individual. For example, in the case of branch 15 of IEEE 57-bus system and branch 2 of IEEE 14-bus system, the WT penetration does not have significant impact on the total power losses.

According to the data presented in Tables 3 and 4, it can be concluded that in the probabilistic modeling of EPS with WT, the RES penetration affects individual EPS parameters ambiguously. Depending on the penetration capacity and the specific EPS scheme, the operating parameters and their probabilistic data change individually. For probabilistic analysis, it is necessary to investigate the values limits, EVs, and CDFs changes in aggregate, e.g., to find the optimal WT capacity for installation, or other optimization problems.

Further scientific work will be devoted to a full assessment of the obtained characteristics. In addition, the use of different wind time series will be considered for the study of CDF changes in the nodes and branches (EV, SD, assessment by the goodness-of-fit criteria), and the necessary modifying of the wind turbine generator model will be made, according



(a) *(b)*

FIGURE 12. CDF of power losses in branch 8.

TABLE 4. Power losses results for IEEE 57-bus system.

The penetration level of wind power, MVA	Branch #	Minimal Apparent power loss, MVA	Maximal Apparent power loss, MVA	Power losses (CDF > 0.99), MVA	Power losses percentage, %
—	1	2.106	79.4	6.691	8.65
	8	1.860	45.431	13.12	30.11
	15	0.0685	75.671	3.218	4.25
20	1	2.175	79.89	6.785	8.73
	8	5.043	76.86	18.81	26.19
	15	0.0384	76.31	2.546	3.34
50	1	2.8641	80.76	7.522	9.65
	8	4.677	75.29	17.62	24.95
	15	0.0025	76.31	3.182	4.17

to the mechanical losses, the specific conditions of connection to the network, etc.

VI. CONCLUSION

For the probabilistic formulation of the problem and the EPS with WTs calculation, the use of probabilistically reliable information is required, as a result of which, for its correct processing and modeling, it is necessary to use a set of methods and tools that can present data not only with a minimum error, but also for all wind repeatability values. Within the framework of the proposed probabilistic approach, a stochastic model of a wind turbine generator was presented for calculating EPS states in a non-deterministic form in the Matpower.

The adequacy of the physical parameters is due to the use of the selected quadratic power curve mathematical model, taking into account the pitch angle control and the technical data of a practical wind turbine. The probabilistic data are supported by the use of a graphical approximation method in conjunction with the goodness-of-fit criteria, according to the results of which the wind time series probability distribution was determined as the Weibull law.

The WT model was successfully tested in IEEE 14 and 57-bus systems using the SIBD method. In addition, the possible fluctuations of the system generation and load were taken into account. The maximum power losses in the branches were determined, as well as their probabilistic characteristics. According to the results obtained, changes in the probabilistic characteristics occur individually, with a predominant trend towards an increase in possible power losses with EV and SD shift, respectively. Nevertheless, in some cases it is possible to observe the absence of dependence of power losses on the penetrated WT capacity, or a tendency to decrease.

The aggregate model of the wind turbine generator and the results obtained will be used to study the impact of wind power penetration in both test and practical power systems. A comparative analysis of the probability distributions of systems without and with wind generation will be carried out to determine the optimal installation locations and maximum penetration capacities.

REFERENCES

[1] J. Hsu, *Multiple Comparisons: Theory and Methods*. London, U.K.: Chapman & Hall, 1996, p. 296.

[2] A. E. Feijoo, J. Cidras, and J. L. G. Dornelas, "Wind speed simulation in wind farms for steady-state security assessment of electrical power systems," *IEEE Trans. Energy Convers.*, vol. 14, no. 4, pp. 1582–1588, Dec. 1999.

[3] A. Karimishad and T. T. Nguyen, "Probabilistic transient stability assessment using two-point estimate method," in *Proc. 8th Int. Conf. Adv. Power Syst. Control, Oper. Manage. (APSCOM)*, Hong Kong, 2009, pp. 1–6.

[4] A. Suvorov, A. Gusev, N. Ruban, M. Andreev, A. Askarov, R. Ufa, I. Razzhivin, A. Kievets, and J. Bay, "Potential application of HRTSim for comprehensive simulation of large-scale power systems with distributed generation," *Int. J. Emerg. Electr. Power Syst.*, vol. 20, no. 5, pp. 1–13, Oct. 2019.

[5] S. Xia, Q. Zhang, S. T. Hussain, B. Hong, and W. Zou, "Impacts of integration of wind farms on power system transient stability," *Appl. Sci.*, vol. 8, no. 8, p. 1289, 2018.

[6] V. Sohoni, S. Gupta, and R. Nema, "A comparative analysis of wind speed probability distributions for wind power assessment of four sites," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 24, pp. 4724–4735, May 2016.

[7] J. Wang, J. Hu, and K. Ma, "Wind speed probability distribution estimation and wind energy assessment," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 881–899, Jul. 2016.

[8] L. Miao, J. Fang, J. Wen, and W. Luo, "Transient stability risk assessment of power systems incorporating wind farms," *J. Mod. Power Syst. Clean Energy*, vol. 1, no. 2, pp. 134–141, Sep. 2013.

[9] V. Milanovic, "Probabilistic stability analysis: The way forward for stability analysis of sustainable power systems," *Philos. Trans. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 375, no. 2100, 2017, Art. no. 20160296.

[10] M. Ebeed and H. E. Shady Abdel Aleem, "Overview of uncertainties in modern power systems: Uncertainty models and methods," in *Uncertainties in Modern Power Systems*, 1st ed. Sohag, Egypt: Academic, 2021, pp. 1–34.

[11] Y. Bay, I. Razzhivin, A. Kievets, A. Askarov, and V. Rudnik, "Obtaining probabilistic characteristics of electrical quantities and their imbalances," *Electrotehnica, Electronica, Automatica*, vol. 67, no. 3, pp. 73–80, 2019.

[12] Y. Bay, V. Rudnik, I. Razzhivin, A. Kievets, and M. Andreev, "Full probabilistic characteristics of power losses in the electrical power system branches," *Electrotehnica, Electronica, Automatica*, vol. 68, no. 3, pp. 32–40, Sep. 2020.

[13] P. Lamaina, D. Sarno, P. Siano, A. Zakariazadeh, and R. Romano, "A model for wind turbines placement within a distribution network acquisition market," *IEEE Trans. Ind. Informat.*, vol. 11, no. 1, pp. 210–219, Feb. 2015.

[14] V. Suresh, "Comparison of solvers performance for load flow analysis," *Trans. Environ. Elect. Eng.*, vol. 3, no. 1, pp. 363–378, 2019.

[15] J. F. Medina Padron and A. E. Feijoo Lorenzo, "Calculating steady-state operating conditions for doubly-fed induction generator wind turbines," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 922–928, May 2010.

[16] Y. C. Chen, P. Dong, and Z. D. Wu, "Analysis of power flow in wind farm with matpower," in *Proc. 7th Int. Conf. Power Electron. Syst. Appl.-Smart Mobility, Power Transf. Secur. (PESA)*, Hong Kong, Dec. 2017, pp. 1–6.

[17] S. O. Baried, R. Billinton, and S. Aboreshaid, "Probabilistic evaluation of transient stability of a power system incorporating wind farms," *IET Renew. Power Gener.*, vol. 4, no. 4, pp. 299–307, 2010.

[18] K. Dongbum, K. Kyungnam, and H. Jongchul, "Comparative study of different methods for estimating Weibull parameters: A case study on Jeju Island, South Korea," *Energies*, vol. 11, no. 2, p. 356, 2018.

[19] H. Kumar, S. Balasubramaniyan, S. Padmanaban, and J. Holm-Nielsen, "Wind energy potential assessment by weibull parameter estimation using multiverse optimization method: A case study of Tirumala region in India," *Energies*, vol. 12, no. 11, p. 2158, 2019.

[20] H. E. Akyuz and H. Gamgam, "Statistical analysis of wind speed data with weibull, lognormal and gamma distributions," *Cumhuriyet Sci. J.*, vol. 38, no. 4, pp. 68–76, Dec. 2017.

[21] S. A. Akdağ and A. Dinler, "A new method to estimate weibull parameters for wind energy applications," *Energy Convers. Manage.*, vol. 50, no. 7, pp. 1761–1766, Jul. 2009.

[22] J. V. Seguro and T. W. Lambert, "Modern estimation of the parameters of the weibull wind speed distribution for wind energy analysis," *J. Wind Eng. Ind. Aerodyn.*, vol. 85, no. 1, pp. 75–84, Mar. 2000.

[23] R. Ross, "Graphical methods for plotting and evaluating weibull distributed data," in *Proc. 4th Int. Conf. Properties Appl. Dielectric Mater. (ICPADM)*, vol. 1. Brisbane, QLD, Australia, Jul. 1994, pp. 250–253.

[24] A. A. Teyabeen, F. R. Akkari, and A. E. Jwaid, "Power curve modelling for wind turbines," in *Proc. UKSim-AMSS 19th Int. Conf. Comput. Modeling Simulation (UKSim)*, Cambridge, U.K., Apr. 2017, pp. 179–184.

[25] V. Sohoni, S. C. Gupta, and R. K. Nema, "A critical review on wind turbine power curve modelling techniques and their applications in wind based energy systems," *J. Energy*, vol. 2016, Jul. 2016, 8519785.

[26] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development," NREL, Golden, CO, USA, Tech. Rep. NREL/TP-500-38060, Feb. 2009.

[27] J. A. Boudreaux, "Design, simulation, and construction of an IEEE 14-Bus power system," Baton Rouge, LA, usa, Louisiana State Univ., 2018, p. 42.

[28] R. Anand and V. Balaji, "Power flow analysis of simulink IEEE 57 bus test system model using PSAT," *Indian J. Sci. Technol.*, vol. 8, no. 23, Sep. 2015.

[29] M. Tajdinian, M. Allahbakhshi, A. R. Seifi, H. R. Chamorro, M. Z. Jahromi, and V. K. Sood, "An enhanced approach for probabilistic evaluation of transient stability," *Int. J. Electr. Power Energy Syst.*, vol. 120, Sep. 2020, Art. no. 106055.

YULY D. BAY received the Dipl.-Ing. degree from Tomsk Polytechnic University, in 2014.

He is currently an Assistant with the Division for Power and Electrical Engineering, Tomsk Polytechnic University. His research interest includes finding the full probabilistic characteristics of the power industry quantities.

ALEKSEY A. SUVOROV received the Engineering and Ph.D. degrees from Tomsk Polytechnic University, in 2014 and 2018, respectively.

He is currently an Assistant with the Division for Power and Electrical Engineering, Tomsk Polytechnic University. His research interests include transient processes simulation and stability problem.

ALEXANDR S. GUSEV received the D.Sc. (Tech.) degree in electrical engineering from Tomsk Polytechnic University, Tomsk, Russia, in 2008.

He is currently a Professor with the Division for Power and Electrical Engineering, Tomsk Polytechnic University. His research interest includes simulation of large-scale EPSs.

IGOR A. RAZZHIVIN received the M.Sc. and Ph.D. degrees from National Research Tomsk Polytechnic University in 2015 and 2020, respectively.

He is currently a Senior Lecturer with the Division for Power and Electrical Engineering, School of Energy and Power Engineering. He is involved in research work, connected with simulation of renewables. His research interests include relay protection and wind power generation.

ALISHER B. ASKAROV received the M.Sc. degree from Tomsk Polytechnic University in 2018, where he is currently pursuing the Ph.D. degree with the Division for Power and Electrical Engineering.

His research interests include simulation of automation control systems and renewables.

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