ELECTROTEHNICĂ, ELECTRONICĂ, AUTOMATICĂ (EEA), 68 (2020), nr. 4, pp.05-10
https://doi.org/10.46904/eea.20.68.4.1108001

Wind Power Plants Influence on Out-Of-Step Operation Mode Parameters of the Power System

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Abstract

One of the problems associated with the integration of renewable energy sources is reducing the total inertia of the electric power system. By substituting the traditional synchronous generators to wind turbines connected to a network via power electronics devices the system the inertia constant is sharply reduced. In addition, the inertia of the system changes over time due to the wind turbine power change. Systems with lower inertia in the serious faults incident loses its stability easier. The question of the reduction of energy system inertia influence on the out-of-step mode parameters is not answered yet. Authors created a grid test model using software-hardware hybrid simulation tool HRTSim. The several experiments to determine the influence of type 4 wind turbine on the parameters of the out-of-step mode is realized. The oscillograms confirming the influence of the wind turbine on the parameters of the out-of-step mode are obtained. Problems of the influence of changes in the inertia of the power system during the integration of type 4 wind turbines on the parameters of the out-of-step mode are considered. The international experience in this field is analysed. The results of the analysis confirmed the insufficient study of this field and the almost complete lack of information about this in the grid codes of foreign countries. The experiments confirmed the theoretical expectation: the higher inertia induction stroke starts later, and the frequency slip is decreased.

Keywords: out-of-step mode, wind turbine, inertia.

Received: 12 September 2020

To cite this article:
RUBAN N., ASKAROV A., RAZZHIVIN I., UFA R. “Wind Power Plants Influence on Out-Of-Step Operation Mode Parameters of the Power System” in *Electrotehnica, Electronica, Automatica (EEA)*, 2020, vol. 68, no. 4, pp. 05-10, ISSN 1582-5175.

1. Introduction

Currently, the pertinent question arises about the applicability of traditional methods of preventing transient stability losing, mainly consisting in the use of high-speed systems for regulating the generators excitation system, fast valving turbine control, generators/loads shedding, etc. as well as out of step protection system (OSP) with renewable energy sources (RES), since it is not known whether they will be effective in a changing dynamic characteristics of large electric power system (EPS). To analyse the world experience in combating this problem, various literary sources were studied, including the grid codes of various countries. For example, the system operators from different countries of the world (USA, China, EU countries, etc.) have enshrined in grid codes [1]-[3] special regulatory requirements for RES-based energy facilities with HVDC technology (these primarily include 3rd and 4th types wind turbines (WT), as well as solar power plants, which are connected to an external EPS, and are already tested in practice and are used in real EPS. Most of the requirements reflected in these regulatory and technical documents are directly related to the quality of electricity of generating facilities, including those based on type 4 WT, acceptable levels of voltage deviation in nodes and grid frequency, which are mainly related to the steady state mode of EPS. In Russia, the operation of emergency control systems is regulated by the system operator standard [4], but this document does not contain information about wind turbines. At the same time, these documents practically do not contain information on the impact of new devices on the stability of the EPS in general and the parameters of the out-of-step mode. The only measure to increase the stability of the EPS with the help of WT in these documents is the inadmissibility of shutting down new generating plants in the event of significant voltage drops near the place where the WT are connected [2].

At the same time range of processes is much wider, and therefore maintain only the voltage at the node to the detriment of active power issuing via multiplier devices may be insufficient to maintain stability operation of the EPS [5], [6].

2. Analysis of the behaviour of OSP in EPS with wind turbines

The most characteristic sign of stability losing is an increase of the mutual angle between the equivalent EMF of two parts of the electric power system connected by a power line. However, tracking this angle directly is technically difficult. Although, perhaps, modern technologies of vector measurements will allow in the future to solve this problem [7], [8]. In this regard, in most of the OSP devices in operation today, mode parameters are used that depend on the mutual angle, by changing which an out-of-step mode can be identified [9], [10].

Meanwhile, it is known that the presence of HVDC devices, including WT converters, in the power system has a direct impact on the operation of relay protection and automation of the rest of the power system equipment. So, for example, in the event of errors in switching the valves of the converter of a DC link, incorrect actions of the distance protection of the AC power lines adjacent to the insert are observed [11], [12].

In addition to the direct impact on OSP devices, one of the possible reasons for the improper operation of OSP system in the EPS may be an increase in the share of RES connected to the EPS through DC link. Thus, the type 4 WT with power converter is separated from the EPS. This leads to the loss of connection of the mechanical moment of the WT with the rest of the EPS. Thus, such generators have a completely different effect on the overall inertia of the EPS compared to traditional energy sources (thermal and hydraulic power plants), since they are isolated from the main electrical network. In the case of replacement of traditional power plants with wind farms, the total equivalent inertial constant of the power system can significantly decrease [13], which follows from:

$$H_{EPS} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{EPS}}, \qquad (1)$$

where H_i and S_i are the constant inertia and the rated apparent power of the *i-th* generator, *n* is the total number of synchronous generators connected to the grid, S_{EPS} is the total power of the EPS, which is equal to the sum of the rated powers of the operating units.

Meanwhile, it is known that this fact can lead to frequency and voltage fluctuations in normal operational modes, as well as a deeper decrease in the absolute frequency and voltage in the event of faults in the EPS [14], [15]. The world is trying to find a solution to this problem in different ways: the introduction of virtual inertia using control systems of WT (mainly of the 4th type); use of additional second-generation FACTS devices or powerful storage with WT, etc., which theoretically, makes it possible to provide additional active power if necessary. However, all these solutions are in the pilot stages of development and tested in a experimental circuits using mathematical modelling. These solutions are mainly focused on "return" of the EPS to its traditional view, by the minimizing effect of the integration of WT on the properties and characteristics of the power system that in the future should not lead to a radical change structure, algorithms, and settings of protection and automation devices installed in such EPS. At the same time, studies related to the study of the influence WT on the parameters of the out-of-step operation mode of the EPS are practically not presented in the literature, and therefore it was decided to analyse this direction in the proposed article.

3. The EPS mathematical model description

To analyse the influence of type 4 wind turbines on the parameters of the out-of-step mode, the EPS model (Figure 1) was used in the software-hardware hybrid simulation tool HRTSim [16].

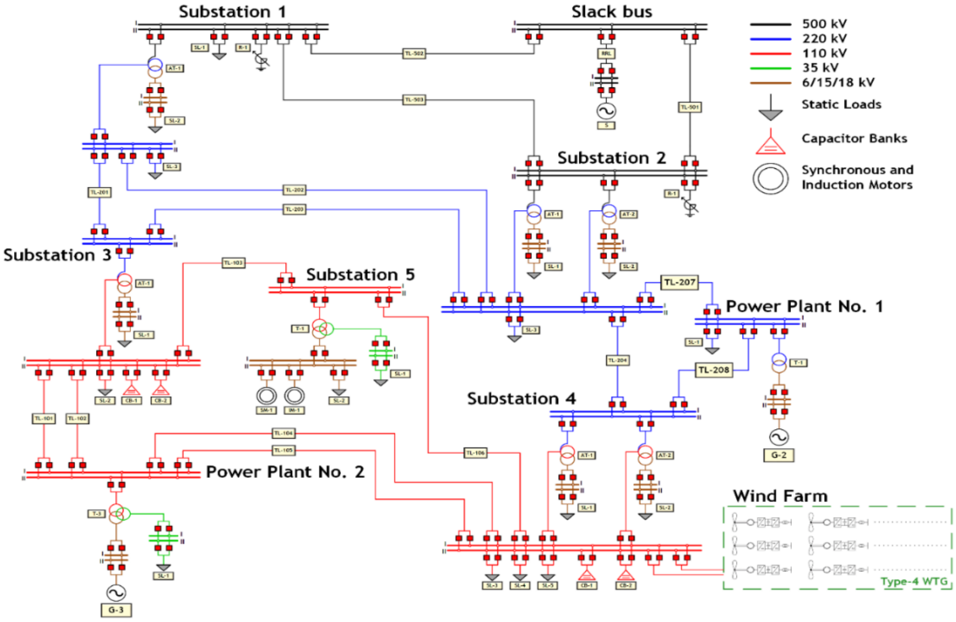


Figure 1. The EPS model

This scheme contains: one slash bus, transmission lines with a voltage of 110-500 kV, power transformers, static and dynamic (synchronous and induction motors) loads, turbine generators G-2 and G-3 (rated power

250 MW), a wind farm of 50 WT with each capacity of 5 MW. The standard model of WT [17] from the HRTSim library was used, as well as a 4-mass transmission model [18]. The generator is connected to the main EPS via a DC-DC Boost Converter. The WT pitch angle control system is used according to the recommendations [19] and is implemented based on a PID controller.

4. Case studies

4.1. *Preparing for the experiments*

The testing process is performed in two stages.

At the first stage, the preparing of the test model is performed:

- EPS model configuration;
- setting up the of monitoring and registration tools of the EPS model operating parameters;
- research scenarios preparing, which allows to make a conclusion about the efficiency of the correctness of the model operation;
- the automation model preparing (translation of the needed automation system to the test system and adding of new parameters and algorithms).

At the second stage, the all-research scenarios are carried out, results are analysed and the conclusion about readiness and applicability is formed.

The EPS parameters before short circuit are given in the Table 1.

Table 1. The EPS parameters

№ of case study	Type of connected generators	Generated power, MW	Voltage in Power Plant No. 1 busses, kV	Voltage in Substation No. 4 busses (High level), kV	Voltage in Substation No. 4 busses (Low level), kV	Power flow through the TL-207, MW	Power flow through the TL-208, MW
1	Turbogenerator	248.7	220	219.7	110.9	198.8	13.8
2	Wind power station	249	219.9	220	111	198.5	14.1

4.2. *The case study description*

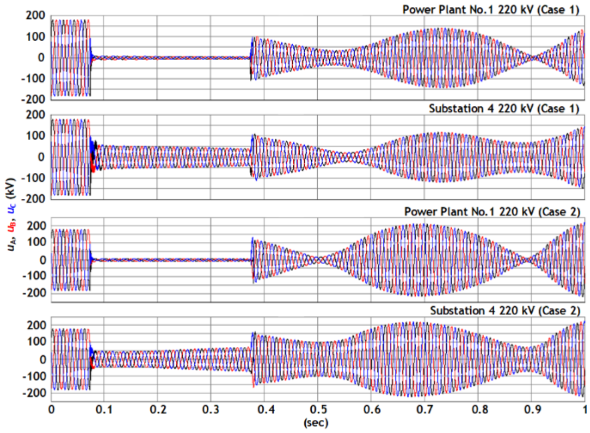
Within the framework of the case study, the effect of reducing the total inertia of the EPS on the parameters of the out-of-step mode was investigated. For this, the case study was carried out as follows: in the original scheme, the power flow of the TL-207 and TL-208 transmission lines was set in such a way that the main power flow was set through the TL-207 transmission line, while the TL-208 transmission line is quite long (150 km). Further, in the test EPS, an emergency situation is simulated in the following steps:

- at the moment of time 0.075 s, a fault with a duration of 0.3 s occurs on the TL-207 transmission line (taking into account the action of the relay protection and the circuit breaker failure backup device);
- at time 0.375, the TL-207 transmission line is disconnected and the process of the synchronous generator G-2 stability losing begins;
- on the TL-208 transmission line there are signs of an out-of-step mode, which should be fixed by the OSP.

To confirm the theses about the impact of the introduction of a significant number of wind turbines of the 4th type on the dynamics of transient processes in the EPS model the case study was repeated twice:

1) Synchronous generator G-3 with a capacity of 250 MW is connected to the EPS and produces maximum power, and a wind farm with a capacity of 250 MW is taken out of operation;
2) Synchronous generator G-3 is disconnected from the EPS, and the wind farm delivers maximum power to the power system (250 MW).

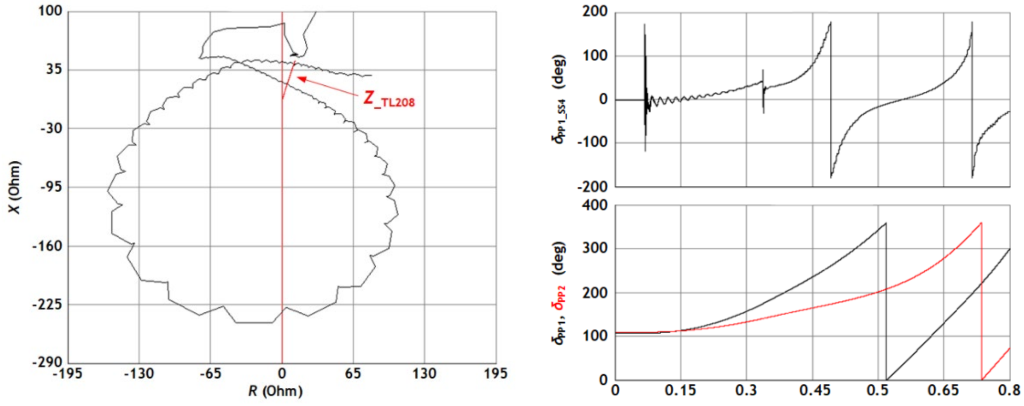
The value of inertia for the G-3 turbine unit is taken as 3.2 s, for the wind power plant0.62 s. To assess the impact of changes in the total inertia of the power district on the parameters of the out-of-step mode, the voltage on the buses Power Plant No. 1, Substation No. 4 (220 kV) was measured (Figure 2).



Legend: u_A, u_B, u_C - phase voltages in different points of EPS model

Figure 2. Phase voltages oscillograms for the out-of-step mode

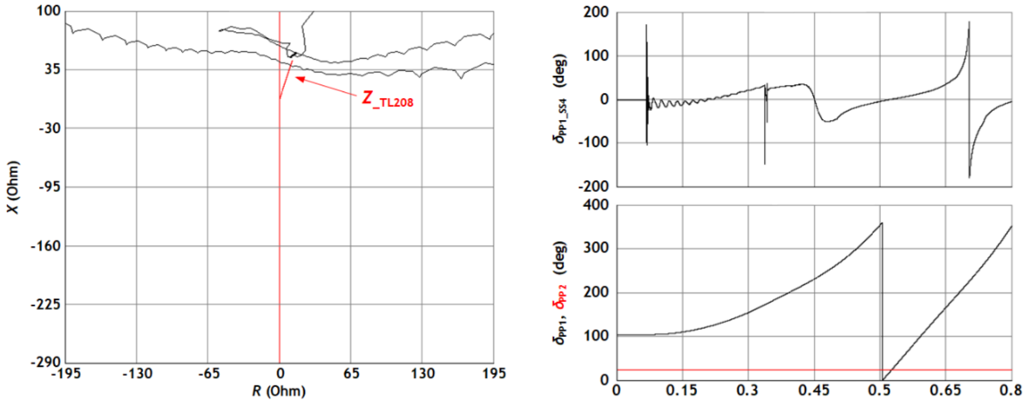
The resistance hodograph (Figures 3a and 4a) is presented to better understand the location of the electrical swing centre (ESC) in the protected area.



(a) (b)

Legend: R, X - active and reactive resistance; δ_{PP1_SS4} - mutual angle between the voltages vectors on the buses Power Plant No. 1 and Substation No. 4; δ_{PP1}, δ_{PP2} - relative angles of generators G-2, G-3

Figure 3. Resistance hodograph: (a), mutual and relative angles; (b) for the TL-208 power line, case 1



a) b)

Legend: R, X - active and reactive resistance; δ_{PP1_SS4} - mutual angle between the voltages vectors on the buses Power Plant No. 1 and Substation No. 4; δ_{PP1}, δ_{PP2} - relative angles of generators G-2, G-3

Figure 4. Resistance hodograph: (a), mutual and relative angles; (b) for the TL-208 power line, case 2

So, the hodograph for case 2 (with a connected wind farm) on the first cycle does not fall into the OSP response area. Thus, the OSP response time is slowed down by the time of one turn. The value of the mutual angle between the voltages on the buses Power Plant No. 1 and Substation No. 4 was also measured. The oscillograms change of this angle are shown in Figures 3b and 4b.

At the same time, the oscillograms clearly show the change in the parameters of the out-of-step mode with a decrease in the total inertia of the energy region, with a higher inertia, the out-of-step mode begins later (over 0.15 s) and the slip frequency decreases.

The long existence of the out-of-step mode is dangerous due to a significant displacement of the ESC, the position of which strongly depends on the circuit-mode state of the EPS and the nature of the load of adjacent substations. An example of an ESC offset is shown in Figure 3a and 4a.

5. Recommendations

It is also necessary to consider that each country has its own specific network codes, with its own individual criteria and technical requirements when connecting wind turbines to the network. However, the numerical indicators of these requirements differ significantly, and therefore, without a preliminary comprehensive analysis, these documents, the solutions, and the recommendations indicated in them cannot be used in conditions of another country [20]. In this regard, the development of recommendations for OSP algorithms adaptation in EPS with 4 types WT is actual. To ensure the normal operation of the EPS work with 4 types WT several measures for adaptation OSP devices has been proposed to:

1. To ensure the reliable operation of the OSP stages operating in the first cycle (first stage), it is necessary that they operates correctly if there are 4 type WT in the network if the assumed ESC according to the results of preliminary modelling is near the end of the protected area, associated with the danger of the ESC leaving the protected area, which will lead to a delay in the out-of-step mode and an increase in the likelihood of its transition to a multi-frequency one. In this case, it is recommended, when detecting the fact of stability losing by means of emergency automation, to form a control action on the network islanding in pre-determined points. It is also recommended to ensure reliable coverage of the HVDC device (with a margin) within the coverage area of the specific OSP set.

2. To ensure the reliable operation of the OSP stages, operating after the completion of several cycles (the second and third stages), it is necessary that they function correctly in the presence of 4 type WT devices in the grid if the assumed ESC according to the results of preliminary modelling is near the end of the protected area. In this case, the ESC can move from the coverage area of one OSP to the coverage area of another, thereby delaying the disconnection of the transmission line each time resetting the cycle meter, while the dynamic loads on the generators increase, which is fraught with damage. It is recommended not to reset the cycle meter, but to continue the virtual counting, and, in the case of the return of the ESC to the OPS operation zone, to carry out the division without holding.

3. In the case of a significant share of generation from wind turbines using HVDC technology in the EPS, it is recommended to use high-speed OSP devices, since the processes in such EPS develop much faster than in traditional ones. However, when calculating model resistances, it is necessary to consider the capabilities of wind turbines using the HVDC technology to maintain the mode (Fault Ride-Through or Low Voltage Ride-Through capabilities).

4. If it is impossible to use high-speed OSP in networks with a significant share of generation from wind turbines using HVDC technology, it is recommended to use an OSP with resistance control with the lowest slip frequency. It is also recommended to refuse to deactivate the first stage, which can lead to a heavier accident and an increase in the probability of transition of the out-of-step mode to the multifrequency mode.

6. Conclusion

As a result of the performed experiments, it was found that *an increase in the share of wind turbines of the 4th type in the total generation of EPS leads to a completely different course of transient processes in it* — with an increase in the share of wind turbines, the system becomes less stable, since the total inertia of the system is significantly reduced. When the proportion of wind turbines becomes more significant, there is a violation of the dynamic stability of the generators and the occurrence of an out-of-step mode. In this case, a further increase in the share of wind turbines leads to an increase in the slip frequency of the out-of-step mode. In turn, an increase in the slip frequency can cause non-operation of the OSP devices, if the time between cycles becomes comparable to the time of changing the parameters during a short circuit.

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Funding Sources

The work was supported by Ministry of Science and Higher Education of Russian Federation, according to the research project № МК-1675.2019.8.

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