

Synthetic inertia controller of a wind power plant as a means of increasing the stability of electric power systems

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ABSTRACT

The article discusses the use of wind power plants as sources of synthetic inertia to enhance power system stability and reduce frequency fluctuations. This research explores the feasibility of implementing a synthetic inertia controller in wind power plants to decrease the magnitude of frequency oscillations during transient operating conditions. The growing integration of wind farms into modern power grids leads to a reduction in the overall kinetic energy, or inertia, available in the system. As a result, the grid may become more vulnerable to disturbances. When the system inertia is too low, frequency stability can be affected, especially when large generating units suddenly fail or disconnect from the grid. In general, a lower level of inertia in the system causes larger frequency deviations following an imbalance in active power. To overcome this issue, a synthetic inertia regulator for wind power plants has been developed, enabling wind turbines to support the grid and reduce the depth of frequency drops during transient events.

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1. INTRODUCTION

The frequency stability of electric power systems, associated with the frequency and angle of rotation of the rotor, is associated with the kinetic energy of rotating masses (synchronous generators and motors) connected to the power system. Distributed generation sources such as photovoltaic and wind power plants connected through power converters do not participate in the process of formation and contribution to the available kinetic energy of the system [1], [2]. The network frequency begins to decrease sharply within a few seconds after a powerful synchronous machine turns off or switches to asynchronous operation.

The amount of frequency reduction in power systems depends on the inertia of synchronous generators. The frequency reduction should be limited during the first 7-10 seconds after turning off the generation source. This allows the primary frequency regulators, with available active power reserves, to restore the rated frequency [3]-[5]. In power systems with a predominant share of electricity generation from renewable energy sources (wind and solar power plants) and a small share of synchronous rotating machines connected to the grid, the frequency changes very sharply when external disturbances occur, which challenges the sustainability of the power system.

Previous studies [1], [2], [6] discuss the application of doubly fed induction generator (DFIG) in primary frequency control and summarize research on DFIG inertia control in wind power. Lee *et al.* [2] proposed an algorithm for inertial control of a wind farm based on a dual-fed asynchronous generator to

maintain the network frequency during strong disturbances. Vidyanandan and Senroy [7] concluded that by adjusting the parameters of the synthetic inertia controller, it is possible to ensure not only the required inertial response, but also to improve the transient stability of power systems. Morren *et al.* [8] studied the influence of different levels of minimum inertia limitations in Europe and in each synchronous region. Key findings showed that increasing inertia constraints are driving up overall electricity generation costs, reductions in renewable energy and carbon dioxide emissions across Europe.

2. METHOD

A possible solution to improve frequency stability is to equip wind turbines with a so-called “synthetic moment of inertia”, that is, to introduce additional inertia into the system in the event of a rapid and/or significant decrease in frequency. In technical terms, kinetic energy is generated by the rotating mass of a wind turbine. Foreign studies have shown that a synthetic moment of inertia can keep the system stable until the primary frequency regulator comes into effect [4]-[6]. Figure 1 shows a block diagram of active power control of a wind power plant (WPP) [9].

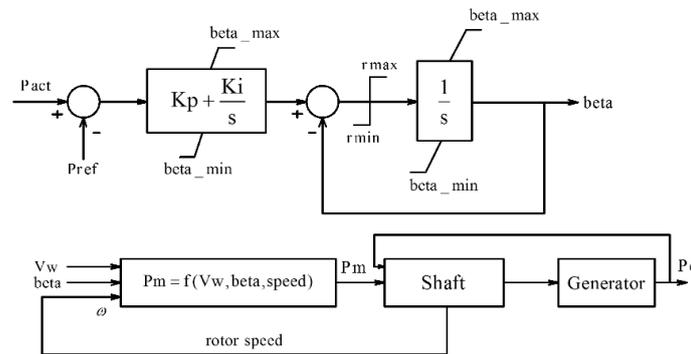


Figure 1. Wind turbine generator controller system.

The turbine blade angle control structure uses a proportional integral (PI) controller that takes into account the error between the actual and reference generator power. The turbine blade rotation angle control output is fed to the mechanical control system. The r_{min} , r_{max} correspond to the minimum and maximum speed of rotation of the turbine blade [10], [11]. The mechanical power (P_m) of a turbine is a function of three input variables such as pitch angle (β), wind speed (V_w) and rotor speed (ω). The rotation speed of the wind turbine is not synchronous with the grid and is controlled to maximize active power production. The wind turbine generator is inherently separated from the grid [12].

The synthetic inertia control structure is to detect significant frequency dips, and temporarily increase the power of the wind turbine, since the wind turbine can quickly store and release large amounts of kinetic energy from the rotating masses through the power electronic converter. However, the release of energy into the network is possible only for a short period of time (up to 30 seconds), and the subsequent restoration of the power of the wind turbine is ensured by the network [13], [14]. The increase in synthetic inertia is achieved by rapidly increasing the generator torque as the network frequency decreases, which leads to a decrease in the rotation speed of the wind turbine. The reduction in rotor speed is the result of converting the kinetic energy of the rotor into electrical energy. The disadvantage of this conversion is that the inertial response is followed by a recovery period during which the wind turbine generator produces less power in order to accelerate the rotor to optimal speed. There is also a risk that the rotor speed will drop too much (e.g. below cut-in speed), causing the wind turbine to shut down [15], [16].

To implement virtual inertia in wind turbine generators, it is necessary to understand the mechanism of wind energy conversion. Wind power can be expressed as [17]:

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v_{wind}^3 \quad (1)$$

The parameters ρ , A and v_{wind} are the air density [kg/m^3], rotor coverage [m^2] and wind speed [m/s] respectively. The share of wind energy converted into kinetic energy is called the power factor $C_p(\beta, \lambda)$ [18], [19]. The power factor has a theoretical upper limit of 0.593, which is called the Betz limit. The power factor

depends on the angle of inclination of the turbine blades β and the ratio of the turbine blade tip speed to the actual wind speed λ . The equation for calculating the coefficient λ is as follows [20]:

$$\lambda = \frac{\omega_{rotor} \cdot R_{rotor}}{v_{wind}} \tag{2}$$

where ω_{rotor} denotes the rotor rotation speed in [rad/s], R_{rotor} is the rotor length in [m]. Maximum power point tracking (MPPT) must change the rotor speed in proportion to the wind speed along with the pitch angle of the blades to find the maximum power factor [21]. By adding the power factor to (1), the mechanical power driving the generator is calculated as follows [22]:

$$P_{mech} = \frac{1}{2} \cdot C_p(\beta, \lambda) \cdot \rho \cdot A \cdot v_{wind}^3 \tag{3}$$

To determine the optimal blade angle, as well as the relationship between mechanical power, wind speed and rotor speed. Figure 2 shows the optimal MPPT trajectory on the example of the characteristic of the dependence of mechanical power on the turbine speed [23], [24]. As illustrated in Figure 2, depending on the wind speed, there is a turbine rotor speed at which the maximum mechanical power is generated at the generator input.

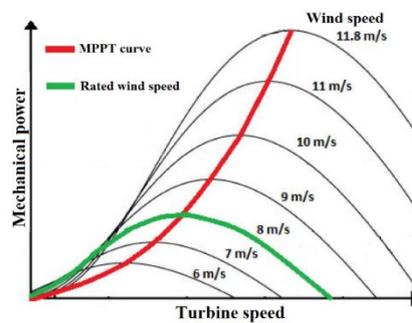


Figure 2. Turbine power characteristics

2.1. Synthetic inertia controller model

Figure 3 shows the power control scheme of the wind turbine, taking into account the model of the synthetic inertia controller. This scheme is a wind turbine control system taking into account two-circuit synthetic inertia regulator. The mechanical part of the control system consists of controlling the angle of rotation of the wind turbine blades to ensure the MPPT. In this case, a signal of the mechanical power of the turbine P_{mech} , summed with the output of the inertia regulator ΔP , is supplied to the input of the electrical part, i.e., the generator.

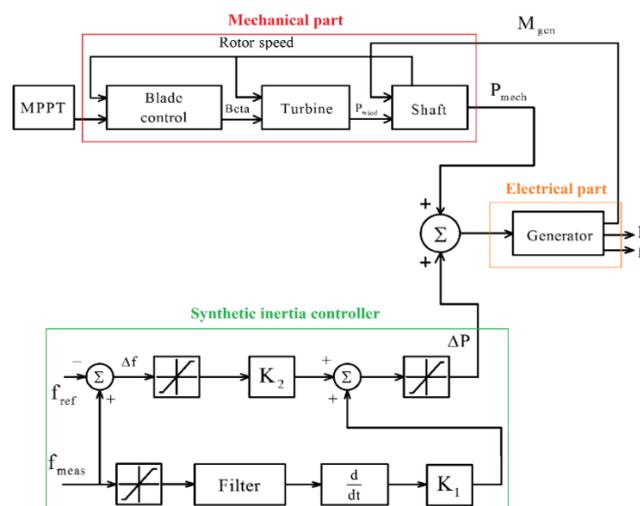


Figure 3. WPP model with synthetic inertia controller

The filter in the synthetic inertia regulator circuit is designed to suppress noise and interference and improve the stability of the regulator. The gain K_1 of the differential channel of the regulator is designed to amplify the rate of change of frequency signal. At the same time, excessively large values of the gain K_1 can lead to a significant acceleration of the turbine rotation, which will affect the mechanical part of the wind turbine. Large values of the coefficient K_2 can lead to a sharp drop in the speed of rotation of the turbine. As a result, the turbine may not restore the original mode of operation after the disturbance is removed. Small values of the gains reduce the efficiency of the synthetic inertia controller [25]-[27].

3. RESULTS AND DISCUSSION

Implement the wind turbine model taking into account the synthetic inertia controller (Figure 3) in the DlgSilent Power Factory software package. We took the gain K_1 equal to 9, and K_2 equal to 25 We investigated the effect of synthetic inertia on stability using the example of a test model of an electric power system shown in Figure 4. The initial data of the system under study are given in Tables 1-3.

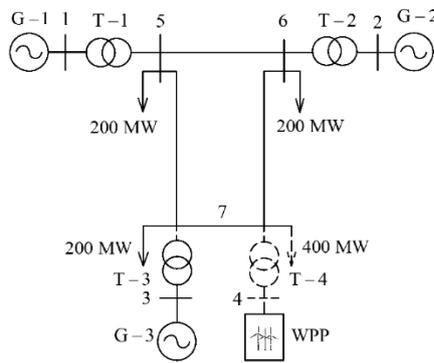


Figure.4. Test power system model

Table 1. Parameters of generators G1-G3

| P_{nom} , MW | $\cos\phi_{nom}$ | U_{nom} , kV | X_d , p.u. | X'_d , p.u. | T_f , sec. |
|----------------|------------------|----------------|--------------|---------------|--------------|
| 200 | 0.85 | 15.75 | 1.84 | 0.295 | 6.4 |

Table 2. Power line parameters

| Line | Wire type | Length km | U_{nom} , kV | X_0 (Ohm/km) |
|------|-----------|-----------|----------------|----------------|
| 5-6 | AS-240/32 | 60 | 220 | 0,435 |
| 5-7 | AS-240/32 | 30 | 220 | 0,435 |
| 6-7 | AS-240/32 | 45 | 220 | 0,435 |

Note. AS – 240/32: A - aluminum conductor, S - steel core, 240 - cross-section of the aluminum part, 32 - cross-section of the steel part.

Table 3. Parameters of transformers

| Transformer | Type | U_k (%) |
|-------------|----------------------|-----------|
| T-1 | TDS-250000/242/15.75 | 11 |
| T-2 | TDS-250000/242/15.75 | 11 |
| T-3 | TDS-250000/242/15.75 | 11 |
| T-4 | TDS-400000/242/15.75 | 11 |

Note. TDS-250000/242/15.75: oil power three-phase two-winding with forced circulation of air and oil, 250000 - rated power in kVA, 242/15.75 - values of rated voltages of HV and LV windings in kV.

To node 7 of the system (Figure 4), instead of generator 3, we connected a wind turbine of the third type (DFIG) with a capacity of 400 MW. Thus, the system had a significant share of wind generation. The first experiment was to connect a 200 MW load to bus 7 and evaluate the behavior of the synthetic inertia controller. Figure 5 shows the frequency change curves of the system during load surge, it is obvious that with the introduction of a powerful wind turbine, the total inertia of the system decreases and a more significant decrease in frequency occurs (curve 3).

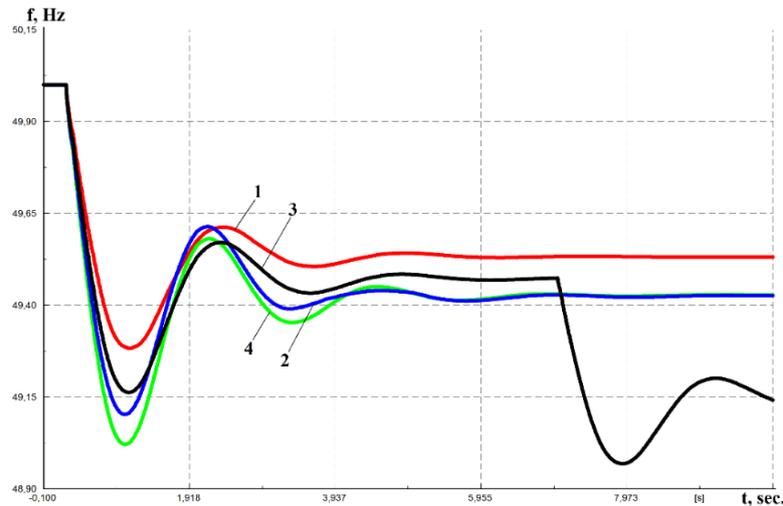


Figure 5. Frequency change curves during load surge (1 – without wind turbines; 2 – wind turbines with synthetic inertia, $K1=9$, $K2=25$; 3 – wind turbines with synthetic inertia, $K1=9$, $K2=55$; 4 – wind turbines without synthetic inertia)

In the presence of a synthetic inertia controller (curve 2), the frequency reduction decreases, which indicates the contribution of the wind turbine to the total inertia of the system during transient conditions. In the absence of a wind turbine (curve 1), the frequency value is somewhat higher, which is explained by the fact that the G1-G3 generators have primary frequency controllers. The presence of a synthetic inertia regulator (curve 3) in the wind turbine control structure made it possible to reduce frequency fluctuations. An increase in the gain $K2$ (curve 4) led to a significant decrease in the rotation speed of the wind turbine and, as a consequence, to the disconnection of the wind turbine from the power system and a further decrease in frequency. After connecting a high-power load to the power system, the system frequency decreased to a new steady state below the nominal value. This is explained by the imbalance of active power caused by the lack of power reserves in the power system, as well as the lack of primary frequency regulators at power plants. Thus, the use of transient synthetic inertia controllers can reduce system frequency dips by adding kinetic energy to the rotating wind turbines.

We next experimented with a three-phase short circuit with further disconnection of line 5-6 (Figure 4). The short circuit was simulated in the middle of the line, and the duration of the short circuit was 0.2 sec. Figure 6 shows the frequency curves of the system during a short circuit on the line.

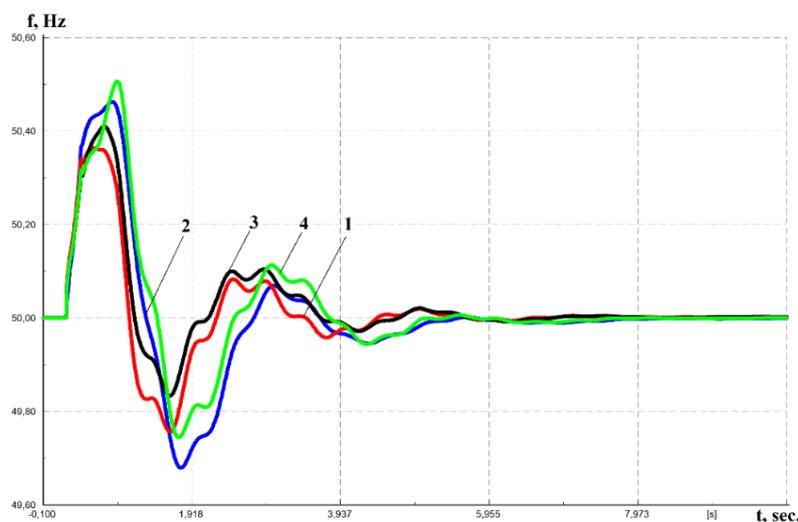


Figure 6. Frequency change curves during short circuit: Figure 6 (1 – without wind turbines; 2 – wind turbines with synthetic inertia, $K1=9$, $K2=25$; 3 – wind turbines with synthetic inertia, $K1=9$, $K2=55$; 4 – wind turbines without synthetic inertia)

In the presence of a wind turbine system without a synthetic inertia controller, a significant increase in frequency was observed (curve 3), which indicates an increase in the accelerating torque on the shafts of synchronous generators and, as a result, a decrease in dynamic stability. In the presence of synthetic inertia (curve 2), the amplitude of frequency oscillations decreased, which is associated with the addition of inertia to the system. In the absence of wind turbines in the system (curve 1), frequency changes were the smallest due to the greater inertia of synchronous generators. By increasing the gain K_2 of the synthetic inertia regulator (curve 4), it was possible to reduce the amplitude of frequency oscillations. When a short circuit occurs, the system frequency increases sharply, which is explained by the appearance of an accelerating torque on the shafts of synchronous generators and an increase in load angles. After eliminating the short circuit associated with disconnecting the power line, the network frequency was restored to a value close to the nominal one. In this case, the system remained stable in frequency.

4. CONCLUSION

The study shows that as the proportion of WPP in the total generation of power systems increases, the system inertia against external disturbances declines, leading to larger frequency fluctuations and reduced stability. The use of properly tuned wind turbine synthetic inertia regulators can allow for a short-term increase in the generated active power by wind generators, thereby compensating for the active power imbalance in the power system for the time required for the operation of the primary regulators of power plants. The disadvantage of using synthetic inertia controllers is that the wind turbine may come to a complete stop and, as a result may lead to a further decrease in the frequency of the system.

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