

Analysis of Dynamic Voltage Fluctuation Mechanism in Interconnected Power Grid with Stochastic Power Disturbances

Yiping Yu, Ping Ju, Yan Peng, Boliang Lou, and Hongyang Huang

Abstract—With the integration of large-scale renewable energy and various new types of loads, the stochastic fluctuation characteristic of the power has seriously affected the secure and stable operation of interconnected power grids. In addition to active power fluctuations of AC tie-lines that have been studied in the past, the problem of dynamic fluctuation of bus voltage is also increasingly prominent. Firstly, the typical power fluctuations of electric railway traction load, smelting load, and wind power generation in modern power systems are presented and the accompanying voltage fluctuations are analyzed. Secondly, the dynamic fluctuation mechanism and distribution characteristic of the system voltage under special forced oscillation and generalized forced oscillation are studied. It is found that when the periodic disturbance induces a special forced oscillation, the voltage fluctuation has the same mode information compared to the power angle fluctuation. And it also has obvious peak characteristics near the natural frequency. When the stochastic disturbance induces generalized forced oscillation, the voltage fluctuations can be decomposed into proportional and resonant components according to its frequency domain characteristic. Finally, the above conclusions are verified by the simulation results of an IEEE 4-generator 2-area system.

Index Terms—Stochastic power disturbance, dynamic voltage fluctuation, special forced oscillation, generalized forced oscillation, dynamic fluctuation mechanism.

I. INTRODUCTION

ACCOMMODATION of renewable energy power generation and reliable power supply by various types of loads are important functions of the modern power systems. However, with the rapid development and the integration of large-scale renewable energy power generation and various new types of loads, their stochastic volatilities pose great challenges to the secure and stable operation of the bulk

power grid [1]–[3]. The power system is an extremely complex nonlinear system. Power generation, transmission, substation, distribution, and consumption are all organically combined. Stochastic disturbances in any one of these links will cause drastic fluctuations of power and voltage in the power grid. This may lead to the maloperation of the protection relay and the risk of chain failure.

There are various disturbances in the power system. The influence of stochastic power fluctuations on power system operation is mainly on the tie-line power fluctuation and the bus voltage fluctuation. In the existing research, the analysis of the tie-line power fluctuation with various disturbances is fairly sophisticated and the estimation method of the power fluctuation amplitude of the tie-line in various oscillations is obtained [4]–[7], while the research on the voltage fluctuation of the interconnected power grid with stochastic disturbance is relatively rare. At present, most research focuses on the power flow uncertainty, aiming at the quasi-steady-state fluctuation characteristic of bus voltage with power fluctuation [8]–[11]. For example, in [6], [7], containing the fluctuation characteristic of wind power and the characteristic of load fluctuation, active power fluctuations of AC tie-line are decomposed in detail, and the complex power fluctuations are analyzed by the probability distribution estimation method. In addition, in [8], the probability distribution of the voltage of each node in a wind farm integration system is obtained with the random power flow method. The voltage fluctuation characteristic caused by stochastic factors is given from the statistical point of view. Reference [10] uses the interval analysis method to deal with node voltage fluctuations in the power grid due to wind power and load fluctuations.

Previous studies have focused on active power fluctuations of AC tie-lines and quasi-steady-state fluctuations of node voltages. In this paper, the mechanism and distribution characteristics of dynamic voltage fluctuation with stochastic power disturbances are analyzed. Firstly, the typical power disturbances such as electric railway traction load, smelting load, and wind power generation, and their corresponding voltage fluctuation phenomena are analyzed. Secondly, the bus dynamic voltage fluctuation mechanism and distribution characteristics under traditional forced oscillation and generalized forced oscillation are studied. Finally, the mechanism and distribution characteristics of dynamic voltage fluctua-

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tion under two conditions are analyzed and validated.

II. TYPICAL POWER DISTURBANCES AND VOLTAGE FLUCTUATIONS IN POWER GRID

This section summarizes the main forms of power disturbance in the power grid, and then analyzes the dynamic characteristic of the corresponding voltage fluctuation.

By analyzing the measured power fluctuation curves of the practical power grid, three kinds of power fluctuation sources are found: the railway traction load, the smelting load, and the active power output of wind farms. We then take the measured curves of the three power fluctuation sources as examples to analyze the forms of power fluctuation in the power system.

With the rapid development of high-speed railway technology, the power of the railway traction load is enhanced and widely distributed and its influence on the interconnected power grid is gradually emerging. The typical load curve of a railway traction load is shown in Fig. 1(a). The fluctuation of the traction load mainly occurs at the time when the train enters and leaves the power supply radius of the traction substation, and the power fluctuation is quite intense. From the measured load curve, it can be seen that the fluctuation of the railway traction load can be divided into a step power fluctuation, a low-frequency slope fluctuation, and a high-frequency stochastic fluctuation. From the amplitudes and numbers of the three components, the step power fluctuation is the main component.

Therefore, when considering the influence of power fluctuation of the railway traction load on the dynamic characteristic of power system, the step fluctuation is the main component considered. It is noted that the amplitude of the step power fluctuation is large and locally up to 50 MW. Thus, the dynamic fluctuation of the whole power grid can be stimulated by this kind of power fluctuation.

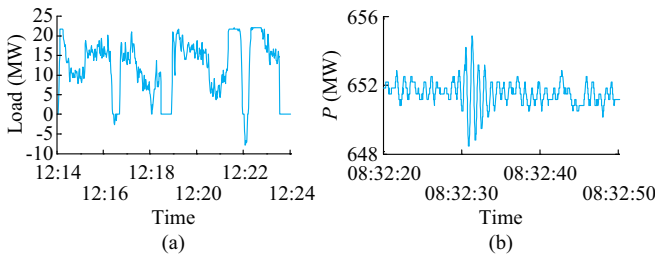


Fig. 1. Disturbance of railway traction load and response of adjacent generator. (a) Disturbance of railway traction load. (b) Response of adjacent generator.

Figure 1(b) shows the active power output of the adjacent generator near the railway traction load. There is a trolley moving out of the station at 08:32 and the active power fluctuation of the load produces a step impact on the power grid. From the curve in Fig. 1(b), it is found that free oscillation of the generator near the railway traction load is excited. Thus, the voltage fluctuation under free oscillation can be stimulated by the step power fluctuation in the power grid.

In recent years, the effect of high-density smelting load on

the dynamics of the interconnected power grid has been increasing. Figure 2(a) shows the daily load curve of a smelting load. It can be seen that the smelting load can be decomposed into a basic load and an impulse load, and the frequency of the impulse is low. The main reason is that in the process of steel smelting, more active power is needed to maintain the temperature in the furnace. In addition, other smelting process operations such as rolling have a high power demand.

Thus, the overall performance is the superposition of the high base load and the impulse load. The frequency of the power fluctuation component of the smelting load is mainly concentrated in the range of 0.7-0.8 Hz, which covers some natural modes of general power systems. Thus, smelting loads may have a great impact on the dynamic characteristic of the power grid. In addition, because of the obvious continuity of the power fluctuation of the smelting load, a forced power oscillation may be induced. As shown in Fig. 2(b), the forced oscillation of the generator near the smelting load is induced by the power fluctuation of the smelting load, and a voltage fluctuation of the system occurs.

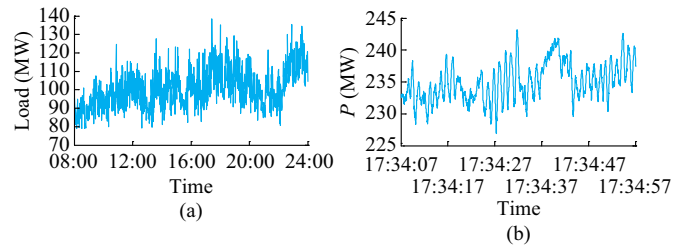


Fig. 2. Disturbance of smelting load and response of adjacent generator. (a) Disturbance of smelting load. (b) Response of adjacent generator.

Previous studies have shown that large-scale wind power integration also has a great impact on the dynamic characteristic of the interconnected power grid. The typical active power output curve of a wind farm at 10:00-11:00 is shown in Fig. 3(a). Figure 3(b) is the active power fluctuation of the adjacent AC tie-line between the areas at 10:00-11:00.

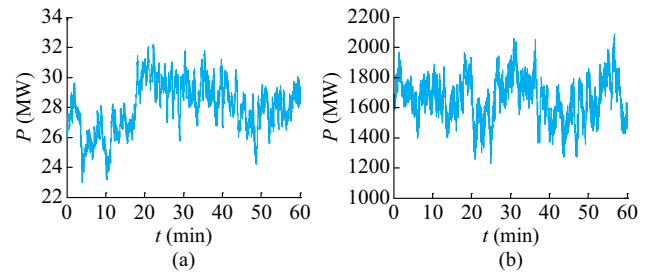


Fig. 3. Power fluctuations of wind farm and adjacent tie-line. (a) Power fluctuation of wind farm. (b) Power fluctuation of adjacent tie-line.

References [12], [13] propose the theory of generalized forced oscillations to explain this phenomenon. Based on the spectral similarity of the wind power fluctuations and the AC tie-line power fluctuations, it is believed that stochastic wind power fluctuations may cause generalized forced oscillations of the power grid.

The above typical forms of power fluctuation can be fur-

ther divided into the step power fluctuation and the continuous power fluctuation. The corresponding voltage response can be divided into the voltage fluctuation under the free oscillation caused by step disturbance, the voltage fluctuation under the special forced oscillation caused by the periodic disturbance, and the voltage fluctuation under the generalized forced oscillation caused by stochastic disturbance.

A step power fluctuation caused by railway traction load will inject a lot of energy into the power grid, thus the natural modes of weak damping ranging from 0.1 to 2.5 Hz are easily excited. Then, the voltage of each node follows the system to free oscillation. When continuous power fluctuation occurs in the power grid such as with the smelting load, the voltage fluctuation under forced oscillation will occur when the frequency of continuous power fluctuation is close to the natural frequency of the system and the amplitude of the voltage fluctuation of some nodes is large [14]. The node voltage under generalized forced oscillations caused by stochastic power fluctuations such as wind power fluctuation, shows oscillation characteristic, and some stochastic characteristic also exist.

Because of the dynamic voltage fluctuation in free oscillations of the power system, the analysis is mainly based on the voltage fluctuation under the negative damping oscillation of the power grid after the disturbance disappears. The phenomenon is relatively simple and the theory is relatively mature, thus the traditional method can be used for the analysis and the calculation [15], [16]. Therefore, this paper mainly focuses on the dynamic voltage fluctuation in the special forced oscillation and the generalized forced oscillations with continuous disturbances.

III. ANALYSIS OF VOLTAGE FLUCTUATION UNDER SPECIAL FORCED OSCILLATION

The special forced oscillation of power system, that is, the traditional forced oscillation, refers to the oscillation of the power system excited by continuous periodic disturbance in the power grid, and the resonance of the power system is excited when the frequency of the disturbance is close to the natural frequency of the power system [17], [18]. The amplitude of the oscillation is directly related to the amplitude of the disturbance and the damping of the mode. After the system enters into steady-state oscillation, it exhibits equal amplitude oscillation, and the larger the damping is, the smaller the amplitude is. With the same damping, the larger the disturbance is, the larger the amplitude of the oscillation is.

The previous research on forced oscillation of power systems has mainly been concerned with the power angle and active power oscillation, and less attention has been paid to the voltage fluctuation.

Suppose that there is an active load disturbance ΔP_l in the node l , thus the active load disturbance vector $\Delta \mathbf{P}_n = [0, 0, \dots, \Delta P_l, \dots, 0]^T$, and the reactive load disturbance vector $\Delta \mathbf{Q}_n = [0, 0, \dots, 0, \dots, 0]^T$. In the special forced power oscillation caused by periodic load disturbance, the time domain expression of the power angle of generator i is [19]:

$$\Delta \delta_i(t) \approx \frac{|\tilde{\phi}_{ir}| |\tilde{\gamma}_r| |\Delta P_l|}{\zeta_r \omega_r} \sin(\omega_r t + \kappa_{ir} + \sigma_r) \quad (1)$$

where $\tilde{\phi}_{ir} = |\tilde{\phi}_{ir}| e^{j\kappa_{ir}}$ is the generator i corresponding element in the right eigenvector of weak damping mode r ; $\tilde{\gamma}_r = |\tilde{\gamma}_r| e^{j\sigma_r}$ is the product of the left eigenvector and the load distribution factor; ζ_r is the damping ratio; ω_r is the oscillation frequency of mode r ; κ_{ir} is the phase of $\tilde{\phi}_{ir}$; and σ_r is the phase of $\tilde{\gamma}_r$.

The state variables follow the right eigenvector distribution in the case of special forced power oscillations caused by periodic load disturbances. In addition to the mode damping and the intensity of the disturbance, the amplitude of the power oscillation is also related to the influence of the disturbance on the oscillation mode.

For a multi-machine system with m generators and n nodes, the internal potential nodes are added at the generator nodes, and their numbers are 1, 2, ..., m . The generator and load nodes of the original power grid are numbered sequentially $m+1, m+2, \dots, m+n$. The linearized network equation can be expressed as:

$$\begin{bmatrix} \Delta \mathbf{P}_m \\ \Delta \mathbf{P}_n \\ \Delta \mathbf{Q}_n \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{m \times m} & \mathbf{H}_{m \times n} & \mathbf{N}_{m \times n} \\ \mathbf{H}_{n \times m} & \mathbf{H}_{n \times n} & \mathbf{N}_{n \times n} \\ \mathbf{M}_{n \times m} & \mathbf{M}_{n \times n} & \mathbf{L}_{n \times n} \end{bmatrix} \begin{bmatrix} \Delta \delta_m \\ \Delta \theta_n \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{m \times m} & \mathbf{J}_{m \times 2n} \\ \mathbf{J}_{2n \times m} & \mathbf{J}_{2n \times 2n} \end{bmatrix} \begin{bmatrix} \Delta \delta_m \\ \Delta \theta_n \\ \Delta V_n \end{bmatrix} \quad (2)$$

where $\Delta \delta_m$ is the deviation vector of generator power angle; $\Delta \theta_n$ and ΔV_n are the phase and amplitude deviation vectors of the node voltage, respectively; \mathbf{H} and \mathbf{N} are the partial derivative matrices of node injection active power to generator power angle, node voltage phase and voltage amplitude; and \mathbf{M} and \mathbf{L} are the partial derivative matrices of node injection reactive power to generator power angle, node voltage phase and voltage amplitude.

Eliminate $\Delta \mathbf{P}_m$, then we obtain:

$$\begin{bmatrix} \Delta \delta_m \\ \Delta \theta_n \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{m \times m} & \mathbf{J}_{m \times 2n} \\ \mathbf{J}_{2n \times m} & \mathbf{J}_{2n \times 2n} \end{bmatrix}^{-1} \begin{bmatrix} \Delta \mathbf{P}_m \\ \Delta \mathbf{P}_n \\ \Delta \mathbf{Q}_n \end{bmatrix} = \begin{bmatrix} \mathbf{K}_{m \times m} & \mathbf{K}_{m \times 2n} \\ \mathbf{K}_{2n \times m} & \mathbf{K}_{2n \times 2n} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{P}_m \\ \Delta \mathbf{P}_n \\ \Delta \mathbf{Q}_n \end{bmatrix} \quad (3)$$

Then,

$$\begin{bmatrix} \Delta \theta_n \\ \Delta V_n \end{bmatrix} = \mathbf{K}_{2n \times m} \mathbf{K}_{m \times m}^{-1} \left(\Delta \delta_m - \mathbf{K}_{m \times 2n} \begin{bmatrix} \Delta \mathbf{P}_n \\ \Delta \mathbf{Q}_n \end{bmatrix} \right) + \mathbf{K}_{2n \times 2n} \begin{bmatrix} \Delta \mathbf{P}_n \\ \Delta \mathbf{Q}_n \end{bmatrix} = \mathbf{K}_{2n \times m} \mathbf{K}_{m \times m}^{-1} \Delta \delta_m + \left(\mathbf{K}_{2n \times 2n} - \mathbf{K}_{2n \times m} \mathbf{K}_{m \times m}^{-1} \mathbf{K}_{m \times 2n} \right) \Delta \mathbf{S}_n \quad (4)$$

where $\Delta \mathbf{S}_n = [\Delta \mathbf{P}_n^T, \Delta \mathbf{Q}_n^T]^T$ is the matrix of the active power disturbance and reactive power disturbance of the nodes in the power grid.

Under the special forced power oscillation caused by periodic disturbance, the voltage amplitude and phase of each node in the power grid fluctuate with the power angle of the generator and the disturbance source at the same frequency. The fluctuation characteristic is similar to the power angle fluctuation. The fluctuation amplitude and phase distribution are affected by the distribution of the power angle oscillation and the location and intensity of the disturbance. The fluctuations of node voltage amplitude and phase are different for active power disturbance and reactive power disturbance.

IV. ANALYSIS OF VOLTAGE FLUCTUATION UNDER GENERALIZED FORCED OSCILLATION

Because of the complexity of the power system and its randomness, the probability of stochastic excitation is higher than that of single frequency excitation. Moreover, the oscillation phenomena caused by some stochastic excitations cannot be completely explained by the special forced oscillation theory. The mechanism of this kind of oscillation is proposed in [12], which is called generalized forced oscillation theory. The generalized forced oscillation is relative to the special forced oscillation, which refers to the forced oscillation excited by stochastic excitation.

Because the amplitude of stochastic excitation in the power system is usually small, the power system can be regarded as a linear system. The transfer function of the frequency domain is assumed to be $H(f)$, the input stochastic excitation can be regarded as a stationary stochastic process, the power spectral density (PSD) function of the stochastic process can be regarded as $S_u(f)$, and the output can be regarded as a stationary stochastic process. The PSD function of the output is assumed to be $S_y(f)$. There are three natural oscillation modes f_{o1} (0.5 Hz), f_{o2} (1.0 Hz) and f_{o3} (1.5 Hz), as shown in Fig. 4. If $S_u(f)$ can cover one mode of the system, the mode will be excited when the disturbance occurs.

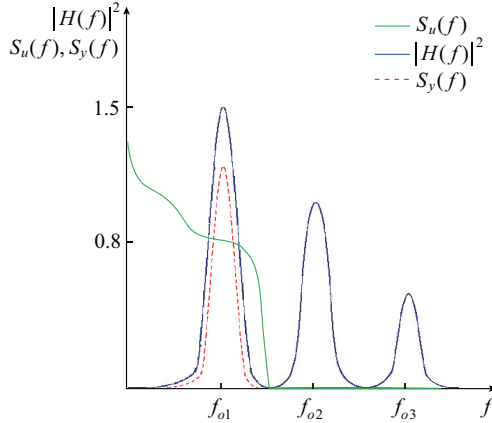


Fig. 4. Excitation and response under generalized forced oscillation.

According to the generalized forced oscillation theory, when the power spectrum of the stochastic power excitation covers some weak damping modes, the forced oscillation of the system will be excited. This is also known as generalized forced oscillation. In the previous research, the study of generalized forced oscillation is mainly concerned with rotor angle and active power oscillations. There is no research on voltage fluctuation under the generalized forced oscillation, which is also important for the power system operation. Compared to rotor angle oscillation, voltage fluctuation under generalized forced oscillation is also affected by steady-state power change. Therefore, the mechanism and analysis method are quite different. The voltage fluctuation under generalized forced oscillation is analyzed in the following text.

For general power grids, the stochastic power disturbance in the power system is relatively small. Thus, the linear sys-

tem model can be used in analysis. According to generalized forced oscillation theory, this kind of power disturbance may excite the oscillation of the power system. In the time domain, the disturbance and system response are strongly stochastic. To explain the mechanism more clearly, it is appropriate to analyze voltage fluctuation by power spectrum in the frequency domain.

For a power system with stochastic power disturbance, the mathematical model is shown in Fig. 5, where ΔP is the input disturbance; ΔU is the corresponding voltage response; and $G(s)$ is the transfer function of power system between voltage response and power disturbance.

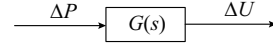


Fig. 5. Mathematical model of voltage response under power disturbance.

Referring to the decomposition method in [20], the transfer function is decomposed as follows:

$$G(s) = G(0) + G_d(s) \quad (5)$$

where $G(0)$ is the steady-state transfer function. In the steady-state equation, s is 0 in the transfer function $G(s)$, and the dynamic part $G_d(s)$ is also 0. Based on the decomposition, the voltage response with stochastic power disturbance can be decomposed as follows:

$$\Delta U_s = G(0)\Delta P \quad (6)$$

$$\Delta U_d = G_d(s)\Delta P \quad (7)$$

where ΔU_s is the steady-state component of the voltage; and ΔU_d is the dynamic component of the voltage. The above transfer function can be represented as a form of frequency domain:

$$H_d(f) = G_d(s)|_{s=j2\pi f} \quad (8)$$

$$H_0 = G(0) \quad (9)$$

where $H_d(f)$ is the transfer function corresponding to ΔU_d ; and H_0 is the system function corresponding to ΔU_s , which reflects the steady-state relationship between the input and the output.

The corresponding power spectrum formulas of the components of the voltage response are:

$$S_{us}(f) = H_0^2 S_{pd}(f) \quad (10)$$

$$S_{ud}(f) = |H_d(f)|^2 S_{pd}(f) \quad (11)$$

where $S_{us}(f)$ and $S_{ud}(f)$ are the power spectra of proportional component and the resonant component of the voltage response, respectively; and $S_{pd}(f)$ is the power spectrum of the power disturbance. Therefore, the voltage response corresponding to this component is mainly related to power flow equations and power disturbance. Thus, it can be called a proportional component. According to generalized forced oscillation theory, if the power spectrum of the stochastic power disturbance covers the weakly damped modes of $H_d(f)$, the forced oscillation will be excited and the voltage will fluctuate dynamically. The mechanism is similar to that of resonance, which may be called a resonant component.

V. SIMULATION RESULTS

An IEEE 4-generator 2-area system is taken for simulation analysis, as shown in Fig. 6. The dynamic voltage fluctuations under the special forced oscillation and the generalized forced oscillation are analyzed, respectively. The generator applies the six-order transient model. There is a weakly damped inter-area oscillation mode with 0.6323 Hz. Specific parameters are in [21].

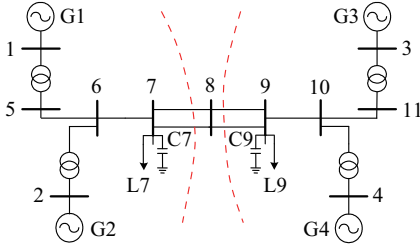


Fig. 6. IEEE 4-generator 2-area system.

A. Special Forced Power Oscillation

Firstly, the distribution characteristic of node voltage fluctuations under special forced power oscillation and traditional negative damping oscillation are analyzed. In the case of negative damping oscillation excited by instantaneous three-phase short circuit at 0.01 s at node 8, the voltage amplitude and phase fluctuations of each node are distributed according to the oscillation mode, as shown in Fig. 7. If the boundary between two oscillation areas is defined as the center of oscillation, the voltage amplitudes of nodes 7 and 8 near the oscillation center fluctuate the most, while the fluctuations of the voltage phase are distributed according to the inter-area oscillation mode. The voltage phase fluctuations are basically consistent in the same area, and the oscillation phase between the areas is opposite and gradually decreases from the generator to the oscillation center.

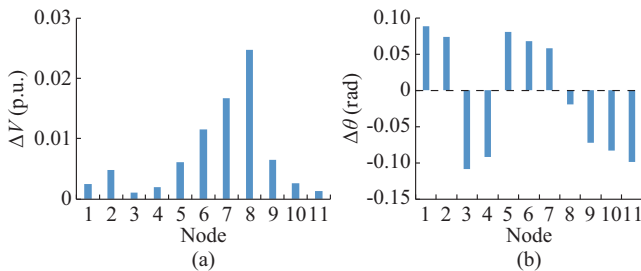


Fig. 7. Voltage fluctuation distribution in negative damping oscillation. (a) Voltage amplitude fluctuation. (b) Voltage phase fluctuation.

A periodic power disturbance is set at node 7, the disturbance amplitude is 30 MW, and the disturbance frequency ranges from 0.1 to 2.5 Hz. At this time, the voltage amplitude fluctuation of the key node near the oscillation center varies with the disturbance frequency, as shown in Fig. 8. The resonance occurs at the system natural frequency of 0.63 Hz, and the voltage amplitude fluctuates most severely. When the power disturbance frequency is far away from the natural frequency of the system, the voltage fluctuations with all frequency excitations have similar amplitudes. Be-

cause the disturbance frequency is far from the natural frequency of the system, the amplitude of the fluctuation is mainly related to the amplitude of the power disturbance, which is independent of the disturbance frequency. When the power disturbance frequency continues to increase and gradually approaches the natural frequency of the system, the amplitude of the voltage fluctuation increases rapidly and reaches a maximum at the natural frequency. Thereafter, as the disturbance frequency increases, the amplitude of the voltage fluctuation decreases.

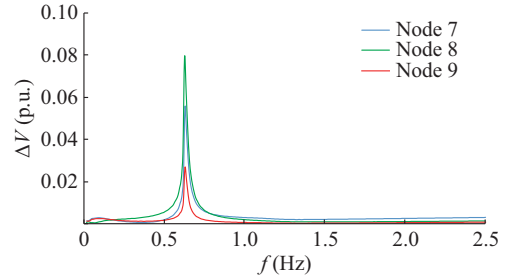


Fig. 8. Voltage amplitude fluctuation at different disturbance frequencies.

With the active power disturbance of the resonant frequency of 0.63 Hz, the oscillation distributions of the voltage amplitude and voltage phase of each node are shown in Fig. 9. Because of the common influence of the oscillation and disturbance source, the voltage amplitude fluctuation distribution is slightly different from the negative damping oscillation. However, the oscillation still plays a leading role. The voltage phase oscillation is basically consistent with the negative damping oscillation. In the case of a special forced oscillation, the voltage phase oscillation and the power angle oscillation have similar information.

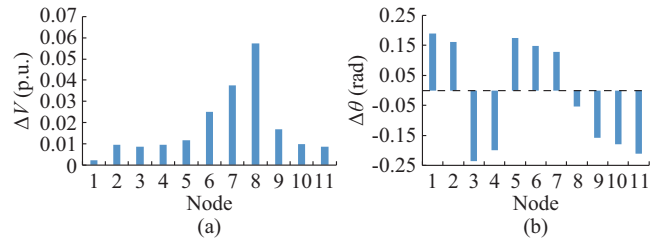


Fig. 9. Voltage fluctuation distribution in forced oscillation caused by active power disturbance. (a) Voltage amplitude fluctuation. (b) Voltage phase fluctuation.

Due to the correlation between voltage fluctuation and reactive disturbance, it is assumed that there is a periodic reactive power disturbance at node 7. The disturbance amplitude is 30 Mvar. The amplitude and phase fluctuation distributions of the node voltage at the resonance frequency are shown in Fig. 10. Different from an active power disturbance, with the same intensive power disturbance, the oscillation response of a reactive power disturbance is obviously smaller, and the voltage fluctuation is also relatively smaller. However, the reactive power disturbance has a great impact on the voltage amplitude fluctuation of the disturbance source at node 7 and has less influence on other nodes. It has little impact on the node voltage phase fluctuation. To

show the influence of the disturbance, Fig. 11 shows the node voltage fluctuation distribution when node 7 has an active power disturbance of 30 MW at a non-resonant frequency of 1.5 Hz. All node voltage fluctuations are small. At this time, the disturbance source plays a leading role. The voltage fluctuations of the disturbance source position node 7 are the most severe, and then gradually decrease according to the electrical distance.

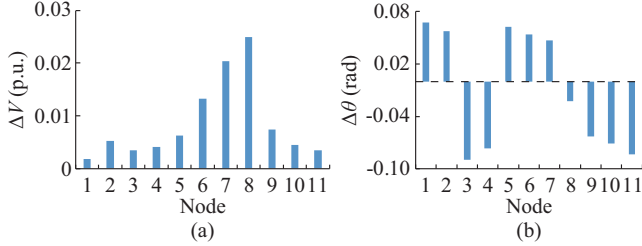


Fig. 10. Voltage fluctuation distribution in forced power oscillation caused by reactive power disturbance. (a) Voltage amplitude fluctuation. (b) Voltage phase fluctuation.

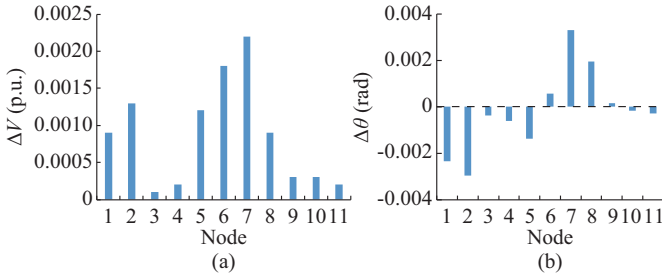


Fig. 11. Voltage fluctuation distribution in non-resonant disturbance forced oscillation. (a) Voltage amplitude fluctuation. (b) Voltage phase fluctuation.

B. Generalized Forced Power Oscillation

To study the voltage response with stochastic power disturbance, the transmission power of the tie-line between areas is adjusted to one quarter of the system capacity. The natural frequency of the system inter-area oscillation mode becomes 0.5 Hz. The load on node 7 is set as the disturbance source, which means that the stochastic power fluctuation is injected into node 7.

In the first simulation, the power disturbance is set within 0.7-0.9 Hz and 1.1-1.3 Hz narrow-band excitations. The time domain curves of the power disturbance and the voltage response are shown in Fig. 12(a) and (b). The PSD of the narrow-band power disturbance and the voltage response are shown in Fig. 13.

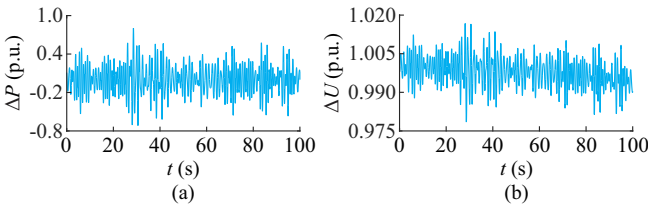


Fig. 12. Narrow-band power disturbance and voltage response without resonant component. (a) Narrow-band power disturbance. (b) Voltage response.

balance in this simulation does not cover the natural frequency of the system, the resonant component is close to zero according to the theory of generalized forced oscillation. Comparing the power spectrum of the power disturbance in the load node and the voltage response, it can be seen that the frequency range and the shapes of the power spectrum are exactly the same, indicating that the voltage fluctuation is almost determined by the proportional component, and the resonant component is close to zero.

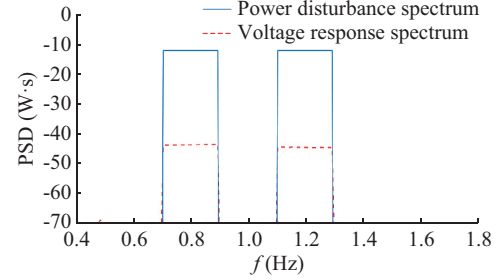


Fig. 13. PSD of power disturbance and voltage response.

In the second simulation, the frequency of the narrow-band power disturbance ranges from 0.3 to 0.6 Hz. The time domain curves of the power disturbance and the voltage response are shown in Fig. 14(a) and (b). Because the proportional component of the voltage fluctuation depends on the system power flow equations, the proportional component of the voltage response is calculated based on the system power flow equations, as shown in Fig. 15(a). According to the decomposition, the resonant component of the voltage response is the difference between the voltage response and the proportional component. The time domain curve of the resonant component is shown in Fig. 15(b). The PSDs of the resonant component, the proportional component and the power disturbance are compared in Fig. 16.

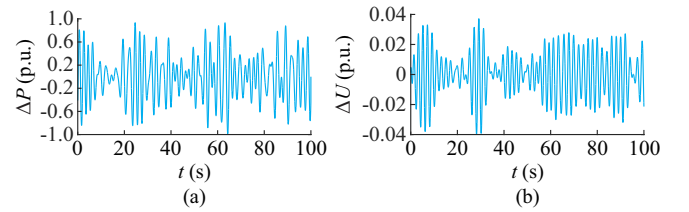


Fig. 14. Narrow-band power disturbance from 0.3 to 0.6 Hz and voltage response containing resonant component. (a) Narrow-band power disturbance. (b) Voltage response.

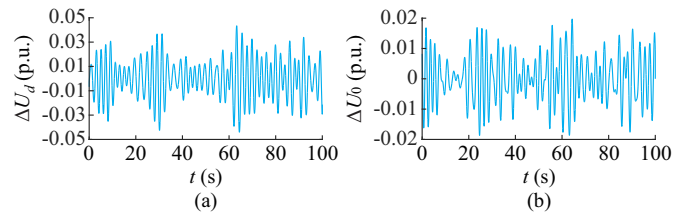


Fig. 15. Proportional component and resonant component of voltage response under narrow-band power disturbance. (a) Proportional component. (b) Resonant component.

Because the power spectrum of the narrow-band distur-

In this simulation, the frequency of the narrow-band dis-

turbance ranges from 0.3 to 0.6 Hz, and the frequency of the inherent mode is 0.5 Hz, which is covered by the narrow-band. It is known from Fig. 15(b) and the power spectrum in Fig. 16 that the generalized forced oscillation occurs with the stochastic disturbance. The PSD of the power disturbance and the resonant component of the voltage response in Fig. 16 show that the resonance component of the voltage fluctuation is excited and the peak frequency is 0.5 Hz. It is reasonable to decompose the voltage response with stochastic power disturbance into a proportion component and a resonant component.

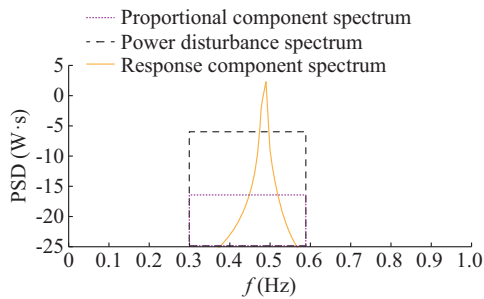


Fig. 16. PSD of power disturbance and voltage response components.

VI. CONCLUSION

In this paper, the mechanisms and distribution characteristic of the typical power fluctuation and the dynamic voltage fluctuation with different power disturbances are analyzed, which lead to the following conclusions.

There are three typical power fluctuation sources in a modern power system, which are railway traction load, smelting load, and output of large-scale wind power. They have the characteristics of power step change, periodic fluctuation and stochastic fluctuation, respectively. The node voltage will fluctuate dynamically along with the negative damped free oscillation, the special forced oscillation and the generalized forced oscillation caused by the three kinds of typical power fluctuations.

The fluctuations of the dynamic voltage amplitude are associated with the disturbance location and type under the special forced oscillation. The distributions of voltage phase fluctuation are similar to that of the negative damping free oscillation. When the special forced oscillation is caused by the periodic reactive power disturbance, the voltage fluctuations of the disturbance source and surrounding nodes are obvious. The voltage fluctuations with a non-resonant mode also have such characteristics, but the fluctuation amplitude is far less than that with resonant mode. The voltage fluctuation under generalized forced oscillation caused by stochastic power disturbance has both stochastic and oscillatory characteristics. Thus, it can be decomposed into a proportional component and a resonant component according to its frequency characteristics.

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