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Investigation of the Influence of Disturbances in the 110 kV Electrical Network on Operating and Dynamic Parameters of the Type-4 Wind Turbine

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ABSTRACT
At present, there is an increased interest in the development of wind power engineering and its implementation into existing electrical networks in Russia. It should be noted that foreign technologies are mainly used now in Russian wind power engineering. At the same time, there are no existing normative documents that regulate the functioning of the considered wind power generating equipment with frequency converters. The investigation presents the development of a mathematical model of a wind turbine (WT) with a multi-pole permanent magnet synchronous generator (PMSG), which allows connecting to the system through a grid-controlled full-power frequency converter. The paper considers the influence of the change of operating parameters of the 110 kV electrical network on the operating parameters of the WT with the PMSG. The dynamic model of the type-4 WT is based on the classical Park-Gorev differential equations. To analyze the developed model, three different types of disturbances at the 110 kV side of the power system are simulated.

Keywords: *Power system, Electrical network, Wind power engineering, Wind turbine, Dynamic model, Synchronous generator, Power converter.*

1. INTRODUCTION

In the last century, there has been an obvious tendency in the development of renewable energy in the world. The development of wind power engineering in the world includes sizing of single low-power wind turbines and their integration into electrical networks. Mass implementation of renewable energy sources into power systems results in a considerable increase of the total number of energy sources operating in a general power grid. This is a consequence of impossibility of visual recognition and manual control of operating conditions of individual power plants [1]. A number of research teams in Russia is studying the operating modes of electrical networks with wind turbines. The investigations of P.V. Ilyushin are particularly highlighted in the area of the development of requirements for WT connection to power grids [1]. The studies of the team led by Professor A.S. Gusev should also be noted, which are associated with modeling of all possible operating modes of wind turbines of various types in electrical networks with the analysis of their stability [2]. In addition, the investigations of V.V. Elistratov are considered, which are devoted to the mathematical modeling of small- and medium-power wind turbines [3,4]. Among the scientists studying aerodynamics of wind turbines of various types and the influence of wind turbines on the electrical network operation, P.P. Bezrukikh, S.V. Gribkov, and V.G. Nikolaev stand out [5]. In Russia, as a rule, operating wind turbines are produced by foreign manufacturers or assembled in Russia under license from imported components with partial allocation of the production of several elements at Russian enterprises [1]. Therefore, wind turbines comply with the requirements of existing foreign technical standard documents. For example, the LVRT (Low Voltage Ride Through) characteristic is used for protection against overheating of IGBT transistors, being a technological protection against thermal influence during overloads by a voltage reduction level (see Figure 1). The operating principle of this technological protection is detailed in the studies of P.V.

Ilyushin, as well as in the publications of other authors [1, 7–14, 16–21].

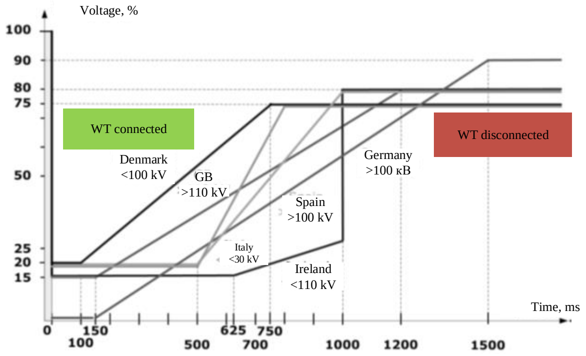
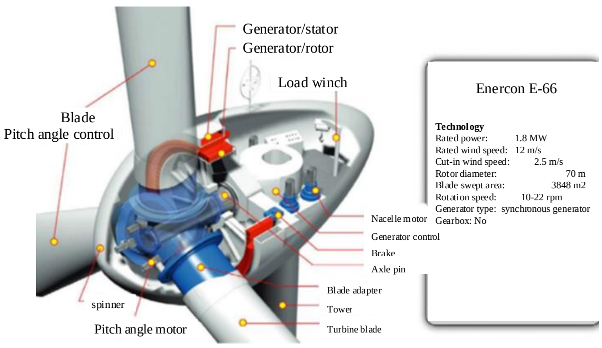


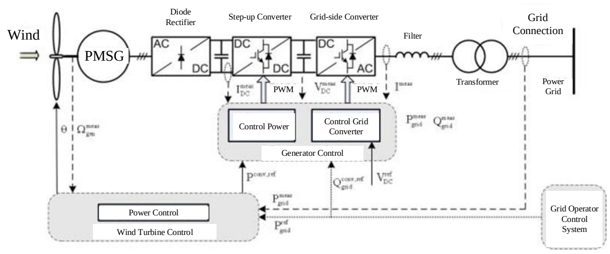
Figure 1 LVRT characteristic of modern wind turbines.

2. PROBLEM STATEMENT

Consider a 10 MW wind power plant consisting of five 2 MW wind turbines, connected to a 35 kV power grid through 35 kV lines of 30 km length per each line (Figure 2). A type-4 wind turbine consists of a synchronous generator connected to a diode rectifier, a DC-DC step-up PWM converter based on IGBT transistors, and a DC-AC PWM converter based on IGBT transistors [17].



a)



b)

Figure 2 Configuration of the investigated Enercon wind turbine of 2 MW [15]: a) nacelle design; b) control circuit.

The technology of type-4 wind turbines allows generating maximum energy from the wind at low wind speeds due to optimization of the turbine speed in this area and minimizing mechanical loads on the turbine during wind gusts [19–20].

3. MATHEMATICAL MODEL OF THE WIND TURBINE

A wind turbine transforms kinetic energy of the wind flow into mechanical energy of turbine rotation. Mechanical power on a wind generator shaft is known to be represented by the following equation [2, 3]:

$$P = \frac{1}{2}\rho A C_p(Z,\beta)\upsilon^3 \quad (1)$$

where υ – wind speed, m/s; ρ – air density, kg/m^3; A – blade-swept area, m^2; β – pitch angle of a wind turbine blade, deg; C_p – power factor of a wind turbine.

The angle β depends on the wind speed. Operation of a wind power plant with variable rotation speed is known to be associated with a zero value of β [12]. Tip-speed ratio can be determined using the following expression [3]:

$$Z = \frac{\omega R}{\upsilon} \quad (2)$$

where ω – angular rotation speed of WT turbine, rad/s; R – turbine radius, m.

The power factor of a wind turbine can be determined by the following equation [3]:

$$C_p(Z,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}} + c_6 Z \quad (3)$$

where $c_1 = 0.517$; $c_2=116$; $c_3=0.4$; $c_4=5$; $c_5=21$; $c_6=0.0068$ at $\beta = 0$.

The coefficient λ_i is defined by the following expression:

$$\lambda_i = 1\Big/\left(\frac{1}{Z+0.08\beta} - \frac{0.035}{\beta^3+1}\right). \quad (4)$$

The WT power factor depends on the pitch angle β and the current value of tip-speed ratio. Figure 3 illustrates the dependence of power factor changes at the fixed angle β with variation of the coefficient λ.

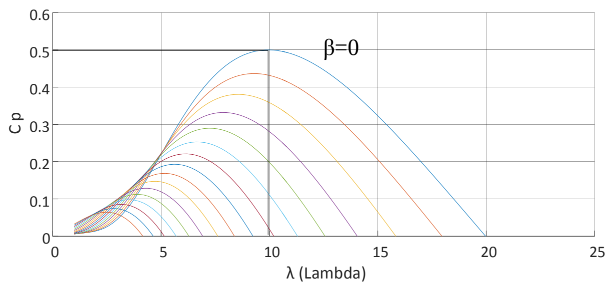


Figure 3 Diagram of the dependence of the power factor at the given angle β of the WT blade on the λ value.

Mechanical power of a wind turbine has a nonlinear dependence on the angle β, wind speed and turbine rotation speed [21]:

$$T_J \frac{d\omega}{dt} = P - P_G \tag{5}$$

where T_J – inertia time constant of the generator rotor, s.; P_G – generator active power.

The angle β has a large impact on the power factor C_p. In the case of operation in the turbine power limitation mode, the β angle control system is implemented in the turbine. In this case, current wind speed is compared with wind speed at the nominal output. If the current speed exceeds the nominal speed, the control system adjusts the pitch angle to reject some of the wind energy and maintain the speed at the nominal level [21]. Figure 4 illustrates the structure of β angle control.

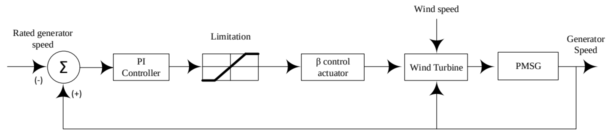


Figure 4 Simplified closed loop β angle control system.

The generator-side power frequency converter controls active power of the generator, which is transmitted into the grid, using a maximum power point tracking (MPPT) system, while the grid-side power converter controls the DC voltage and reactive power. To analyze and study the operating modes of the grid WT with the PMSG and evaluate the possibilities of regulating the generator rotation speed at variable wind speed and the generator rotation speed at optimal power generation into the 110 kV network, the mathematical model of the wind turbine with variable rotation speed was developed [4]. The paper [21] describes the basic laws of automatic control of a frequency converter. It should be noted that the d-axis current control algorithm is used to simplify the voltage control. A simplified mathematical model is represented by Equation (6) and Figure 5.

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L_d}\left(u_d - i_d \cdot r_s + L_q \cdot \omega \cdot i_q\right) \\ \dfrac{di_q}{dt} = \dfrac{1}{L_q}\left(u_q - i_q \cdot r_s - L_d \cdot \omega \cdot i_d - \Psi\omega\right) \\ M_G = \dfrac{3}{2} p\left[\Psi_m i_q + \left(L_d - L_q\right) i_d i_q\right] \end{cases} \tag{6}$$

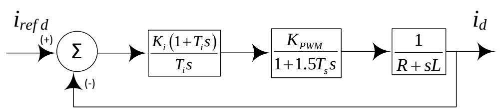


Figure 5 Simplified model of the d-axis current control loop of the frequency converter [21].

The present paper considers the mathematical models of the wind turbine as part of a wind power plant (WPP) in the implementation of normative disturbances from the 110 kV network by the following scenarios (Figure 6):

1) a sharp voltage drop by 25% in the 110 kV electrical network;

2) remote three-phase short circuit in the 110 kV network.

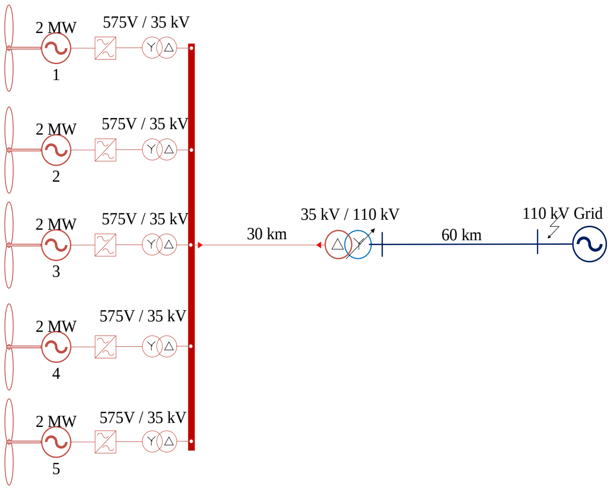


Figure 6 Fragment of the investigated electrical network.

A simple model obtained in the d-q coordinates of the rotor is applied for the mathematical modeling of the PMSG. The transition from (a, b, c) phase coordinates to (d, q) coordinates can be performed using the Park-Gorev transformations [13].

Then, neglecting the offset voltage of the zero point – U_0, due to the property of symmetry, the PMSG model in the d-q coordinates can be determined in the following form:

$$\begin{cases} u_d = i_d R + L_d i_d - \Psi_q \omega_s \\ u_q = i_q R + L_q i_q - \Psi_d \omega_s \end{cases} \tag{7}$$

where R – the stator resistance; u_d, u_q – d and q components of stator voltage respectively; L_d и L_q – inductances in d and q axes; ω_S- rotation speed of the stator electromagnetic field.

$$\begin{cases} \Psi_d = L_d i_d - \Psi_m \\ \Psi_q = L_q i_q \end{cases} \tag{8}$$

where Ψ_d and Ψ_q – magnetic fluxes in d and q axes; Ψ_m – the constant flux due to the presence of permanent magnets on the rotor.

Table 1 shows the parameters of the generator of the type-4 WT with the PMSG [17].

Table 1. Input data of the generator and the turbine for modeling

Parameters	Value
Power	2 MW
Voltage	730 V
xd reactance	1.305 p.u.
xd' reactance	0.296 p.u.
xd'' reactance	0.252 p.u.
xq reactance	0.474 p.u.
xq' reactance	0.243 p.u.
xq'' reactance	0.18 p.u.
Time constant T_{d0}'	4.49 s
Time constant T_{d0}''	0.0681 s
Time constant T_{q0}''	0.0513 s
Inertia time constant of the generator rotor	0.62 s
Gearbox	No

When analyzing a wind farm, the grid is usually represented as a busbar that maintains a constant grid voltage and grid frequency [3]. Therefore, to solve the problem of mathematical modeling of a 110 kV electrical network, the main assumption was a presence of the infinite power source.

Based on the previous equations, the expression describing active and reactive power generation is presented as follows:

$$\begin{cases} P_G = \frac{3}{2}\left(u_d i_d + u_q i_q\right) \\ Q_G = \frac{3}{2}\left(u_q i_d - u_d i_q\right) \end{cases} \quad (9)$$

4. RESULTS OF MATHEMATICAL MODELING

As the result of mathematical modeling, the operating parameters of the WT rotation speed, WPP active power and the change of reactive power are considered.

The results shown in Figure 7 were obtained using Matlab Simulink. In the case of a short circuit and a voltage change in the 110 kV network due to overload, the disturbance period was 100 ms. The figure demonstrates the influence of the disturbance nature on the WPP operating parameters. It follows from the results of mathematical modeling that even remote short circuits have a considerable influence on the WPP stability.

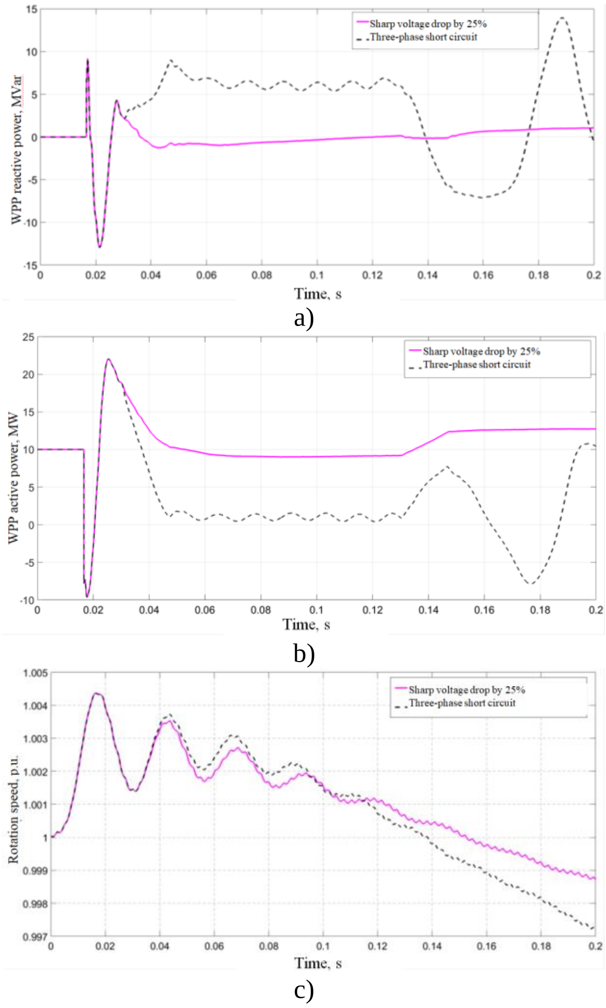


Figure 7 Results of mathematical modeling of WPP generation: a) active power; b) reactive power; c) oscillogram of generator rotation speed changing.

5. CONCLUSION

The obtained results of mathematical modeling allow evaluating the dynamics of WPP operating parameters changing during the implementation of the considered disturbance scenarios. Further investigations will be directed to the use of a WT mathematical model in simulating WT participation in the primary frequency control in the power system.

AUTHOR'S CONTRIBUTIONS

Andrey Achitaev and Richard Tarbill analyzed publications and obtained a mathematical model. Vyacheslav Astapov carried out modeling in Matlab and analyzed the results.

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