Medium and long term voltage stability simulation of power system under high proportion of new energy substitution

Zheyuan Zhao, Chenglong Sun*, Juan Zhu, Hao Qin and Shouhu Ma
Huai’an Power Supply Company, Huai’an, Jiangsu, 223000, China
*E-mail: huaian95598@js.sgcc.com.cn

Abstract. In order to maintain the stability of the current and voltage of the power system under the high proportion of new energy sources, a simulation method for the medium and long-term voltage stability of the power system under the proportion of high and new energy substitution is studied. Based on the simplified model of a high-proportion new energy alternative power system, the voltage stability conditions of the system are analyzed. After studying the influence of dynamic load changes on the voltage stability of the power system, continuous parameters are introduced based on the principle of quasi-steady-state simulation to realize the simulation analysis of voltage stability. The comparative analysis of the simulation results proves that the simulation method not only has high accuracy, but also shortens the simulation time by about 41.87%. The simulation effect is good, and it is suitable for the long-term voltage stability simulation of the power system.

1. Introduction
The modern interconnected power system is a highly complex nonlinear system with many and complex stability-related problems and a variety of manifestations. Voltage stability refers to the ability of a power system to maintain a stable voltage at all buses in the system after a given initial operating state is disturbed. While voltage collapse refers to a process where a chain of accidents accompanied by voltage instability leads to a large power system blackout or abnormally low voltage[1-2]. Voltage stability in time domain can be divided into short-term voltage stability and long-term voltage stability, where long-term voltage stability refers to the voltage stability associated with the slow dynamic components of the system[3-4]. The medium and long-term dynamic simulation is the dynamic simulation of a longer process after the power system is disturbed, and the medium and long-term simulation can analyze the dynamic characteristics of the power system in a longer period of time[5]. For the high proportion of new energy alternative power system, the control strategy of the power system is different from the conventional power system, and the control model and response characteristics of the system are diverse, which affect the dynamic characteristics of the whole system. Foreign scholars use the frequency characteristics of new energy sources such as wind energy, load margins, and interior point algorithms of new energy integration to simulate and analyze the voltage stability of power systems[6-7]. The above study does not consider the nonlinear oscillation and harmonic stability problems caused by the introduction of equipment, which is computationally intensive and not suitable for simulation for a longer period of time, and is suitable for the study of transient voltage stability. It is of great importance to study an accurate and fast simulation method for long-term voltage stability. Therefore, in combination with the above analysis, this paper will study the simulation method for long-term voltage stability in power systems with high percentage of new energy substitution.
2. Medium and long term voltage stability simulation of power system under high proportion of new energy substitution

2.1. Simplified model of high scale new energy alternative power system

The operation can be concentrated to the unit with the largest capacity and ignore the influence of the access location on the system[8]. The simplified model of the high scale new energy replacement power system established in this paper is shown in Fig. 1.

![Simplified model of power system under high scale new energy substitution](image)

Figure 1 Simplified model of power system under high scale new energy substitution

As can be seen from Fig. 1, the power system is divided into a 3-node system, where node S is the reference generator (equivalent to the infinity bus), node G is the conventional unit (group), and node W is the new energy unit (group) after replacing the conventional power source. Mathematically, the power system is a nonlinear system consisting of differential, differential and algebraic equations[9]. When considering only discrete events and neglecting the difference equations, the power system can be described by the following differential algebraic equations.

\[
\begin{align*}
\dot{x} &= f(x, y, p) \\
0 &= g(x, y, p)
\end{align*}
\]  

(1)

In the above formula, \(x\) is the state quantity, such as the power angle, frequency, flux, transient or subtransient potential, control system state variable and dynamic load variable of power generation equipment. \(y\) is a variable subject to algebraic constraints, such as node voltage amplitude and angle, etc. \(p\) is the system control parameter vector.

2.2. Power system voltage stability condition analysis

According to the system model established above, it is assumed that the injected power of W is \(P_W + jQ_W\), and the injected power is represented by equivalent admittance[10]. The power system network equation under the replacement of high proportion of new energy is as follows:

\[
\begin{bmatrix}
Y_{GG} & Y_{GW} \\
Y_{WG} & Y_{WW} - Y_W
\end{bmatrix}
\begin{bmatrix}
\dot{U}_G \\
\dot{U}_W
\end{bmatrix}
= \begin{bmatrix}
I_G - Y_{GS} \dot{U}_S \\
- Y_{WS} \dot{U}_S
\end{bmatrix}
\]  

(2)

In the above formula, \(Y_{GG}\) and \(Y_{WW}\) are conventional unit nodes and wind power unit nodes respectively; \(Y_{GW}\) and \(Y_{WG}\) are the mutual admittance matrices between conventional power supply nodes and new energy unit nodes; \(Y_{WW}\) is the admittance matrix of the replaced unit node; \(Y_{GS}\) and \(Y_{WS}\) are the mutual admittance matrices between the conventional unit and the replaced unit and the balance node respectively; \(Y_W\) is the diagonal matrix formed by the equivalent admittance of injected power; \(\dot{U}_S\) is the voltage of the balance node; \(I_G\) is the Norton equivalent current vector of the conventional generator set. When the generator adopts the classical second-order model, \(I_G\) satisfies the following equation:
\[ I_{G(k)} = \frac{E_{G(k)}}{x'_{d(k)}} \angle \delta(k) - 90^\circ \] (3)

In the above formula, \( k \) represents the \( k \)th unit; \( x'_{d(k)} \) is the direct axis transient reactance of the conventional equivalent unit \( k \); \( E_{G(k)} \) is the conventional equivalent terminal voltage of the unit; \( \delta \) is the conventional equivalent power angle of the unit.

2.3. Power system dynamic load analysis

Loading is composed of many electrical equipment supply lines and reactive compensation equipment in substations at all levels. It is very difficult to describe its dynamic process in detail. In the study of voltage stability, the resistance is taken as the state variable to describe the comprehensive load of the power system. The mathematical expression is as follows:

\[ \frac{dR_E}{dt} = -\frac{R_E^2}{T_E} (P_T - P_E) \] (4)

In the above formula, \( P_T \) is the mechanical power output by dynamic load; \( P_E \) is the electromagnetic power absorbed by the dynamic resistance; \( \frac{R_E^2}{T_E} \) is the time constant; \( R_E \) is the system load impedance. The self-recovery load models widely used in long-term voltage stability research include additive model and multiplicative model. The results show that the additive model is easy to encounter singularity because it introduces a constant power term into the transient load characteristics.

2.4. Medium and long-term voltage stability simulation implementation

In this study, continuous parameters are introduced on the basis of quasi-steady state simulation to realize the rapid simulation of medium and long term voltage stability of power system by using the description of a series of transient equilibrium points. Taking the load index \( \alpha \) of the self-recovery load as a continuous parameter, the following simulation equation is established.

\[ 0 = f(x(t), y(t), z_d(t), \alpha) \]
\[ 0 = g(x(t), y(t), z_d(t), \alpha) \]
\[ z_d(t) = h_d(x(t), y(t), z_d(t), \alpha) \] (5)

In the above formula, \( x(t) \) is all short-term state variables; \( y(t) \) is the algebraic variable of power system, such as node voltage amplitude and phase angle; \( z_d \) is the long-term variable of discrete variation; \( h_d \) is the differential equations representing the change process of short-term transient load. Transform the multiplicative load expression into the form of state variable, and integrate and solve the formula (7) to obtain the corresponding active power and reactive power load indexes \( \alpha \) and \( \beta \).

So far, the simulation analysis of the medium and long term voltage stability of the power system under the replacement of high proportion of new energy is realized.

3. Example analysis

The simulation results of power system using FTS simulation method are taken as a reference. The analysis results of the proposed simulation method and QSS simulation method are compared with the reference values. The simulation results of the QSS simulation method and the simulation results of the proposed simulation method are compared with those of the FTS simulation method. The simulation data are obtained by changing the operation of the example system with different processing and using the three simulation methods.
3.1. Algorithm system

The structure of the power system used in the case study is shown in Fig. 2. In this study, the power system is divided into three regions, as shown by the dashed lines in Fig. 2. Among them, region 2 includes nodes 4-15 and 31-32, region 3 has nodes 16, 19-24 and 33-36, and the rest of the nodes are divided into regions. Region 1 contains 8 load nodes and 4 generator nodes; region 3 contains 5 load nodes and 4 generator nodes; there are 6 load nodes in region 2, namely nodes 4, 7, 8, 12, 15 and 31, while there are only two generator nodes: 31 and 32, for the load center area with insufficient local power supply. Region 1 and region 3 are connected by a contact line 16-17, region 2 and region 3 are connected by a contact line 15-16, and region 1 and region 2 are connected by two contact lines 3-4 and 9-39. The generator nodes of the system are numbered as nodes 30-39 and named G1-G10, respectively.

![Figure 2 Single line diagram of the algorithm system](image)

3.2. Data and Analysis

The algorithm simulation is divided into two groups according to the setting of the algorithm system, the first group adjusts the load in each region of the system, and the second group adjusts the load of the nodes in the system. The specific analysis results of the power system voltage stability simulation are as follows.

1. Increase load and disconnection by region

   The disturbance to the power system is: when t=2s, the load of region 2 increases by 20%, and when t=50s, region 1 and region 3-4 are disconnected. The voltage curve of node 32 obtained by the three simulation methods is shown in Fig. 3.

![Figure 3 Voltage curve of node 32](image)
As can be seen in Fig. 3, the power system maintains transient stability both after the fault and after the limiter action in such system fault scenarios. Compared with the FTS simulation, the simulation results of QSS are acceptable from the curve. The results of the simulation analysis of the three methods on the action time of the limiter are listed in Table 1, which shows that although the QSS simulation method is correct in judging the number and order of the excitation and armature current limiters in the power system, it is not accurate in judging the specific action time. The second shortcoming of QSS simulation is verified by the fact that the judgment of the action time of the limiter in this paper is very close to the judgment result of FTS, and the sequence of action of the limiter triggered at the similar time can be correctly distinguished.

| Restrictor action sequence | FTS simulation method | QSS simulation method | Simulation method in this paper |
|----------------------------|-----------------------|-----------------------|---------------------------------|
| G4 excitation current limiter operation | 21.48 | 20.10 | 21.57 |
| G3 Excitation current limiter operation | 65.60 | 64.32 | 66.08 |
| G3 armature current limiter operation | 85.35 | 72.48 | 85.99 |
| G3 Excitation current limiter return | 100.79 | 86.54 | 101.32 |
| G2 armature current limiter operation | 223.54 | 221.95 | 227.63 |

(2) Cut the machine and increase the load according to the node

The disturbance added to the system is as follows: when t=2s, generator G2 of node 31 is cut off by 50% (assuming it is composed of two parallel generators, and one of them is cut off); when t=50s, the load of node 8 is increased by 10.5%. In region 2, only nodes 31 and 32 are generator nodes, which are load centers with insufficient local power supply. G2 cutter generally has a severe disturbance to this region, and combined with the sudden load growth of node 8 in this region, it has a major impact on the whole system. The voltage curve of node 31 simulated by the three methods is shown in Fig. 4.

As can be seen from the curve in Fig. 4, the premise of QSS simulation assuming that the electromechanical transient process of the system can gradually attenuate and subside and enter the
subsequent long-term dynamic process may no longer be true under the condition of the chain action of the limiter caused by serious faults such as cutting machine. The FTS simulation results show that the system voltage gradually oscillates and destabilizes after the excitation current limiter of generator G4 and armature current limiter of G3 operate one after another.

4. Conclusion
As the new energy strategy continues to be implemented, the energy consumption ratio of new energy is getting higher and higher. New energy units are connected to the power system in the form of direct grid connection or replacement of conventional units, which has a certain degree of impact on the voltage stability of the power system. This paper proposes a simulation method for medium and long-term voltage stability of power system under high percentage of new energy replacement, and proves the practical feasibility of the method through arithmetic analysis. In the subsequent study, the transient stability evolution mechanism of the power system under the high proportion of new energy substitution will be investigated, so as to analyze the influence of small disturbances on the operation stability of the power system.

References
[1] Isaiah Adebayo, Yanxia Sun. (2017). New Performance Indices for Voltage Stability Analysis in a Power System. Multidisciplinary Digital Publishing Institute, 10(12): 2042.
[2] Ma Rui, Li Mo. (2019). A novel random fuzzy P-Q-V voltage stability security region of power system interconnected with DFIG high penetration. International Transactions on Electrical Energy Systems, 29(2): e2711.
[3] Sarnari A J, Ivanovi R, S Al-Sarawi. (2019). Augmenting load flow software for reliable steady-state voltage stability studies. International Transactions on Electrical Energy Systems, 29(9): e12047.
[4] Raheel Zafar, J. Ravishankar, John E. Fletcher, Hemanshu Pota. (2020). Multi-Timescale Voltage Stability-Constrained Volt/VAR Optimization With Battery Storage System in Distribution Grids. IEEE Transactions on Sustainable Energy, 11(2):868-878.
[5] Wanjun Huang, David J. Hill. (2020). Network-based analysis of long-term voltage stability considering loads with recovery dynamics. International Journal of Electrical Power and Energy Systems, 119(1):105891.
[6] Ali Selim, Salah Kamel, Francisco Jurado. (2020). Voltage stability analysis based on optimal placement of multiple DG types using hybrid optimization technique. International Transactions on Electrical Energy Systems, 30(10): e12551.
[7] Gao Y, Chen L X, Huang S, et al. Research on Photovoltaic Voltage Conversion Mode Based on Rural Low Power Microgrid[J]. Computer Simulation, 2020, 37(11):65-70.
[8] Bialas Hubert, Pawelek Ryszard, Wasiak Irena. (2021). A Simulation Model for Providing Analysis of Wind Farms Frequency and Voltage Regulation Services in an Electrical Power System. Energies, 14(8): 2250-2250.
[9] Pouria Akbarzadeh Aghdam, Hamid Khoshkhoo. (2020). Voltage stability assessment algorithm to predict power system loadability margin. IET Generation, Transmission & Distribution, 14(10): 1816-1828.
[10] Nou Pheakna, Zhang Yiyi, Yang Yude. (2021). The Impact of Voltage Stability Constraint L-Index on Power System Optimization Base on Interior Point Algorithm by Considering the Integration of Renewable Energy. Journal of Physics: Conference Series, 1887(1): 012031.