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Assessment of wind power generation impact on the distance protection operation

N Yu Ruban, A B Askarov, A V Kievets and V E Rudnik
School of Energy and Power Engineering, Tomsk Polytechnic University, Tomsk Russia
E-mail: rubanny@tpu.ru

Abstract. In the article an experimental power system consisting of Russian equipment, as well as 220 kV power line distance protection, are simulated in the RTDS Simulator. The settings were calculated and the polygonal characteristics of distance protection were constructed. A sequential installation of wind turbines into various nodes of the power system was carried out and the correct operation of the protection was verified. As a result of the study, the impact of wind turbines on the distance protection when they are connected between the protection installation site and the point of the short circuit is revealed. The analysis of this impact is made. Possible ways to solve the identified problems are proposed, such as the use of adaptive distance protection, as well as numerous studies of the behaviour of wind turbines in various operating modes for further analysis and possible adjustment of guidelines for relay protection using new algorithms for calculating and configuring of distance protection. The results of this work can be used to improve and clarify the recommendations for tuning, produced by manufacturers of relay protection devices, which currently do not take into account the impact of wind power generation.

1. Introduction

Nowadays, alternative energy is gaining popularity. In modern power systems introduce new generating sources based on renewable energy. One of these are wind turbines. Their structure and behavior in different modes of operation of the power system differs significantly from the traditional synchronous generators existing in the power system. Therefore, it is necessary to investigate their behavior both in normal operating conditions of the power system and in emergency mode, that is, in case of various kinds of damages. It should be understood that wind turbines affect both the state of the power system as a whole and its individual parts. An integral part and the main type of electrical automation, without which normal and reliable operation of modern power systems is impossible, is relay protection. According to [1], the main protection of lines 110–220 kV is distance protection (mainly three-stage), based on monitoring changes in the calculated line resistance.

Thus, the purpose of this paper is to study the impact of wind power generation on the operation of distance protection of a 220 kV power line.

In this paper, it is proposed to simulate a wind turbine equipped with a squirrel-cage induction generator (SCIG) [2]. This generator is selected due to the prevalence in Russia and European countries. Although this model is a representative of the older generation, there are still a lot of such wind turbines, they are fully exploited and used everywhere.

In paper [3], as a review, different factors affecting distance protection in a power system with integrated renewable energy sources were considered, such as: (a) intermittent nature of a renewable source, (b) types of wind generators, (c) fault characteristics and nature of faults. After that, a generalized conclusion is made that the highly variability and intermittent nature of renewable energy sources in different network topologies causes changing in the levels of short-circuit currents and losing of coordinated operation of relay protection. It is also stated that renewable energy integration at the transmission level affect the reach of the distance relays and lead to their maloperation. The paper [4] summarizes many studies in which it was stated that: (a) fault characteristics of wind turbines have different behavior compared with synchronous based generators, (b) wind turbines do not provide sustained short-circuit currents during fault, (c) short-circuit current is pertinent to wind speed, penetration levels and number and type of wind turbine generator (d) relay selectivity is difficult to obtain with source impedance variation and bidirectional fault currents, (e) excessive fault-clearing times jeopardize distributed generator stability, and (f) traditional protection schemes limit distributed generation connection capacity. The paper [4] carried out studies using the RTDS Simulator. It can be concluded from the presented results that increasing wind penetration in distribution systems would have a detrimental effect on the distance relay operational characteristics. As a result, the operational characteristic of a distance relay expands and shrinks as a function of the wind penetration levels and wind speeds. In paper [5], the behavior of SCIG in case of short circuit on power lines is considered. Attention is drawn to the fact that the SCIG short-circuit current can exceed the rated current by more than six times. It is concluded that this type of wind generator introduces the greatest amount of short-circuit current, compared with other types of wind generators.

Based on the identified problems in papers [3–5], this paper proposes to simulate an experimental power system using Russian equipment and conduct appropriate studies to assess the effect of wind generators on the operation of distance protection that meets Russian standards.

2. Simulation in the RTDS simulator

2.1. Test scheme simulation

An experimental scheme of the power system has been developed and modeled in the RTDS Simulator. The structural view of the scheme is presented in Figure 1.

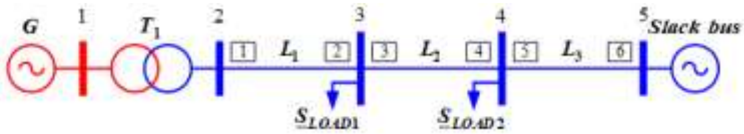

Figure 1. Experimental scheme.

On each power line in the scheme (Figure 1) two sets of protection are installed – at the beginning and at the end of the line. In this paper, a complete calculation was made only for the set number 1, located at the beginning of the power line L_1. Protection of the remaining lines is necessary for the coordination of the protection stages of the line L_1.

2.2. Simulation of distance protection

The simulation of distance protection in the RTDS Simulator is carried out using a special block, for which the input values are the measured values of the phase voltages on the buses at the beginning of each power line and currents in the corresponding lines and the output values are resistance and reactance.

2.3. Calculation of distance protection settings

The calculation results are summarized in table 1.

Table 1. Protection stages settings.

Stage Number	Settings
I	$\underline{Z}_{set}^{\mathrm{I}} = 37.535 \cdot e^{j78^\circ}$ Ohm
II	$\underline{Z}_{set}^{\mathrm{II}} = 72.56 \cdot e^{j78^\circ}$ Ohm
III	$\underline{Z}_{set}^{\mathrm{III}} = 116.365 \cdot e^{j77^\circ}$ Ohm

Thus, for set 1 of the distance protection of the power line $\boldsymbol{L_1}$, the settings of three stages were calculated.

2.4. Plotting of Distance Protection Polygonal Characteristics

According to [6], when setting the distance protection polygonal characteristics, it is necessary to calculate the settings for the resistance, as well as one of the angles for the third stage characteristic, which takes into account the detuning from the load mode. When calculating the setting by resistance, the arc resistance at short-circuit at the end of the protected area is estimated. The electric field strength of the arc is assumed to be 2500 V/m, the arc length is taken to be equal to the distance between the phase conductors, which is 4.5 m for a selected section of a single-circuit power line of 220 kV [7].

Figure 2 shows the polygonal characteristic of all stages of the distance protection of the power line L1 on a scale of 1:1. It is based on the calculated settings and geometrical considerations in the Microsoft Visio software package. In Figure 2 there are following designations: Z_{set} is a setting of the protection stage; φ_1 is an angle of maximum sensitivity, assumed to be equal to the angle of setting; φ_2 is an angle of inclination of the face 0-1, assumed to be −15° for the first and second stages, for the third stage is calculated separately according to [6]; φ_2 is an angle of inclination of the face 0-4, is assumed to be 115° according to [6]; R_{set} is a setting for the resistance. The face 2–3 passes through the end of the straight line Z_{set} and is located parallel to the axis R. The characteristic of the first stage is shown in blue, the second – green, the third – lilac.

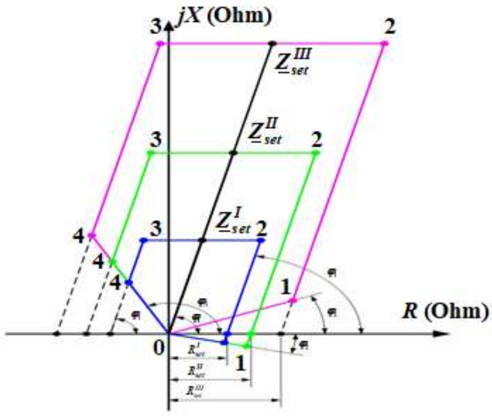

Figure 2. Distance protection polygonal characteristics.

Further characteristics were built in the RTDS Simulator.

3. Experiments in the RTDS Simulator

3.1. Verification of distance protection operation

When simulating three-phase-to-ground (3LG) faults and line-to-line (LL) faults in various nodes of the circuit, it was found that the impedance measured by distance protection falls into protection reach of the first, second and third stages. From which it can be concluded that the protection is correct and responds to all types of phase-to-phase faults.

3.2. Wind Turbine Model

The model of the first type of generator SCIG was chosen as the implemented wind turbine. This model consists of a windmill, a generator, a control system and its own transformers for connection to a 220 kV network. In the windmill model, it is possible to set the wind speed (input value) and remove the torque (output value) from the wind turbine shaft, which is transmitted to the rotor shaft of the asynchronous generator through the gearbox. It is known that the power generated by wind turbines depends on wind speed. Thus, in the presented model it is possible to change the values of the input wind velocity and obtain different values of the power generated. During the experiments, it was found that at a wind speed of 54 km/h = 15 m/s, the wind generator produces a maximum power of 6.36 MW.

3.3. Installing wind turbines at the beginning of the protected line

In previous experiments, one source was connected to the buses of the beginning of the protected power line $\boldsymbol{L_1}$ – generator ***G*** (Figure 1) with a rated capacity of 100 MW. In this experiment, two sources were selected so that the total generation in the buses of the beginning of the power line L_1 remained approximately equal to 100 MW. One part of the power is generated by the newly installed generator ***G*** (Figure 3), and the other by several wind turbines. Thus, in addition to the generator ***G***, five wind turbines with a maximum capacity of 6.36 MW are connected to the buses of the beginning of the line $\boldsymbol{L_1}$ (Figure 3), then the total capacity of the wind power plant (WPP) is 31.8 MW.

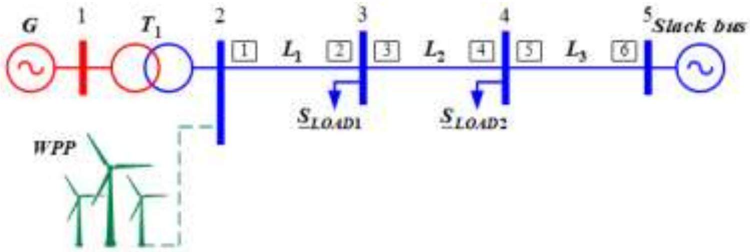

Figure 3. Experimental scheme with the installation of wind turbines at the beginning of the protected power line $\boldsymbol{L_1}$.

After that, experiments with three-phase-to-ground (3LG) faults and line-to-line (LL) faults in various nodes of the circuit were conducted and the operation of distance protection was checked. The change in the level of generated power behind the protection, caused by the installation of a wind turbine at the beginning of the protected line L_1, does not affect the impedance measured by the distance protection during phase-to-phase faults.

3.4. Installing wind turbines at the end of the protected line

In this experiment, the power sources remained the same, but the wind farm, consisting of five wind turbines, is now connected to the buses at the end of the protected power line $\boldsymbol{L_1}$ (Figure 4).

With this configuration of the circuit, recalculation of the distance protection settings is necessary, since a new power source has appeared in the node without generation. The calculation results are summarized in table 2.

In addition, when setting the distance protection polygonal characteristics, the settings for the resistance were recalculated. After that, experiments with 3LG faults and LL faults in various nodes of the circuit were carried out and the operation of distance protection with new characteristics was verified.

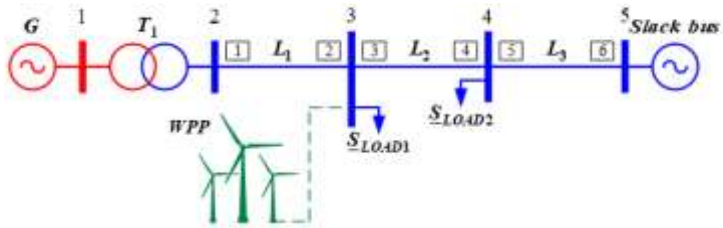

Figure 4. Experimental scheme with the installation of wind turbines at the end of the protected power line $\boldsymbol{L_1}$.

Table 2. Protection stages settings.

Stage Number	Settings
I	$\underline{Z}_{set}^{\mathrm{I}} = 37.535 \cdot e^{j78°}$ Ohm
II	$\underline{Z}_{set}^{\mathrm{II}} = 75.088 \cdot e^{j78°}$ Ohm
III	$\underline{Z}_{set}^{\mathrm{III}} = 106.956 \cdot e^{j79.7°}$ Ohm

It is established that with phase-to-phase faults at the end of the protected power line $\boldsymbol{L_1}$, distance protection measures the impedance, which is actually equal to the impedance of the line $\boldsymbol{L_1}$, and connecting wind turbines to short-circuit buses does not affect the measured impedance.

The results of the simulation of phase-to-phase faults at the end of the adjacent line $\boldsymbol{L_2}$ at various wind speeds are shown in Figures 5–7. As can be seen, with increasing wind speed and, consequently, power output by the wind turbine to the network, the hodograph of the measured impedance moves in the direction of decreasing the resistance and increasing the reactance. When installing the wind turbine at the end of the protected power line $\boldsymbol{L_1}$ and simulating a LL fault on the buses at the end of the adjacent line $\boldsymbol{L_2}$, the impedance hodograph does not fall into any of the distance protection reaches.

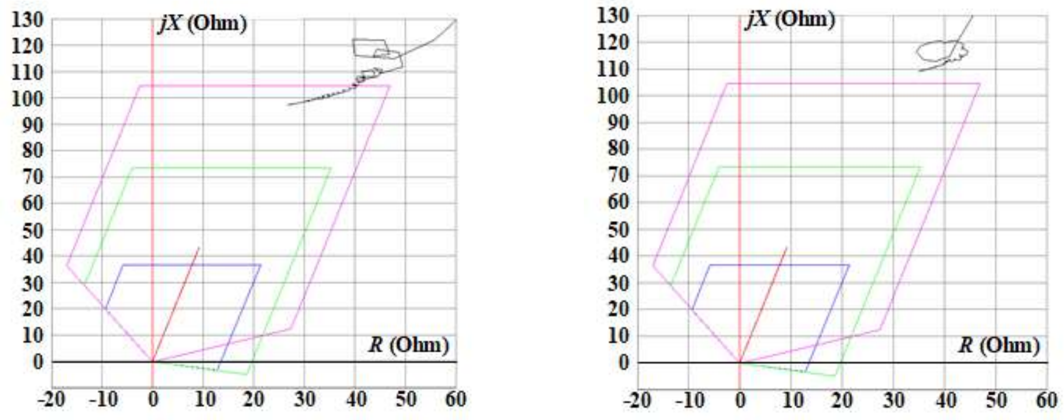

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Figure 5. Hodograph of (a) the phase A impedance in case of a 3LG fault and (b) the impedance between phases A and B in case of a LL fault at the end of the adjacent line $\boldsymbol{L_2}$ at wind speed of *18 km/h = 5 m/s.*

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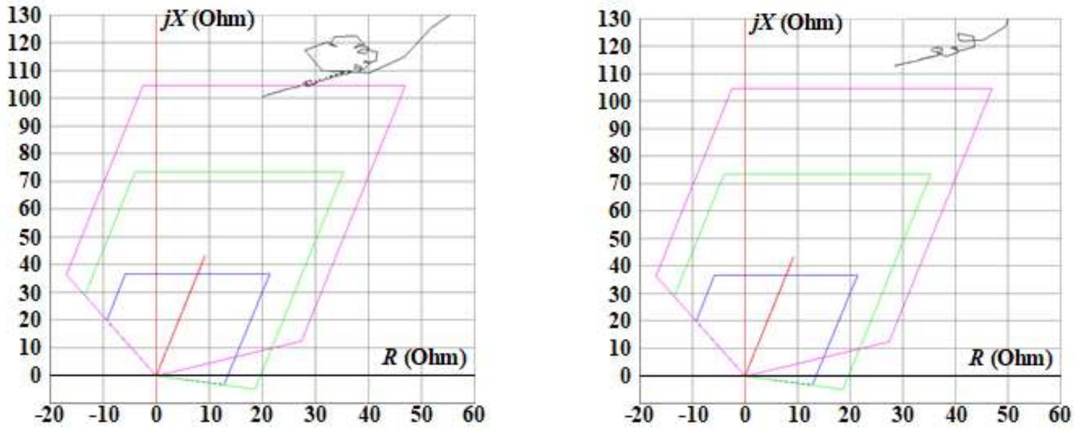

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Figure 6. Hodograph of (a) the phase A impedance in case of a 3LG fault and (b) the impedance between phases A and B in case of a LL fault at the end of the adjacent line L_2 at wind speed of *36 km/h = 10 m/s.*

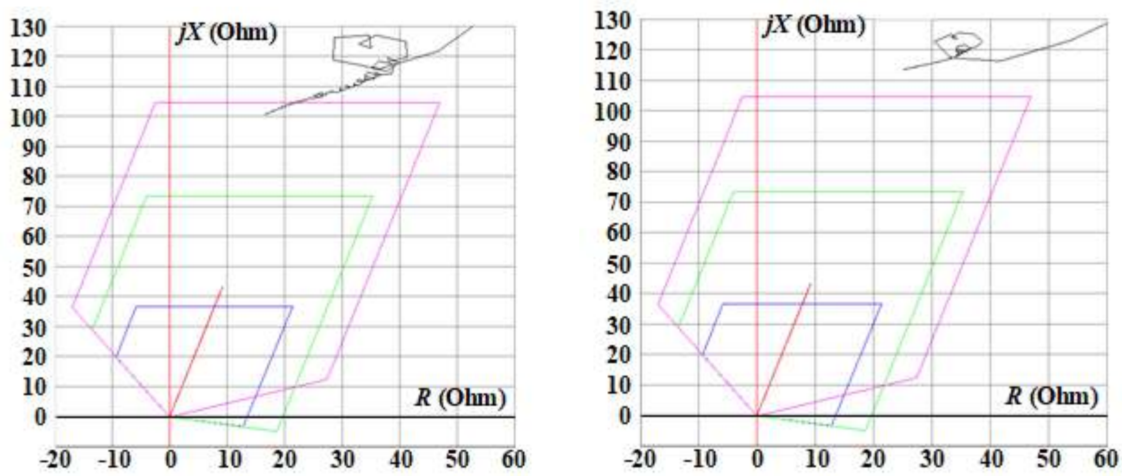

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Figure 7. Hodograph of (a) the phase A impedance in case of a 3LG fault and (b) the impedance between phases A and B in case of a LL fault at the end of the adjacent line L_2 at wind speed of *50 km/h ≈ 14 m/s.*

The connection of wind turbines to the buses in the beginning of the protected line and the change in the level of the power generated by them does not affect the impedance measured by the distance protection during phase-to-phase faults at all subsequent points on the protected and adjacent lines. This is due to the absence of additional generation between the protection installation site and the short-circuit point.

After connecting the wind turbine to the end of the protected line, distance protection settings were recalculated, as a result of which an increase of the protection reach of the second stage and decrease of the protection reach of the third stage were detected. When simulating phase-to-phase faults at the end of the protected line, it was established that the presence of wind turbines in the same node also does not affect the impedance measured by the distance protection, since the protection measures the impedance from its installation to the short circuit point. When modelling phase-to-phase faults at the end of an adjacent line (Figures 5–7), it was found that with increasing wind speed and, consequently, power output by wind turbines to the network, the hodograph of the measured impedance moves in the direction of decreasing resistance and increasing reactance. It is also noted that with 3LG faults, when wind turbines operate in the generation mode close to the maximum power, the point of the measured

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impedance is practically at the boundary of the protection reach of the third stage of distance protection. And with LL faults, the hodograph of the measured impedance does not fall into any of the protection reaches, which in this case indicates the failure of the remote backup function.

4. Introduction

According to the research, the effect of wind generators on the distance protection of a 220 kV power line has been revealed. The reasons for such deviations are: (a) a different behaviour of SCIG generators during a short circuit compared to traditional synchronous generators, which seems to be an important factor for determining the characteristics of distance protection, (b) the variation in wind speed and character significantly affects the reach of the distance relays set. This leads to changes in the apparent impedance seen by the protective relay and also causes changes in the reach setting of the relay.

The use of adaptive distance protection, as well as studies of the behaviour of wind turbines in various operating modes for further analysis and possible adjustment of guidelines for relay protection using new algorithms for calculating and configuring distance protection can be solutions to the identified problems.

Acknowledgments

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