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Nonlinear transient voltage and frequency-coordinated control strategy for the renewable energy sending system

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In order to ensure that the voltage and frequency of the sending system with a high proportion of renewable energy access under transient port energy impact can be controlled within the allowed fluctuation range, a nonlinear multi-objective transient voltage and frequency-coordinated control strategy for the renewable energy sending system is proposed in this paper. First, the dynamic balance characteristics of the renewable energy sending system under transient energy impact are analyzed by establishing an equivalent power source model, and the frequency and voltage state equation of the sending system considering transient energy impact is studied and established. Then, considering the supporting effect of energy storage on the voltage and frequency of the renewable energy sending system, a nonlinear transient frequency and voltage-coordinated control model of the renewable energy sending system is proposed. Finally, the aforementioned conclusions are verified by simulation analysis. The simulation results show that the proposed control method can realize voltage and frequency stability control under transient energy. The effective energy tracking control algorithm can better utilize the fast energy regulation characteristics of battery energy storage, which can effectively reduce the fluctuation amplitude of the transmission system and restore synchronization in a short time. The voltage frequency control algorithm can significantly reduce the amplitude of voltage and frequency fluctuations, and can realize the rapid suppression of voltage and frequency fluctuations.

KEYWORDS

renewable energy, sending system, energy storage system, nonlinear control strategy, voltage and frequency control

1 Introduction

Under the goal of peak carbon dioxide emissions and carbon neutrality, large-scale renewable energy supply is one of the main development directions in the future (Liu et al., 2020; Lu et al., 2021; Wang et al., 2022). Considering the uncertainty and weak controllability of renewable energy supply, further research on frequency and voltage control methods for a renewable energy sending system is necessary (Wang et al., 2020; Zhang et al., 2020; Cai et al., 2021).

There are currently many literature studies on transient energy control methods of a power grid. Wang et al. (2022) proposed an accurate current sharing and voltage regulation approach in hybrid wind/solar systems for the first time, which realized accuratecurrent sharing and voltage regulation and ensured the maximum utilization rate of renewable energy. As an important breakthrough in the field of system parameter stability identification, Wang et al. (2020) innovatively proposed a line impedance collaborative stability region identification method, which showed that the proposed line impedance collaborative stability region identification method has good effectiveness and low conservatism through simulation verification. Zhang X. et al. (2021) proposed the transient frequency stability emergency control for the power system interconnected with offshore wind power. A control method for a DC power grid based on voltage source converter transient voltage recovery was proposed by Rimorov et al. (2021). Rao et al. (2021) proposed a transient energy balance control strategy for a new energy grid. Li et al. (2022) proposed a deviation suppression method for transient frequency of a new energy grid in order to ensure the voltage security of the receiving-end power grid under both steady-state and N-1 faults. Huang et al. (2019) proposed a calculation method for the voltage security boundary of the receiving-end power grid through the equivalence of the transient process. Kiaei and Lotfifard (2018) proposed a novel decentralized control strategy for an interconnected power system, which can improve the transient performance and power supply reliability. Kammer and Karimi (2019) proposed a transient energy control method for the power grid base on model predictive control, which can increase the transient stability of the power system. Based on the droop control theory and the generalized incidence matrix, Wang et al. (2021) prospectively proposed an adaptive step search strategy to obtain the droop coefficient-coordinated stability region, which realized the analysis and evaluation of the stability region of an independent power supply system composed of multiple batteries. Wu and Wang (2020) proposed an optimized control method for grid frequency and voltage, considering the uncertainty of new energy. Xu et al. (2021) proposed a mode-adaptive power–angle control method for transient stability. Zhang S. et al. (2021) proposed a transient energy control method for power grids based on a resistance superconducting fault current limiter and additional power controller. Radovanović and Milanović (2022) proposed a dynamic equivalent model for the hybrid renewable energy (HRES) power plant corresponding control transient energy control method, which can evaluate the overall transient stability of the power grid reliably.

On the other hand, some scholars analyzed and studied the communication requirements in the control process of the sending system in order to realize the dynamic control of the voltage and frequency of the sending system with a high efficiency and low delay (Amjad. et al., 2023). In order to improve the accuracy of the information transmission in distributed generation control systems and reduce the cost of communication equipment, communication-free intelligent edge control regarding the voltage and current for DC microgrids has been innovatively proposed by WangLiu et al. (2023), which can solve the problem of voltage regulation and current control at the same time, and has high adjustment accuracy. In order to improve the control efficiency of energy routers under the condition of unsmooth communication networks, an edge-control strategy for energy routers based on cyber-energy dual modulation has been proposed for the first time by Wang et al. (2023a), which can realize the cooperative control of distributed power sources without additional communication network devices and can effectively improve the operating efficiency of the system. Based on information technology, Gorski (2023) proposed a messaging mode of service-oriented architecture, microservices, and the messaging protocol of the Internet of Things. Considering the communication requirements of the control process, Wang et al. (2023b) innovatively proposed a fully distributed dynamic edge-event-triggered current-sharing control strategy of a multi-bus DC microgrid with power coupling, which avoids continuous communication between adjacent agents and realizes distributed dynamic control of the multi-bus DC microgrid. Rui et al. (2020) innovatively proposed a reduced order small-signal closed-loop transfer function model, which is used to analyze the stability of a multi-converter microgrid and improve the control performance of a power grid converter. The results of the aforementioned literature studies provide certain theoretical guidance for the study of the transient stability of power grids. However, with the increasing construction of grids containing a high proportion of renewable energy, it is of great significance to develop a nonlinear transient voltage and frequency-coordinated control strategy for the renewable energy sending system that considers energy storage coordination.

The aforementioned literature studies are beneficial to the study of transient stability of the power grid. However, with the increase in the high proportion of renewable energy access, it is of great significance to carry out an accurate and rapid control method of transient energy of the sending system considering energy storage coordination. Therefore, a nonlinear multi-objective transient voltage and frequency-coordinated control strategy for the renewable energy sending system is proposed in this paper. The main research contents and innovations of this paper are as follows:

1) Based on the state equation of the sending system, the voltage and frequency change characteristics of the sending system under the transient energy impact are analyzed by establishing the equivalent power source model and the dynamic model of the battery energy storage. The frequency and voltage state equation of the sending system is established, considering the transient energy impact.
2) The trajectory evolution characteristics of the frequency and voltage of the equivalent power source of each node in the sending network are analyzed. On this basis, the nonlinear transient voltage and frequency-coordinated control strategy for renewable energy generation systems is established.
3) The equivalent network model of the sending system is built, and the transient voltage frequency control method proposed in this paper is analyzed and verified.

2 Frequency and voltage dynamic model of the sending system under transient energy

Since the battery storage system can quickly and flexibly regulate its input and output active power, it can play an important role in suppressing the power fluctuation between grid regions and enhancing the dynamic stability of the interconnected grid (Jiang et al., 2021). Therefore, in order to ensure that the voltage and frequency fluctuation characteristics of each local area of the sending system under transient port energy impact are controlled within the allowed fluctuation range as much as possible, it is necessary to control the system energy balance and system voltage and frequency characteristics with the coordination of the battery storage system by using the various components in the sending system that can participate in the fast energy control of the transient process, such as thermal power units, photovoltaic power generation systems, and wind power systems.

When considering the DC-side dynamic process of the battery storage system, the frequency and voltage state evolution process of each node of the equivalent synchronous machine in the renewable energy sending system under the action of transient port energy is a hybrid AC–DC system state equation combining the dynamic model of the AC equivalent synchronous machine and the dynamic model of the DC system. The changes in the voltage amplitude and frequency of each power node of the system are influenced by the active power balance characteristics of the sending system, and depend on the excitation characteristics of each equivalent synchronous power source and the damping characteristics of the sending system at the same time. Therefore, after the renewable energy sending system enters the transient process, the frequency and voltage of each node of the sending system should be controlled at a good level as much as possible, which can be achieved by the coordinated control of the excitation characteristics of each equivalent power source and the DC damping characteristics provided by the battery energy storage system.

Based on this, the frequency–voltage dynamic characteristics of the sending system under transient energy are analyzed in this paper. Then, a frequency–voltage dynamic model of the sending system under transient energy is established.

2.1 Frequency and voltage dynamic model of the equivalent synchronous power source

The node number of the AC–DC hybrid sending system is set to $m+n$. After considering the dynamic process on the DC side of the battery storage, the state equation of the equivalent synchronous power source for the AC–DC hybrid system considering the excitation characteristics is

$$\begin{cases} \dot{\delta}_i = (\omega_i - 1)\omega_0, \\ \dot{\omega}_i = \left(P_{mi} - P_{ei} - D_i(\omega_i - 1)\right)/T_{Ji}, \\ \dot{E}'_{qi} = \left[E_{fi} - E'_{qi} - \left(X_{di} - X'_{di}\right)I_{di}\right]/T'_{d0i}, \end{cases} \tag{1}$$

where $\dot{\delta}_i$, $\dot{\omega}_i$, and $\dot{E}'_{qi}$ are the power angle, rotor angular velocity, and transient potential, respectively, of the equivalent synchronous power source at node i of the renewable energy sending system during the transient process; ω_0 is the rated synchronous angular velocity of the renewable energy sending system; I_{di} is the direct-axis component of the output current of the equivalent synchronous power source at node i of the renewable energy sending system; P_{mi} is the input energy of the equivalent synchronous power source at node i of the renewable energy sending system; E_{fi} is the excitation voltage of the equivalent synchronous power source at node i of the renewable energy sending system; X_{di} and X'_{di} are the direct-axis equivalent reactance and direct-axis transient reactance of the equivalent synchronous power source at node i of the renewable energy sending system, respectively; T'_{d0i} is the transient time constant of the equivalent synchronous power source at node i of the renewable energy sending system; T_{Ji} is the rotor inertia time constant of the equivalent synchronous power source at node i of the renewable energy sending system; and D_i is the damping coefficient of the equivalent synchronous power source at node i of the renewable energy sending system.

When the battery storage is connected to the ith node of the renewable energy sending system, if the battery storage system is converting the DC power into AC power input to the grid, that is, when the battery energy storage system is in discharge state at this time, the active power P_{ei} of the equivalent synchronous power source in Eq. 1 should be

$$P_{ei} = P_{aci} + P_{dci} + P_{Li}, \tag{2}$$

where P_{aci} and P_{dci} are the AC input power and DC input power at node i of the renewable energy sending system, respectively; P_{Li} is the total equivalent active load power at node i of the renewable energy sending system.

When the battery storage is connected to the ith node of the renewable energy sending system, if the battery storage system is converting the AC power into DC power input to the battery energy storage system, that is, when the battery energy storage system is in the charging state at this time, the active power P_{ei} of the equivalent synchronous power source in Eq. 1 is

$$P_{ei} = P_{aci} - P_{dci} + P_{Li}. \tag{3}$$

2.2 DC-side dynamic model of the battery energy storage system

In this study, a first-order inertial link model is used to describe the DC-side dynamic model of the battery energy storage system:

$$\dot{P}_{dc} = \frac{1}{T_{dc}}\left(-P_{dc} + P_{dcr} + u_{dcs}\right), \tag{4}$$

where P_{dcr} is the power value given at the DC side of the battery energy storage system when the renewable energy sending system is in a steady state; u_{dcs} is the additional control amount exerted on the DC side of the battery energy storage system during the transient process of the renewable energy sending system; and T_{dc} is the inertia time constant of the battery storage system DC-side power response during the transient process of the renewable energy sending system.

2.3 Transient power balance model of the renewable energy sending system

The total node number of the renewable energy sending system is set to $m + n$, where the node with an equivalent synchronous power source is m, and the node with the battery storage system and capable of DC damping control is n. It is assumed that all nodes relate to the load, that is, all nodes relate to equivalent load impedance, regardless of whether it has an equivalent synchronous power source or battery storage system.

After considering the input and output characteristics of the DC side of the battery storage system, the power balance equation of the renewable energy sending system can be expressed as

$$\begin{bmatrix} \dot{S}_g \\ \dot{S}_b \\ \dot{S}_l \\ \dot{S}_r \end{bmatrix} = \begin{bmatrix} \dot{E}'_{gq} \\ \dot{U}_B \\ \dot{U}_L \\ \dot{E}'_{rq} \end{bmatrix} \begin{bmatrix} \dot{I}_g \\ \dot{I}_b \\ \dot{I}_l \\ \dot{I}_r \end{bmatrix}^* = \begin{bmatrix} \dot{E}'_{gq} \\ \dot{U}_B \\ \dot{U}_L \\ \dot{E}'_{rq} \end{bmatrix} \begin{bmatrix} Y_{GG} & Y_{GH} & Y_{GL} & Y_{GR} \\ Y_{BG} & Y_{BH} & Y_{BL} & Y_{BR} \\ Y_{LG} & Y_{LH} & Y_{LL} & Y_{LR} \\ Y_{RG} & Y_{RH} & Y_{RL} & Y_{RR} \end{bmatrix}^* \begin{bmatrix} \dot{E}'_{gq} \\ \dot{U}_B \\ \dot{U}_L \\ \dot{E}'_{rq} \end{bmatrix}^*, \tag{5}$$

where $\dot{S}_g$, $\dot{S}_b$, $\dot{S}_l$, and $\dot{S}_r$ are the complex power of the traditional equivalent synchronous power source, the complex power of the battery storage system, the complex power of the equivalent load, and the complex power of the renewable energy equivalent synchronous power source during the transient process of the renewable energy sending system, respectively; $\dot{E}'_{gq}$, $\dot{U}_B$, $\dot{U}_L$, and $\dot{E}'_{rq}$ are the transient potential of the traditional equivalent synchronous power source, the voltage of the battery storage system, the voltage of the equivalent load, and the transient potential of the renewable energy equivalent synchronous power source during the transient process of the renewable energy sending system, respectively; $\dot{I}_g$, $\dot{I}_b$, $\dot{I}_l$, and $\dot{I}_r$ are the current of the traditional equivalent synchronous power source, the current of the battery storage system, the current of the equivalent load, and the current of the renewable energy equivalent synchronous power source in the transient process of the renewable energy sending system, respectively; and Y is the network conductance matrix of the renewable energy sending system during the transient process.

From the aforementioned power balance equation, the total equivalent active power of the equivalent synchronous power source and battery storage system connected to node i in the renewable energy sending system can be obtained as

$$P_{ei} = E'_{qi} \sum_{j=1}^{m} E'_{qj} \left(G'_{ij} \cos\delta_{ij} + B'_{ij} \sin\delta_{ij} \right) + E'_{qi} \sum_{j=m+1}^{n} I_{Bj} \left(G''_{ij} \cos\psi_{ij} + B''_{ij} \sin\psi_{ij} \right), \tag{6}$$

where $\delta_{ij} = \delta_i - \delta_j$ is the phase angle difference between the power angles δ_i and δ_j of the two equivalent synchronous power sources connected at nodes i and j in the renewable energy sending system; $\psi_{ij} = \delta_i - \varphi_{Bj}$ is the phase angle difference between the power angle δ_i of the equivalent synchronous power source connected at node i and the AC side voltage phase angle φ_{Bj} of the battery energy storage system in the renewable energy sending system.

2.4 Transient frequency–voltage equation of state for the renewable energy sending system

After considering the DC damping characteristics of the battery storage, the state equation of the renewable energy sending system under the discrete-time system can be expressed as the AC–DC hybrid state equation:

$$\begin{cases} x(k+1) = f[x(k), \xi(k)] + G[x(k), \xi(k)]u(k), \\ \beta[x(k), \xi(k)] = 0, \end{cases} \tag{7}$$

where $x(k)$ represents the state variables such as the power angle, frequency, transient potential, and DC power of the battery storage system of each power node in the renewable energy sending system; $\xi(k)$ represents the active and reactive components of the output power of the equivalent synchronous generators of hydropower, thermal power, wind power, and photovoltaic power sources in the renewable energy sending system, that is, the straight-axis and cross-axis components of the output current of each equivalent synchronous power source; $u(k)$ represents the equivalent synchronous generator excitation voltage control variables of hydropower, thermal power, wind power, and photovoltaic power sources, and DC control variables of the battery storage system in the renewable energy sending system; f is the relationship function of the state variables between the equivalent synchronous generator compound power, power angle, frequency, transient voltage, and DC power of the battery storage system at each power node in the renewable energy sending system; G is the relationship function between the controllable input variables in the system and the state variables of the sending system, where the state variables include equivalent synchronous complex power, power angle, frequency, transient voltage, and DC power of the battery energy storage system at each power node of the transmission system; and β is the equation of complex power balance of the sending system.

Assume that the equivalent synchronous power source in the renewable energy sending system is node $1, 2, \ldots, m$ and the battery energy storage system is node $m+1, m+2, \ldots, m+n$. The relationship function of the state variables between the equivalent synchronous generator compound power, power angle, frequency, transient voltage, and DC power of the battery storage system at each power node in the renewable energy sending system can be described as shown in Eq. 8, which is determined by the AC–DC hybrid state equation:

$$f = \begin{bmatrix} f_1(x,\xi) \\ f_2(x,\xi) \\ \vdots \\ f_m(x,\xi) \\ f_{m+1}(x,\xi) \\ \vdots \\ f_{m+n}(x,\xi) \end{bmatrix} = \begin{bmatrix} (\omega_1 - 1)\omega_0 & \dfrac{P_{m1} - P_{e1} - D_1(\omega_1 - 1)}{T_{J1}} & \dfrac{-E'_{q1} - \left(X_{d1} - X'_{d1}\right)I_{d1}}{T'_{d01}} \\ (\omega_2 - 1)\omega_0 & \dfrac{P_{m2} - P_{e2} - D_2(\omega_2 - 1)}{T_{J2}} & \dfrac{-E'_{q2} - \left(X_{d2} - X'_{d2}\right)I_{d2}}{T'_{d02}} \\ \vdots & \vdots & \vdots \\ (\omega_m - 1)\omega_0 & \dfrac{P_{mm} - P_{em} - D_m(\omega_m - 1)}{T_{Jm}} & \dfrac{-E'_{qm} - \left(X_{dm} - X'_{dm}\right)I_{dm}}{T'_{d0m}} \\ 0 & 0 & \dfrac{-P_{dc(m+1)} + P_{dcr(m+1)}}{T_{dc(m+1)}} \\ \vdots & \vdots & \vdots \\ 0 & 0 & \dfrac{-P_{dc(m+n)} + P_{dcr(m+n)}}{T_{dc(m+n)}} \end{bmatrix}. \tag{8}$$

According to the AC–DC hybrid state equation, the relationship function between the controllable input variables in the system and the state variables of the sending system can be described as shown in Eq. 9:

$$G = \begin{bmatrix} G_1(x,\xi) \\ \vdots \\ G_m(x,\xi) \\ G_{m+1}(x,\xi) \\ \vdots \\ G_{m+n}(x,\xi) \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0 & \frac{1}{T'_{d01}} & & & & & & \\ & & & \ddots & & & & & \\ & & & & 0 & 0 & \frac{1}{T'_{d0m}} & & & \\ & & & & & & & \frac{1}{T'_{d0(m+1)}} & & \\ & & & & & & & & \ddots & \\ & & & & & & & & & \frac{1}{T'_{d0(m+n)}} \end{bmatrix}. \tag{9}$$

The complex power balance equation of the renewable energy sending system can be described as

$$\beta(x,\xi) = \left[\beta_1(x,\xi)\cdots\beta_i(x,\xi)\cdots\beta_{m+k-p}(x,\xi)\right]^T, \tag{10}$$

where

$$\beta_i(x,\xi) = \begin{bmatrix} I_{qi} - \sum_{j=1}^{m} E'_{qj}\left(G'_{ij}\cos\delta_{ij} + B'_{ij}\sin\delta_{ij}\right) - \sum_{j=1}^{k} I_{Bj}\left(G''_{ij}\cos\psi_{ij} + B''_{ij}\sin\psi_{ij}\right) \\ I_{di} - \sum_{j=1}^{m} E'_{qj}\left(G'_{ij}\sin\delta_{ij} - B'_{ij}\cos\delta_{ij}\right) - \sum_{j=1}^{k} I_{Bj}\left(G''_{ij}\sin\psi_{ij} - B''_{ij}\cos\psi_{ij}\right) \end{bmatrix}. \tag{11}$$

3 Nonlinear transient voltage and frequency coordinated control strategy for the renewable energy sending system

3.1 Nonlinear transient voltage and frequency coordinated model for the sending system

This paper studies and establishes the power and excitation characteristics of the equivalent synchronous power source during the transient process of the renewable energy sending system, as well as the transient frequency–voltage equation of state for the renewable energy sending system considering the DC side characteristics of the battery energy storage system. Based on this finding, when the renewable energy sending system is impacted by transient port energy, based on the propagation characteristics of transient port energy in the system, further judgment is made on whether the frequency and voltage changes in the equivalent power supply at each node of the delivery network will deviate too much from the expected trajectory. Based on the frequency and voltage trajectory evolution characteristics of each equivalent power source node, the voltage and frequency of the equivalent power source are controlled at each node of the renewable energy sending system.

The voltage frequency state evolution trajectory of the transient stability equilibrium points (x_e, y_e) of the renewable energy sending system is defined as

$$\begin{cases} \dot{x}_e = f(x_e, y_e) + G(x_e, y_e)u_r, \\ 0 = \rho(x_e, y_e). \end{cases} \tag{12}$$

When the renewable energy sending system is in a steady state ($\dot{x}_e = 0$), the corresponding steady-state input control quantity is u_r. When the renewable energy sending system is in a transient process, the deviation equation of state Eq. 7 under the state evolution trajectory is

$$\begin{cases} \Delta\dot{x} = \Delta f(x,y) + y(x,y)\Delta u, \\ 0 = \Delta\rho(x,y), \end{cases} \tag{13}$$

where $\Delta\dot{x} = \dot{x} - \dot{x}_e$, $\Delta u = u - u_r$, $\Delta f = f(x,y) - f(x_e, y_e)$, and $\Delta\rho = \rho(x,y) - \rho(x_e, y_e)$.

The output function of voltage and frequency of the renewable energy sending system corresponding to the dynamic system in Eq. 7 is

$$g = h(x,y). \tag{14}$$

The frequency and voltage control target deviation ξ in the transient process that needs to be controlled and constrained under the transient stability condition of the renewable energy sending system is

$$\xi = \Delta g = g - g_r, \tag{15}$$

where g_r represents the evolution trajectory of frequency and voltage output functions for each equivalent power source node when the renewable energy sending system is in a transient stable equilibrium state $(\dot{x}_e = 0, u_r)$.

According to the aforementioned analysis, the frequency and voltage control target deviation ξ in the transient process of the renewable energy sending system is independent of the stable equilibrium state of the system and its corresponding state variables. On this basis, it can be concluded that

$$\dot{\xi} = \Delta\dot{g} = \dot{g}. \tag{16}$$

According to the aforementioned two equations, this paper constructs a multi-objective dynamic control system for the frequency and voltage of the equivalent synchronous power source of the sending network node under the transient stability of the renewable energy sending system.

$$\dot{\xi} = A\xi + Bu, \tag{17}$$

where u represents the control input of active power and excitation voltage of each node equivalent synchronous power source, and the DC-side power control input of the battery energy storage system. The coefficient matrices A and B are as follows:

$$A = \begin{bmatrix} A_1 & & & & \\ & \ddots & & & \\ & & A_i & & \\ & & & \ddots & \\ & & & & A_{m+n} \end{bmatrix}, B = \begin{bmatrix} B_1 & & & & \\ & \ddots & & & \\ & & B_i & & \\ & & & \ddots & \\ & & & & B_{m+n} \end{bmatrix}. \tag{18}$$

The diagonal matrices A_i and B_i are of the Brunovsky standard form:

$$A_i = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{\mu_i\times\mu_i}, B_i = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}_{\mu_i\times 1}, \tag{19}$$

where μ_i is the subsystem dimension of the ith input of the multi-objective dynamic control system.

According to Lyapunov theory, the feedback control law of a linear system is designed.

$$u = -K\xi, \tag{20}$$

where $\xi = (A - BK)\xi$, $(A - BK)$, and $\mathrm{Re}(\lambda i[A - BK]) < 0$. $K = R^{-1}B^TP$ is the control matrix. R is the positive definite weight matrix, P is the solution of the Riccati equation $PA + A^TP - PBR^{-1}B^TP = -Q$, and Q is the positive definite matrix.

Therefore, the linear control law of the ith subsystem designed to make the system stable can be expressed as

$$\begin{aligned} u_i = \xi_i^{\mu_i} &= -k_i^1\xi_i^1 - k_i^2\xi_i^2 - \cdots - k_i^{\mu_i}\xi_i^{\mu_i} \\ &= -k_i^1\Delta g_i^1 - k_i^2\Delta g_i^2 - \cdots - k_i^{\mu_i}\Delta g_i^{\mu_i}. \end{aligned} \tag{21}$$

Then, the nonlinear equivalent input μ_i is solved. If the algebraic variable in the algebraic equation is an explicit function, the algebraic variable is derived. If the algebraic variables in the algebraic equation are implicit functions, the calculation is as follows:

$$\begin{cases} \Gamma_f\xi_i^{\mu_i} = \Gamma_f\Delta h_i^{\mu_i}(x,y) = \\ \left[\dfrac{\partial\Delta h_i^{\mu_i}(x,y)}{\partial x} \quad \dfrac{\partial\Delta h_i^{\mu_i}(x,y)}{\partial y}\right]\Lambda(x,y)\Delta f(x,y), \\ \Gamma_G\Gamma_f^0 h_i^{\mu_i}(x,y) = \\ \left[\dfrac{\partial\left(\Gamma_f^0\Delta h_i^{\mu_i}(x,y)\right)}{\partial x} \quad \dfrac{\partial\left(\Gamma_f^0\Delta h_i^{\mu_i}(x,y)\right)}{\partial y}\right]\Lambda(x,y)G(x,y), \end{cases} \tag{22}$$

$$\Lambda(x,y) = \begin{bmatrix} I_n \\ -\left[\dfrac{\partial\Delta\rho}{\partial y}\right]^{-1}\dfrac{\partial\Delta\rho}{\partial x} \end{bmatrix}, \tag{23}$$

where $\Lambda(x,y)$ is the relation transformation matrix and I_n is an $n\times n$ identity matrix. The equivalent nonlinear control input corresponding to the linear input u_i is obtained as

$$\begin{aligned} u_i &= \left[\Gamma_G\Gamma_f^0\Delta h^{u_i}(x,y)\right]^{-1}\left[v_i - L_f\Delta h_i^{u_i}(x,y)\right] \\ &= \left[\Gamma_G\Gamma_f^0\Delta h^{u_i}(x,y)\right]^{-1}\left[-k_i^1\xi_i^1 - \cdots - k_i^{u_i}\xi_i^{u_i} - \Gamma_f\Delta h_i^{u_i}(x,y)\right], \end{aligned} \tag{24}$$

where $\Delta h^{u_i} = \left[\Delta h_1^{u_1}\cdots\Delta h_{(m+k)}^{u_{(m+k)}}\right]^T$.

3.2 Excitation control model of the equivalent synchronous power source in the renewable energy sending system

When the system is subjected to large disturbances, the excitation control can maintain the stability of the system voltage and frequency. The power balance and rotor power angle of the system are the keys to determine the frequency and voltage stability. Therefore, the angular frequency, active power, and terminal voltage of the generator are selected as the output functions, and the target deviation can be expressed as

$$\xi_i = \begin{bmatrix} \Delta\omega_i \\ \Delta P_{ti} \\ \Delta U_{gi} \end{bmatrix}. \tag{25}$$

The multi-objective equation is constructed based on the target deviation, and the multi-objective sub-equation of generator excitation control corresponding to the ith subsystem is

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{P}_{ti} \\ \Delta\dot{U}_{gi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \Delta\omega_i \\ \Delta P_{ti} \\ \Delta U_{gi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}v_i. \tag{26}$$

The linear feedback control law is designed to stabilize the system:

$$u = \Delta\dot{U}_{gi} = -K\xi = -k_i^1\Delta\omega_i - k_i^2\Delta P_{ti} - k_i^3\Delta\dot{U}_{gi}. \tag{27}$$

Then, the Γ derivative of the target deviation ΔU_{gi} is obtained as follows:

$$\begin{aligned} \Gamma_f &= \Delta U_{gi} \\ &= \left[\frac{\partial\Delta U_{gi}}{\partial x} \quad \frac{\partial\Delta U_{gi}}{\partial y}\right]\Lambda(x,y)\Delta f_i(x,y) \\ &= -\sqrt{\Delta U_{gi}^2 - \left(X_{qi}\Delta I_{qi}\right)^2}\left(X_{di}\Delta I_{di} + T'_{d0}X'_{di}\Delta\dot{I}_{di}\right)/\left(T'_{d0}U_{gi}\right) \\ &\quad + \left(X_{qi}^2\Delta I_{qi}\dot{I}_{qi}\right)U_{gi}/ - \left\{\Delta U_{gi}^2 - \left(X_{qi}\Delta I_{qi}\right)^2\right\}/\left(T'_{d0}U_{gi}\right), \end{aligned} \tag{28}$$

$$\begin{aligned} \Gamma_G\Gamma_f^0\Delta U_{gi} &= \left[\frac{\partial\left(\Gamma_f^0\Delta U_{gi}\right)}{\partial x} \quad \frac{\partial\left(\Gamma_f^0\Delta U_{gi}\right)}{\partial y}\right]\Lambda(x,y)G_i(x,y) \\ &= \frac{\sqrt{\Delta U_{gi}^2 - \left(X_{qi}\Delta I_{qi}\right)^2}}{\left(U_{gi}T'_{d0i}\right)} \end{aligned} \tag{29}$$

The equivalent additional excitation control input is

$$\begin{aligned} E_{fi} &= \left[\Gamma_G\Gamma_f^0\Delta U_{gi}\right]^{-1}\left(u_i - \Gamma_f\Delta U_{gi}\right) \\ &= \left[\Gamma_G\Gamma_f^0\Delta U_{gi}\right]^{-1}\left(-k_i^1\xi_i^1 - k_i^2\xi_i^2 - k_i^3\xi_i^3 - \Gamma_f\Delta U_{gi}\right) \\ &\quad \left[\Gamma_G\Gamma_f^0\Delta U_{gi}\right]^{-1}\left(-k_i^1\Delta\omega_i - k_i^2\Delta P_{ti} - k_i^3\Delta\dot{U}_{gi} - \Gamma_f\Delta U_{gi}\right). \end{aligned} \tag{30}$$

For the system without a wide-area signal acquisition, the control signal can be controlled by using the local conventional acquisition signal as follows:

$$\begin{cases} I_{di} = \left(Q_{ei} + X_{qi}I_{gi}^2\right)/ \\ \sqrt{\left[U_{gi} + \left(Q_{ei}X_{qi}\right)/U_{gi}\right]^2 + \left[\left(P_{ti}X_{qi}\right)/U_{gi}\right]^2} \\ I_{qi} = \sqrt{I_{gi}^2 - I_{di}^2}. \end{cases} \tag{31}$$

The control law designed in this paper can implement control behavior in advance based on the trend of target quantity changes, which makes the control law have advanced predictability.

3.3 Nonlinear additional control model of the battery energy storage system

The nonlinear additional control of the battery energy storage can suppress the power fluctuation of the power grid, increase the system damping, and improve the transient stability of the system through the fast power control of the DC system. Therefore, the control target deviation is determined as the deviation of system frequency $\Delta\omega$ between the actual operation and stable operation, the power deviation of AC tie lines ΔP_{ac}, and the DC transmission power deviation ΔP_{dc}. The deviation power relationship obtained by replacing the constant load with impedance equivalent is

$$\Delta P_{cni} = \Delta P_{ti} - \Delta P_{dni}. \tag{32}$$

The target equation based on the target deviation is as follows:

$$\begin{bmatrix} \Delta\dot{\omega}_{ij} \\ \Delta\dot{P}_{cni} \\ \Delta\dot{U}_{dni} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_{ij} \\ \Delta P_{cni} \\ \Delta\dot{U}_{dni} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v_i. \tag{33}$$

According to the control algorithm proposed in this paper, the DC linear control law is

$$u_i = \Delta P_{dni} = -k^1\Delta\omega_{ij} - k^2_{dni}\Delta P_{cni} - k^3_{dni}\Delta P_{dni}, \tag{34}$$

$$\Delta P_{dni} = -\frac{1}{T_{dd}}\Delta P_{dni} + \frac{1}{T_{dd}}\Delta u_{dcc}, \tag{35}$$

where $K_{dni} = \left[k^1_{dni} \quad k^2_{dni} \quad k^3_{dni}\right]^T$ is designed according to the Lyapunov method.

According to aforementioned equations, the DC nonlinear additional control of battery energy storage can be obtained as

$$\Delta u_{dcc} = \Delta P_{dni} - T_{dd}\left(-k^1_{dni}\Delta\omega_{ij} - k^2_{dni}\Delta P_{cni} - k^3_{dni}\Delta P_{dni}\right). \tag{36}$$

4 Example analysis

4.1 Basic data

The topological structure of the equivalent network model of the renewable energy sending system is shown in Supplementary Figure S1. The typical source-load curve of the sending system is shown in Supplementary Figure S2. The three-phase short-circuit fault at node 2 shown in Supplementary Figure S1 is taken as an example to verify the effectiveness of the transient energy balance robust control model of the sending-end system established in this paper.

The total load of the renewable energy sending system of node 2 is 12,000 MW, the AC transmission power is 2,300 MW, and the DC transmission power is 2,800 MW. The total load of the receiving system of node 1 is 15,200 MW, and the DC power accessed from the sending system is 3,000 MW. The total load of the receiving system at node 3 is 50,000 MW, and the AC power accessed from the sending system is 2,000 MW. In the renewable energy sending system shown in Supplementary Figure S1, PV1 and PV2 are photovoltaic power nodes, WP1 and WP2 are the wind power nodes, HG1 is the node of hydroelectric units, G1 and G2 are the nodes of thermal power units, and ES1, ES2, ES3, and ES4 are the nodes of energy storage systems.

4.2 The fault is not cut within the limit time

When a three-phase short circuit occurs at node 2 of the renewable energy sending system and the fault is not cut within the limit time, the equivalent power angle instability curve and its corresponding transient port energy tracking situation at node 2 are shown in Supplementary Figure S3.

As shown in Supplementary Figure S3, when a three-phase short circuit occurs at node 2 of the sending system and the fault is not cut within the limit time, the system obtains a large amount of transient energy. Comparing the power angle variation characteristics of the system with and without the proposed transient energy balance robust control model, the following results can be obtained: although the system is equipped with battery energy storage, if the effective energy tracking control algorithm is not adopted, the fast energy balance characteristics of the battery energy storage in the sending system cannot be fully utilized, and the system will still be unstable. After adopting the energy balance control, the system has good stability performance and can quickly pull the power angle back to synchronization in the second pendulum.

At the same time, as shown in Supplementary Figure S3, the energy tracking control algorithm proposed in this paper can quickly judge the port energy obtained by the sending system when the transient fault starts. The port energy response is achieved through effective coordination between the energy storage and other power sources in the renewable energy sending system.

When a three-phase short circuit occurs at node 2 of the sending system and the fault is not cut within the limit time, the frequency and voltage change curves of the equivalent synchronous power source at nodes 1 and 2 of the sending system are shown in Supplementary Figure S4.

As shown in Supplementary Figure S4, when a three-phase short circuit occurs at the exit of the channel of the renewable energy sending system and the fault is not cut within the limit time, the frequency and voltage of the equivalent synchronous power source at nodes 1 and 2 of the grid are significantly affected due to the large unbalance of the system transient energy and its rapid propagation in the system. However, under the action of the voltage frequency control algorithm proposed in this paper, the exceedance time of the voltage and frequency is short, which has little impact on the system. On the contrary, if the frequency and voltage multi-objective nonlinear control model proposed in this paper is not adopted, the frequency and voltage of the grid-connected power supply at nodes 1 and 2 will have a large deviation. The transient energy obtained by the system is large.

4.3 The fault is cut within the limit time

When a three-phase short circuit occurs at node 2 of the sending system and the fault is cut within the limit cutting time, the equivalent power angle instability curve at node 2 of the sending system node and its corresponding transient port energy tracking are shown in Supplementary Figure S5.

As shown in Supplementary Figure S5, when a three-phase short circuit occurs at node 2 of the sending system and the fault is cut within the limit time, the transient energy obtained by the system is small. By comparing the power angle variation characteristics of the system with and without the proposed transient energy balance robust control model, the following results can be obtained: adopting effective energy tracking control algorithms can better utilize the fast energy regulation characteristics of battery energy storage. The fluctuation amplitude of the sending system can be effectively reduced, and synchronization can be restored in a shorter time.

When a three-phase short circuit occurs at node 2 of the sending system and the fault is cut within the limit time, the frequency and voltage change curves of the equivalent synchronous power source at nodes 1 and node 2 of the sending system are shown in Supplementary Figure S6.

As shown in Supplementary Figure S6, if a three-phase short circuit occurs at node 2 of the renewable energy sending system and the fault is cut within the limit time, the propagation of transient energy in the system has little influence on the frequency and voltage of the equivalent synchronous power source at nodes 1 and 2, due to the transient energy imbalance of the system being small. At the same time, the voltage frequency control algorithm can significantly reduce the amplitude of voltage and frequency fluctuations, and can realize the rapid suppression of voltage and frequency fluctuations.

5 Conclusion

In order to ensure the dynamic balance of the total energy of the renewable energy sending renewable energy generation system and the stability of the system under the transient port energy impact, a nonlinear multi-objective transient voltage and frequency-coordinated control strategy for the renewable energy sending system is proposed in this paper.

By analyzing the dynamic balance characteristics of the renewable energy sending system under transient energy impact, the frequency and voltage state equation of the sending system considering transient energy impact is studied. The trajectory evolution characteristics of the frequency and voltage of the equivalent power source of each node in the sending network are analyzed. On this basis, the nonlinear transient voltage and frequency-coordinated control strategy for renewable energy generation systems is established. The simulation results show that the coordinated control strategy proposed in this paper can realize the transient energy balance control of the renewable energy sending system, and ensure that the frequency and voltage fluctuations of the system do not exceed the limit.

In this paper, the transient voltage and frequency stability of the weak sending system with large-scale wind and photovoltaic energies are mainly studied. With the development of future energy networks, multi-energy conversion and storage devices such as hydrogen production, fuel cell, heat pump, heat storage, and hydrogen storage and gas storage devices will be connected to the sending system. Further research is needed on the transient voltage and frequency stability analysis theory of the renewable energy sending system.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

This article was written by QW, who carried out the design and data analysis of the main research; KZ led the writing of the article; SM and ZC gave guidance to the paper; and SC proofread all the drafts and objectively proofread the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1227940/full#supplementary-material

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