Method for determining the critical parameters of the sustainability of an energy system with integrated renewable energy sources

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Abstract. This paper proposes a method for modeling the regime of a power system with integrated variable renewable sources - wind power units and solar PV installations, the generation of which is continuously changing in accordance with the random variability of wind speed and solar radiation. Wind speed and solar radiation data were obtained for real regions in which a 240 MW wind farm and a 230 MW solar PV power plant are currently under construction. A method is proposed for calculating the value of the critical stress in the system for indefinitely changing wind speed and the level of its fluctuations, which determine the stochastic variability of the system regime. For each interval of change in wind speed, a set of probable modes of the system and the corresponding critical voltages in the network of the system are determined. The computational experiments were performed for the 30-node IEEE scheme.

Introduction

In the electric power systems (EPS) over the past 30 years, there have been significant changes, both in the structure of generation and in electrical transmission and distribution networks.

Modern EPS contain mode control devices that make it possible to make power facilities (generators, buses) flexible in controlling the generation of active and reactive power and their distribution, as well as control the demand for consumed power, thereby creating the best conditions for covering the power balance under various random disturbances.

In these cases, voltage instability is considered one of the main threats to the safety of the operation of modern EPS. In recent years, renewable energy sources (RES) have been widely used in energy systems to improve the efficiency of functioning and reduce the impact of harmful emissions on the environment. The increase in the generated power of RES in the power system began to have a significant impact on voltage stability [1, 2]. The article investigates the influence of the growth in the power of integrable wind generators on the change in the limits of voltage stability, the assessment of the possibility of violation of stability during shutdowns of system elements.

The risk of violating the stability of the power system is determined by the probability that one of the main elements of the system (generator, line or section of the power supply network) will continue to function without failures for a certain period of time. The growth of renewable energy (primarily solar and wind) is expected to increase in order to reduce the use of fossil fuels. However, solar and wind energy have risks and uncertainties of deteriorating voltage stability limits, which must be taken into account when controlling the flow distribution of the electrical network of the power system [3].

Compared to power systems using synchronous generators (SGs), power systems with significant installed capacity renewable energy sources (RES) (the so-called inverter power systems) [4, 5] do not have sufficient inertia, which requires more in-depth studies of sustainability problems in such systems with RES. For these purposes, appropriate analytical methods are needed, on the basis of which it is possible to obtain voltage stability estimates in a power system with a large integrated power of variable renewable sources, which are controlled by a scheme with inverters.

Voltage stability in a power system with RES has become important from the point of view of the continuity of trouble-free power supply to consumers. Compared to traditional energy systems, the ability to control voltage in an electrical distribution network with connected renewable sources is limited [6].

In most cases, the integration of high-capacity RES into the power system is carried out by connecting them through electrical networks of distributed generation. To directly connect renewable energy sources to a distributed generation network, power inverters (SI) are used. Generating wind and solar installations equipped with SI are usually called inverter generators (IG).

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At present, in power systems, a significant proportion of the generated active power of IG installations operated in power systems can be large (up to several hundred megawatts) and have large mechanical inertia. The large inertia of the rotors of these IGs is prevented by a sharp change in the rotor speed, which contributes to the stabilization of the system mode during disturbances.

Unlike SG, IG installations are located closer to the load connected to the DG system, and in cases where a large amount of RES connection with variable generation is used in DG, they create problems associated with controlling power flows and voltage stabilization in the system [7-9].

The concepts and methods of sustainability studies used for conventional power systems are not sufficient to analyze the sustainability of power systems containing a large capacity of renewable energy sources with variable output (power plants with Wind and PV power plants).

Voltage stability in a power system with RES is an important parameter, the control and management of which will allow assessing the stochastic variability of the current state of the power system, from the limit state (maximum flows, critical voltages at the nodes). Voltage instability occurs in the form of a gradual decrease in its value in some nodes of the system. This is due to the inability of DG systems to provide enough generated electricity to cover the growing demand in the system [10].

At all possible levels of RES generation stochasticity, the integration of renewable sources will improve the voltage profile by reducing power losses [11, 12].

The paper investigates the influence of connecting a high-power wind farm on the limits of voltage stability in the power system.

With a deterministic setting of the power generation value of a wind farm for fixed wind speeds, the voltage stability margin can be estimated in a simplified way from the curves [13].

1 Methods for estimating the probability of distribution of critical stress values during stochastic mode changes in a power system with a wind farm operating in the range of wind speed variability up to the nominal

1.1 Methods of sequential weighting of the power system mode

The essence of these methods is to identify the share of the contribution of each source to cover a given amount of load growth and the corresponding part of the losses from the transmission of this power through the network. Let K_{Gi} be an indicator of the growth of $P_{Gi,0}$ active power generation by the i generator and be the base (nominal) value of the power generation of this source. In this case, the generation power P_{Gi} at the point after the increase in power can be written:

$$P_{Gi} = P_{Gi,0}\left(1 + K_{Gi}\right) \quad (1)$$

where $i = 1,2,...,n$ for all participating generators.

The value K_{Gi} shows the degree of participation of the $i-$th generator in violation of the voltage stability limit.

1.2 Load limit maximization method

This method is based on a surface approximation that describes the space of states of the power system in the coordinates of the generating capacities of the stations. The essence of the approach based on state surface modeling is outlined below. The possibility of separability of the limit load condition is shown. A method is proposed for the maximum load limit for power transmission over the network (dedicated transmission line). As a result, the application of this method makes it possible to build a model of the value of the maximum load of the system, depending on the variability of the increase in sources. By approximating the surface of the maximum power transfer in the form of Functions depending on the increase in the power of generators (GD_i), it is possible, using well-known optimization methods, to find the maximum point of the curve of the function, $P_{np}^{\max}$. The identification of the model $P_{np}\left(GD_i\right)$ and the determination of its maximum can be made by carrying out the following computational procedures:

1. Determination of the dependence $P_{np}\left(GD_i\right)$ on the power variability of each $i-$th generator. The set of values $P_{np}\left(GD_i\right)$ is determined from a series of curves $P-U$ for different generators GD from a series of selected ones. In this case, the model $P_{np}\left(GD_i\right)$ is described in the form of a first-order dependence for each individual generator, except for the balancing one. If we construct continuous curves $P_{np}\left(GD_i\right)$ for all i generators, then we can represent the expression for the general case as the following polynomial:

$$\left[P_{np}(GD)\right]_j = B_{j,0} + B_{j,1}GD_j + \cdots + B_{j,n}GD_j^n = B_{j,0} + \sum_{p=1}^{n} B_{j,p}GD_j^p \quad (2)$$

where $\left[P_{np}(GD)\right]_j$ –is a polynomial approximation of the dependence $P_{np}(GD)$ for the case of studying the interaction between two generators (a basic generator and another generator connected to buses j); $B_{j,p}$ – polynomial coefficients; $n-$ number of coefficients; B_0 – permanent member is equal for all $B_0 = B_{j,0}$.

2. The surface $P_{np}(GD_i)$ is approximated for the multidimensional case, subject to the conditions of separability of the state. For all n-generators, the surface $P_{np}(GD)_j$ is defined as:

$$P_{np}(GD) = B_0 + \sum \left[P_{np}(GD)\right]_j,\ j = 1,...,n \qquad (3)$$

Equation (3) describes the surface for all possible options from among the selected generators. A combination of all polynomial equations (2) with the same constant B_0 is determined, the value of which is taken as in paragraph 1.

3. The best vector $P_{np}(GD)$ is determined by the maximum value P_{np}. This best vector $P_{np}(GD)$ is found as the maximum of function (3) under the following constraints: $\Sigma GD_j = 1$ and $0 \le GD_j \le 1$.

Stage 1 studies can be performed using the ETAP software package to determine the voltage stability limit in terms of fulfilling commercial conditions, while stages 2 and 3 require the use of software in solving problems of analysis and operational control. The proposed method has been tested for various versions of the IEEE test scheme.

2 Simulation results

Fig. 1 shows a fragment of a 30-node IEEE single-line test circuit, on the basis of which the studies were performed. There are 4 generator buses in the system, one of which represents a common connection point for the wind farm (buses B2 and B3). There are 10 buses and 34 branches, with the sum of loads connected to the component $P_n = 283{,}4\,MBm$; $Q = 126{,}2\,MBAp$. The total installed capacity of the wind farm (stage 1) with a total of 60 wind turbines (2 MW each).

On Fig. 2 shows the curves for changing the power limit in the system for the options for the participation of pair generators 1-2; 1-6; 1-8 when regulating the mode of transmission of the total load in the event of an emergency failure of one of the lines (case N-1).

At the same time, it is clear from the picture that in the case of G1-4, regulation with the 4th source is possible up to the price of generation, but it is not possible for the prices of generation after that. In other words, it is not possible to adjust the entire range. However, in the case of G1-2, it is known that the adjustment margin is large, and it is possible to ensure the stable mode of the system in the entire range.

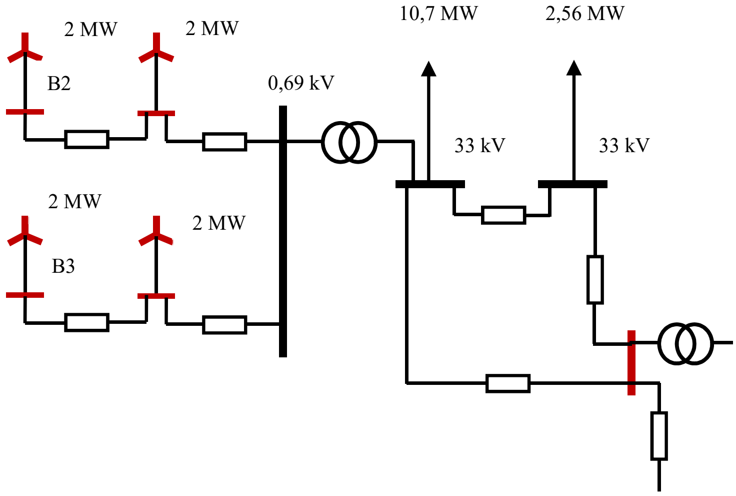

Fig. 1. Fragment of 30 nodal IEEE single-line test circuit

The case of G1-2 is not suitable for adjustment. It should be noted that the obtained results were adapted to the real conditions as much as possible, as the most probable accidents in the electrical system for the Azerenergy system during one year were investigated and damage to the 110 kV power transmission line was found. In this case, the case of accidental opening of the electric transmission line was also considered. According to the N-1 criterion, the power transmission line is considered to be sequentially opened from protection.

Options for integration in the RES system for the Azerenergy system were also considered. The results were obtained using the ETAP 19.5 software package. The results obtained at wind speeds of 14 m/s, 10 m/s and 5 m/s are shown in Tables 1 and 2.

Note that the wind speed values given in the tables reflect real values obtained from local metrological stations for distant regions of Azerbaijan.

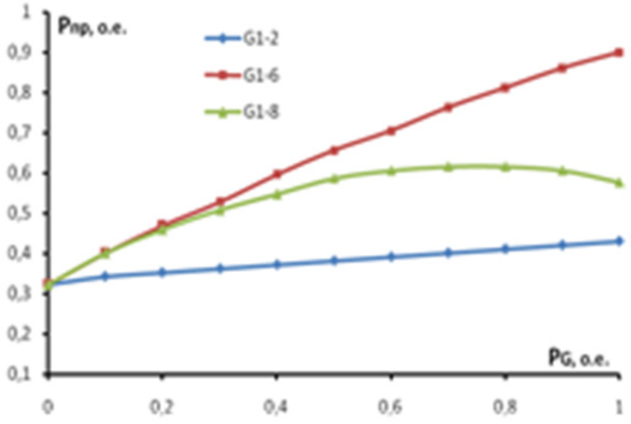

Fig. 2. Changing the limit of transmitted power in the case of one regulating source and emergency shutdown of one element

Table 1. Limiting values of transmitted power and critical voltages in the node of connection of the wind farm to the power system for the values of the load curve in different periods and different values of the network load in terms of active power

Wind speed 14 m/sec		
Load	Critical voltage, %	Power from buses 3_30
0	0	0
106	52,84	170,6
20	90,64	30,6
10	94,98	20,6
Operating point	98,97	10,6
Additional points		
100	55,85	110,6
70	68,18	80,6
50	76,95	60,6
30	86,11	40,6
Wind speed 10 m/sec		
0	0	0
175	30,82	185,6
30	84,08	40,6
20	88,9	30,6
10	93,56	20,6
Operating point	97,89	10,6
Additional points		
170	32,51	180,6
160	35,33	170,6
100	53,66	110,6
70	65,48	80,6
50	74,49	60,6
Wind speed 5 m/sec		
0	0	0
178	26,74	188,6
30	82,6	40,6
20	87,6	30,6
10	92,45	20,6
Operating point	96,99	10,6
Additional points		
170	27,48	180,6
160	30,99	170,6
100	50,98	110,6
70	63,32	80,6
50	72,66	60,6

Table 1 shows the limit values of the transmitted power and critical voltages at the node of the wind farm connection to the power system, depending on the network load in terms of active power, and in Table 2 - the limit values of the transmitted reactive power and critical voltages for reactive power values. Based on the values given in the table, it is possible to estimate the stability limit of the system with the increase of the share of renewable energy sources in the daily consumption.

Table 2. Limit values of transmitted reactive power and critical voltages in the wind farm connection point to the power system for reactive power values

Wind speed 14 m/sec		
Q, load	Critical voltage, %	reactive power from buses 3_30
72	53,58	73,9
70	55,04	71,9
60	60,37	61,9
50	65,42	51,9
30	76,62	31,9
20	83,14	21,9
10	90,52	11,9
Operating point	98,97	1,9
Wind speed 10 m/sec		
178	31,55	179,9
100	48,76	101,9
50	66,37	51,9
30	76,56	31,9
20	82,71	21,9
10	89,76	11,9
Operating point	97,89	1,9
Wind speed 5 m/sec		
0	0	0
278	18,55	279,9
200	29,43	201,9
178	32,63	179,9
100	48,36	101,9
50	65,7	51,9
30	75,81	31,9
20	81,91	21,9
10	88,96	11,9
Operating point	96,99	1,9

3 Analysis of the influence of an integrated wind farm on the limits of voltage stability

The integration of a wind station into the power system depends on many factors, such as data on wind speeds for a long period of observation, the presence of a connection with a system capable of providing the maximum power generation by the wind station, the presence of a source of active power generation in the absence of the possibility of generating a wind station, and many others. Thus, it may not be possible to integrate a wind farm by connecting to a “weak” system bus or through a weak area of a system distribution network closer to the wind farm to be connected. In addition, the load of the system also changes over time. Therefore, the work considered the influence of load variability, as well as the connection scheme of a wind farm on the stability of the system voltage. It should be noted that the operational and short-term forecasting of the daily load schedule for the day and a longer period ahead, in this work, is taken as given.

On Fig. 3 shows the voltage values depending on the wind speed of 5, 10 and 14 m/s at a load of 20 and 30%. As can be seen, at the point of connection of the wind turbine, the voltage value improves with increasing speed, i.e. with an increase in power output from a wind generator.

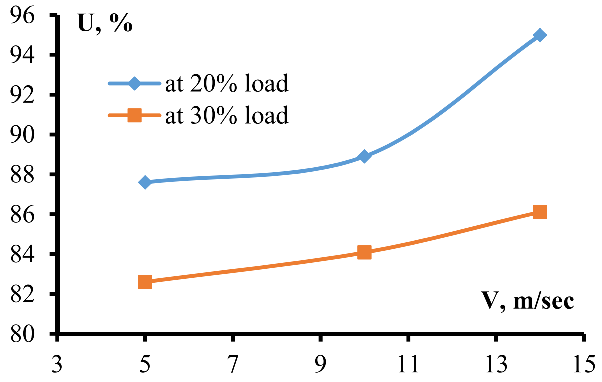

Fig. 3. Dependence of the voltage value on the wind speed at 20% and 30% load.

Conclusion

1. In the electrical system, with the growth of wind power generation and solar PV power plants, the risks of voltage instability may increase, which have deeper consequences for post-failure conditions caused by the shutdown of lines and generators. The influence of integrating a large share of wind energy generation on the stability of the voltage of the power system is considered. On the basis of computer simulation on IEEE test circuits, it was found that the magnitude of the generation power of a wind farm, its connection scheme to the power system, the position of the load curve in the studied interval have a significant impact on the stability of the system voltage.

2. A preliminary analysis of the results of modeling the modes of power systems with wind turbines shows that wind farms connected to some nodes of the system can be used as a set of additional tools to increase voltage stability.

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