Simulating wind power plants for relay protection problems

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Abstract. Wind turbines with a capacity of several kilowatts and megawatts are actively used by the electric power industry in China, Europe, the USA and other countries. The wind has an intermittent nature, depending on the territory, can change its speed from 2 to 25 m/s during the day. It’s necessary to study the dynamic impact of the wind farm and to adequately model their operation under different wind loads, taking into account that wind energy constitutes a significant part of the structure of electricity production in many countries, which is reflected in the transients in the power system. Changing or disturbance of the wind flow is reflected on the change of the real power output of each wind turbine. To study the operation modes of wind turbines under different conditions with different methods of specifying wind energy, short-circuit tests were conducted on the 690V wind turbines. The study of the operation of wind turbines in the network with various wind models clearly showed differences in the oscillograms of the current in time, that in order to assess the influence of the work of the wind turbine on the network, the dynamics changes in the wind turbine in faults.

1. Introduction

Today wind energy is a rapidly developing direction in the world power generation. Wind turbines (WT) with capacity from several kilowatts to megawatts are actively being introduced in China, Europe, the USA and many other countries. The introduction of renewable energy sources (RES) is one of the most discussed topics in Russia, recently Rosatom and Rusnano received the right to build about 1.5 GW of wind power in Adygea, Krasnodar Territory, Rostov Region, Kalmykia, Astrakhan Region and Stavropol Territory [1–2]. A trend is the transition from a centralized energy production to distributed generation objects, an integral part of which is RES.

Indeed, it takes less time to build and start wind power plant WPP, in comparison with traditional ones, however, WPP have their shortcomings. The wind has an intermittent nature, it is uncontrollable and depending on the territory it can vary throughout the day from 2 to 25 m/s. Despite the fact that modern wind forecasting technologies help with design and operation of WPP allowing grid companies and manufacturers to obtain up-to-date information on the potential resource of wind energy in the next hours or days. However, forecasting is not perfect, and there are still differences between actual and predicted wind behavior [3].

In cases where the share of electricity generated by WPP is relatively small in the power system and in emergency modes relay protection and automation can switch off such WPP without much influence on the power system. However, today the installed capacity of individual wind farms in different countries reaches several hundred megawatts, which affects the operation of the electric power system (EPS). Due to the rapid growth of wind generation, and the fact that at present wind energy constitutes a significant part of electricity production in many EPSs around the world, there is a need to study the...
wind farms behavior dynamics and adequate modeling of their operation under different wind loads conditions, emergency regimes of the EPS etc.

The change or disturbance of the wind flow changes the actual output power of each WT. The WT are installed in large areas where, due to turbulence and the nature of the wind distribution, at one and the same time, the WT transform different energy and produce an unequal power, which requires detailed study when assessing their influence on the EPS in different operating modes. In particular, the change in the values and directions of the short-circuit currents, which can lead to a false tripping of the overcurrent relay protection. This is important when implementing WPP in distribution networks, where relay protection is configured for a particular grid section. In the case of the use of a WPP with a voltage converter, the short-circuit currents have small runaway values, as a result the relay protection may not operate correctly [4–5].

A number of researchers in Europe, China and the United States are addressing the problems identified, but there are no common relay protection settings algorithms and require a particular approach that takes into account the design features of the WT, network parameters, wind flow, etc. In this article, a study is made of the WPP operation in various operation modes for estimating the values of the short-circuit currents at different wind speed parameters and the model of its representation.

2. Model description

The short-circuit experiments were carried out on 690 V buses of WPP located in the study network (figure 1) to research the WPP operation modes in different conditions under different methods of wind power assignment. The equivalent electric power system (EPS) U=115 kV is presented as a balancing unit (Infinite Bus), WPP is connected to the network through the step-up transformers and transmission line.

![Figure 1. Model of researched power system.](image)

The WPP model is a synchronous generator with a phase rotor connected to the network (figure 2) via converter, which allows the turbine to operate at a controlled angular velocity. WPP of such design are used in medium- and high-capacity power plants from 1 to 10 MW. Due to the large number of pole pairs, the generator is capable of operating at a lower angular velocity. The model of the wind wheel mechanics is described by the equilibrium state of several dynamic processes. The simulation model takes into account the processes associated with the mass rotation, bending and torsion – the WPP elements [6].

![Figure 2. WPP model.](image)
The WPP mechanical part is considered as a system, consisting of two elements with mass and inertia (inertial mass) connected to each other through a spring, which is the equivalent of the turbine shaft stiffness [7–8]. The converter model is represented by the converter on the rotor side and the converter on the network side, which use controllable power electronic switch devices (IGBT) for the AC voltage generation from the DC voltage source [9].

3. Research
Modeling was made in the Matlab Simulink complex. For the WPP model parameters of the EDS W2000 wind generator, with a rated power of 2 MW have been taken [10]. In wind power engineering depending on a research problem the WPP various models are applied. For example, for problems of assessment of potential of the developed electric energy of WPP and forecasting of its average annual values it is enough to use the average speed of wind received on the basis of statistical data, but for assessment of influence of the work of WPP on a power supply system in emergency operation of work, studying of dynamic characteristics of WPP in various operating modes it is necessary to consider the chaotic nature of wind power.

In the work for a research exact parameters of the wind flow (Fig. 1 (a) measured on the 120th second interval at the height of 80 m are taken (Vavg = 10.74 m/s). Also for comparison the analysis of work of WPP in the mode of short circuit when using the model of wind recommended by the international standard, state standard specification and normative documents where the time model of wind speed is represented as the sum of two components:

\[ V_{\text{wind}} = V_0 + V_t \]  

where \( V_0 \) is the average wind speed in the \( i \)-th time interval,

\( V_t \) – dynamic (turbulent) component of wind speed [11–14].

To describe the turbulent component of wind speed in wind power, empirical models of spectral density, the functions of Davenport, von Karman and Kaimal are predominantly used. In this paper we used the spectral model of Kaimal at \( V_0 = 10.74 \text{ m/s} \). The constructed wind models are shown in figure 3.

![Figure 3. Results of wind speed simulation](image)

a) real data; b) the spectral model of Kaymal

It is obvious that the nature of the dependence of wind speed on time in the models presented differs significantly from one another and, as a consequence, affects the choice of method of speed control of the windmill, determines the requirements for the control system of WT.
3.1. Simulation of the operation of the system under study in normal mode

Figure 4 shows oscillograms of currents and voltages on 690V bus in wind simulation from full-scale experimental data and from wind simulation from the Kaimal spectral model.

![Oscillograms of currents and voltages](image)

**Figure 4.** Parameters of three-phase voltages \(U_A, U_B, U_C\) and currents \(I_A, I_B, I_C\) on 690V bus

- a) real data
- b) the spectral model of the Kaimal

The voltage of the WPP due to the operation of the converter does not change its amplitude values at different wind speeds \(U = 690\text{V}\), in contrast to the current values, which varies from 436 A to 2900 A, depending on the wind speed with real wind load data and from 932 A up to 1685 A using the spectral model of Kaimal. The values of the WT currents for a different setting of wind parameters have a significant difference. Wind simulation using the conventional approach does not reflect zero wind values, and also averages the peak wind speed in gusts, which naturally affects the power of the produced WPP, which depends proportionally on the wind speed.

3.2. Investigation of the WPP in the mode of three-phase and single-phase fault

Experiments of three-phase and single-phase faults on 690V bus using two models of wind flow. Below there are the oscillograms of the currents measured of the WPP at the fault time.

![Oscillograms of currents during faults](image)

**Figure 5.** Three-phase fault experience

- a) an oscillogram of three-phase currents \(I_A, I_B, I_C\) at the moment of almost complete absence of wind \((t = 20.085 \text{ sec.})\), duration of faults 0.5 sec.
- b) an oscillogram of three-phase currents \(I_A, I_B, I_C\) at the moment of the peak wind value \((t = 69.0 \text{ seconds})\), the duration of the fault is 0.5 sec.
- c) an oscillogram of three-phase currents \(I_A, I_B, I_C\) using the spectral model of the wind in Kaimal
The steady-state current of the three-phase fault is 3.013 kA, 3.057 kA and 3.016 kA, respectively. The values of the working currents of wind turbines measured at real wind flow data in peak wind speeds $I_{\text{nom}} = 2.88$ kA, slightly differs from the current of the three-phase fault, which confirms the possibility of false triggering of relay protection.

Figure 6. Single-phase fault experience
a) an oscillogram of three-phase currents ($I_A$, $I_B$, $I_C$) at the moment of almost complete absence of wind ($t = 20.085$ sec.), duration of faults 0.5 sec.
b) an oscillogram of three-phase currents ($I_A$, $I_B$, $I_C$) at the moment of the peak wind value ($t = 69.0$ seconds), the duration of the fault is 0.5 sec.
c) an oscillogram of three-phase currents ($I_A$, $I_B$, $I_C$) using the spectral model of the wind in Kaimal

The steady-state current of a single-phase fault is 1,113 kA, 1,037 kA and 1,401 kA, respectively. The current of the WPP virtually does not change and does not exceed the value of $I_{\text{nom}} = 2.88$ kA in all cases of modeling of wind energy. Consequently, the detection of fault currents by relay protection bodies is difficult. In unsymmetrical modes, the fault current continues to flow in intact phases, zero and reverse sequence currents, which can lead to serious damage to the generator and other network equipment [15].

4. Conclusion
The WPP operation research in the network with different wind models clearly showed differences in the received current oscillograms, what is relevant in the order to assess the impact of WPP integration on the network, the dynamics of the WPP behavior in emergency conditions. The values of WPP fault currents are almost identical in the case of three-phase fault at various methods of the wind flow energy modeling. However, at peak values of wind velocity, the values of WPP nominal currents are close to fault currents. The relay protection behavior in such situations is poorly researched, and there is a need for adequate setting of relay protection operating current, taking into account the chaotic nature of WPP power generation to avoid miss operation or false tripping in the fault cases. The situation could be aggravated with an increase in the WPP installed capacity at the peak values of wind energy, and there could be difficulties not only with the correct operation of the current relays, but also with the distance protection.

The single-phase short-circuit experiment showed that the values of short-circuit currents do not differ from the normal regime currents. The single phase-to-ground faults are more than 90% of fault cases in power systems, that indicates the need for a detailed research of the asymmetric regimes effect
on the operation of each wind turbine and wind farms as a whole. There is an urgent need to develop new design of relay protection for the WPP which are using the converters and having DC and AC networks.

It is necessary to revise the existing protection systems in the case of the RES integration in the EPS of the South of Russia, in particular wind generators in the distribution network. It is a complex technical task, so, in this case, the problems identified in the paper could be a serious obstacle to the widespread integration of wind generation in Russia.

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