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Identification model for weak areas of transient energy balance in EESs based on dynamic grid partitioning

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In response to the high uncertainty of large-scale new energy output in the electrical energy system (EES) and the weak controllability of energy output at multiple time scales, this paper proposes a weak grid identification model for transient energy balance in EESs based on grid partitioning, which has an increasingly complex impact on the weak areas of transient energy balance in the sending-end network. First, the accumulation of port energy during transient faults and the propagation mechanism of port energy in the sending-end system were studied, and an EES transient energy propagation mechanism model was established. Then, considering the energy balance support requirements of nodes, an EES grid partitioning model was established. Afterward, based on the characteristics of transient energy propagation and a grid partitioning model, an identification model for weak areas of transient energy balance in EESs was constructed. Finally, based on actual operating data, numerical simulations were conducted, and the results showed that the proposed weak grid identification model for transient energy balance can meet the requirements for transient stability analysis and transient energy balance characteristic analysis during actual operation of power grids.

KEYWORDS

EES, transient stability, dynamic grid partition, weak area identification, transient energy

1 Introduction

Under the guidance of the adjustment of the energy consumption structure and the strategic policy of “carbon peak and carbon neutrality,” the construction of an EES connected to new energy (Li Y. et al., 2019; Li et al., 2020) with new energy as the main body is deepening. China is gradually forming a power grid pattern of large-scale cross-regional interconnected systems consisting of wind power and photovoltaic resource-rich sending-end power grids in the western and northwestern regions through long-distance UHV AC and DC channels, and eastern load-intensive regional power grids (Wu et al., 2018; Huang et al., 2019; Li and Liu, 2019; Li et al., 2021). At present, the development of new energy faces the following three problems. First, the total installed capacity of new energy is far beyond the load, and limited by the characteristics of conventional power supply and power grid structures (Da Cruz Sessa and Mariano Lessa Assis, 2018), the difficulty of new energy consumption is prominent. Second, a large amount of new energy power stations leads to a reduction of conventional power supply in the system, the reduction of system inertia, frequency and voltage response characteristics, and a significant increase in the security risk of power grid operation (Li C. S. et al., 2019). Third, the new energy power station has no energy storage link, which is a disturbance source for the power grid and has no adjustment ability. Therefore, the stability circumstance of large-scale new energy connected to the power grid urgently needs to seek new means to assist traditional units to promote the ensemble regulation ability of the power grid (Bhui and Senroy, 2017; Zhang J. et al., 2022; Zhang DW. et al., 2022). The research and establishment of the transient energy stability criterion and weak area identification method of transient energy balance in new energy sending-end systems forms the theoretical and algorithm basis for further research on the robust control model of transient energy balance in sending-end systems based on battery energy storage coordination and can also provide the theoretical basis for the optimization of transient stability-related constraints for the optimal configuration of battery energy storage in sending-end systems (Heetal, 2020).

At present, researchers all around the world have already conducted in-depth studies on the DC transmission of EESs connected to new energy, power grid stability, and identification of weak areas of transient energy balance. In HAN et al. (2018), for solving the transient overvoltage problem of AC bus caused by DC blocking in the HVDC transmission system sending end, the emergency shutdown strategy of triggering DC blocking is improved to slow down the triggering process of DC blocking and ensure the stable operation of wind turbines. In order to maintain the safety and stability of the HVDC transmission system and avoid the outage of the HVDC transmission system caused by transient fault of the DC line (Xu et al., 2019; Ding et al., 2021), Muniappan (2021) added the fault restart function of the DC line in DC control protection. Scientific and reasonable division of the grid is the key to the continuous implementation of the target grid of the sending-end power grid.

The scientific and reasonable division of grids and the identification of weak areas are key to the sustainable implementation of the target grid structure of grid transformation. LIU et al. (2010) considered the uncertainty of changes in the location of fault points and proposed a method to determine the commutation fault-related area (CFCR), searching for weak areas. In FU et al. (2011) and CAI et al. (2017), active margin index, sensitivity index, and other parameters were chosen as indicators to identify weak areas in the grid region, or full network voltage scanning was used for identification. However, for more complex systems, the calculation of this identification method is more complex. XIAO et al. (2016) proposed a new method that combines an improved modal method and a P-V curve to identify weak areas, but the accuracy of identifying weak areas still needs to be improved.

In summary, there is relatively little research on EES partition based on the energy balance capability. Therefore, this paper studies the propagation mechanism of transient energy in an EES during fault occurrence and establishes a transient energy propagation mechanism model for EES fault ports. Considering the energy balance support requirements of nodes in EESs, we establish an EES grid partitioning model. The transient energy propagation characteristics and the identification method of the EES energy balance weak partition area were also studied. Finally, a simulation model for identifying the weak grid of transient energy balance in the EES was established. Based on the analysis results, it can be concluded that the proposed method for identifying the weak grid of transient energy balance can meet the analysis requirements of the power grid.

2 Transient energy propagation mechanism of fault ports in the EES

2.1 Unconstrained transient energy propagation model for fault ports in the EES

To study the propagation mechanism of transient energy at the fault port in the EES during the occurrence of a fault, this paper establishes an unconstrained propagation model for transient energy:

$$N(x)\ddot{x} + D(x,\dot{x})\dot{x} + H(x) + G(x,\dot{x}) = u \tag{1}$$

where $x \in R^n$, $\dot{x}\in R^n$, and$\ddot{x}\in R^n$ are the state phasors of each node, the derivative of state phasors, and the second derivative of the corresponding system in the transmission process of the fault port energy under the transient fault state, respectively; $N(x) \in R^{n\times n}$, $D(x,\dot{x})\dot{x}$, $H(x) \in R^n$, and $G(x,\dot{x}) \in R^n$ are the inertia influence relation matrix, forward energy propagation term, reverse energy propagation term, and energy loss term when the fault port energy is transmitted in the interconnected system network under the transient fault state, respectively; and $u \in R^n$ is the control variable of the influence of power supply and load connected to each node on the energy of the fault port in the transient fault state.

The energy action model of node s can be transformed into the following form:

$$\begin{cases} N_i(x_s)\ddot{x}_s + D_s(x_s,\dot{x}_s)\dot{x}_s + H_s(\dot{x}_s) + G_s(x_s,\dot{x}_s) + A_s(x_s,\dot{x}_s,\ddot{x}_s) = u_s \\ A_i(x_s,\dot{x}_s,\ddot{x}_s) = \left\{ \sum\limits_{r=1,r\neq s}^{n} N_{sr}(x_s)\ddot{x}_s + [N_{ss}(x_s) - N_s(x_s)]\ddot{x}_s \right\} \\ \quad +\left\{ \sum\limits_{r=1,r\neq s}^{n} D_{sr}(x_s,\dot{x}_r)x_s,\dot{x}_r + [D_{sr}(x_s,\dot{x}_s) - D_s(x_s,\dot{x}_s)]\dot{x}_s \right\} \\ \quad +[\overline{H_s}(x_s) - H_s(x_s)] \end{cases} \tag{2}$$

where $x_s,\dot{x}_s,\ddot{x}_s,\overline{H_s}(x_s),G_s(x_s,\dot{x}_s)$, and u_s represent the s-th component of vectors $x,\dot{x},\ddot{x},\bar{H}(x),G(x,\dot{x})$, and u, respectively; $N_{sr}(x)$ and $D_{sr}(x,\dot{x})$ are the s-th and r-th components of the matrix $N(x)$ and $D(x,\dot{x})$, respectively; and $A_s(x,\dot{x},\ddot{x}) \in R$ is the energy transfer subsystem cross-linking term of node s.

Setting $x_s = [x_{s1} \quad x_{s2}]^T = [x_s \quad \dot{x}_s]^T (s = 1,2,\cdots,n)$, the port transient energy transitive relation network of the aforementioned formula can be transformed into the following form:

$$\begin{cases} \dot{x}_s = B_s x_s + C_s[f_s(x_s,\dot{x}_s) + g_s(x_s)u_s + h_s(x_s,\dot{x}_s,\ddot{x}_s)] \\ \dot{y}_s = D_s x_s \end{cases} \tag{3}$$

where x_s is the state phasor of node s, y_s is the output of node s, and

$$\begin{cases} B_s = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; C_s = \begin{bmatrix} 0 \\ 1 \end{bmatrix}; D_s = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \\ f_s(x_s, \dot{x}_s) = N_s^{-1}(x_s)[-D_s(x_s, \dot{x}_s)\dot{x}_s - H_s(x_s) - G_s(x_s, \dot{x}_s)]; \\ g_s(x_s) = N_s^{-1}(x_s); \\ h_s(x_s, \dot{x}_s, \ddot{x}_s) = -N_s^{-1}(x_s)A_s(x_s, \dot{x}_s, \ddot{x}_s) \end{cases} \tag{4}$$

2.2 Transient energy transfer model for EES ports based on multiple constraints

During the transient energy balance control process of the EES fault port, when constrained by load fluctuations, wind and photovoltaic output fluctuations, transmission line capacity, and other constraints, each constraint condition is uniformly represented as follows:

$$\lambda(x, t) = 0 \tag{5}$$

where $x \in R^n$ represents the variables of each node in the EES; λ: $R^n \rightarrow R^m$ represents the state variable constraint function corresponding to each node; and m is the dimension of the constraint condition acting on the transient energy transmission of the port in the transient energy balance control process.

The derivative of the aforementioned equation is taken to obtain

$$\dot{\lambda}(x, t) = \frac{\partial \lambda(x, t)}{\partial x}\dot{x} + \frac{\partial \lambda(x, t)}{\partial t} \tag{6}$$

The definition is as follows:

$$\begin{cases} K_\lambda(x, t) = \dfrac{\partial \lambda(x, t)}{\partial x} = \dfrac{\partial \lambda}{\partial x} \\ \dot{Q}(t) = \dfrac{\partial \lambda(x, t)}{\partial t} \end{cases} \tag{7}$$

where $K_\lambda(x, t)$ is the $m \times n$-dimensional Jacobian matrix, $\dot{Q}(t)$ is the change vector of the state variable constraint condition, and its size depends on the change rate of the state variable. Eq. 6 is represented as follows:

$$\dot{\lambda}(x, t) = K_\lambda(x, t)\dot{x} + \dot{Q}(t) \tag{8}$$

The relationship between the effect of each state constraint on the transient energy transfer path and mode of the port p and its corresponding x in the spatial coordinate system composed of each node in the EES is as follows:

$$p = I(x) \tag{9}$$

Eq. 5 can be rewritten as follows:

$$\lambda(p, t) = \lambda(I(x), t) \tag{10}$$

At this time, the Jacobian matrix is as follows:

$$K = K_\lambda(x, t) = \frac{\partial \lambda}{\partial p}\frac{\partial I(x)}{\partial x} \tag{11}$$

Assuming $\delta\lambda(p)$ as the contribution of the constraint condition to the changes in the transient energy transfer joint path and mode of the fault port, the following can be obtained:

$$\delta\lambda = \frac{\delta\lambda}{\delta p}\delta p = 0 \tag{12}$$

Taking the Lagrange multiplier $f \in R^m$ into account, we can obtain the following:

$$\left(\frac{\delta\lambda}{\delta p}\delta p\right)^T f = 0 \tag{13}$$

Set

$$(\delta p)^T G_2 = 0 \tag{14}$$

where G_2 represents the action of multidimensional constraints on the change of the transient energy transfer path and mode at fault ports; δp is the variation of various parameters under the action of G_2 after the transient energy propagation of the fault port ends. From Eqs 13, 14, it can be concluded that

$$(\delta p)^T G_2 - \left(\frac{\delta\lambda}{\delta p}\delta p\right)^T f = 0 \tag{15}$$

Transforming the state constraint G_2 into the system state space of the transient energy balance control process at the fault port, we obtain the following:

$$G_1 = K^T f = K_\lambda^T(x, t)f \tag{16}$$

In summary, the system model for the transient energy balance control process of fault ports considering n state constraints is as follows:

$$N(x)\ddot{x} + D(x, \dot{x})\dot{x} + H(x) + G(x, \dot{x}) = u + K_\Phi^T(x, t)f \tag{17}$$

The variables of each node in the network defined in the aforementioned system are as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, x_1 \in R^{n-m}, x_2 \in R^m \tag{18}$$

Eq. 18 is substituted into Eq. 5 to obtain

$$\Phi(x_1, \Omega(x, t), t) = 0 \tag{19}$$

where $x_2 = \Omega(x_1, t)$, and Eq. 18 can be expressed by variable x_1 as

$$x = \begin{bmatrix} x_1 \\ \Omega(x_1, t) \end{bmatrix} \tag{20}$$

From the derivation of Formula 20, we obtain

$$\begin{aligned} \dot{x} &= \begin{bmatrix} \dot{x}_1 \\ \dfrac{\partial \Omega(x_1, t)}{\partial x_1} + \dfrac{\partial \Omega(x_1, t)}{\partial t} \end{bmatrix} \\ &= \begin{bmatrix} J_{n-m} & 0 \\ \dfrac{\partial \Omega(x_1, t)}{\partial x_1} & J_m \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{\partial \Omega(x_1, t)}{\partial t} \end{bmatrix} \\ &= U\dot{\theta} + I \end{aligned} \tag{21}$$

where $U = \begin{bmatrix} J_{n-m} & 0 \\ \dfrac{\partial\Omega(x_1,t)}{\partial x_1} & J_m \end{bmatrix} \in R^{n\times n}$, $\dot{\theta} = \begin{bmatrix} \dot{x}_1 \\ 0 \end{bmatrix} \in R^n$, and $I = \begin{bmatrix} 0 \\ \dfrac{\partial\Omega(x_1,t)}{\partial t} \end{bmatrix} \in R^n$.

Eq. 21 can be obtained by calculating the second derivative of x:

$$\ddot{x} = U\ddot{\theta} + \dot{U}\dot{\theta} + \dot{I}. \tag{22}$$

From Eqs 20–22, it can be concluded that

$$\begin{aligned} &N(x)\left(U\ddot{\theta} + \dot{U}\dot{\theta} + \dot{I}\right) + D(x,\dot{x})\left(U\dot{\theta} + \dot{I}\right) \\ &+H(x) + G(x,\dot{x}) = u + K_{\Phi}^{T}(x,t)f \end{aligned} \tag{23}$$

By separating the state constraint terms in the network node variable parameters, the node s model can be obtained as follows:

$$\begin{aligned} &N_s(x_s)\ddot{x}_s + D_s(x_s,\dot{x}_s)\dot{x}_s + H_s(x_s)+ \\ &G_s(x_s,\dot{x}_s) + A_s(x_s,\dot{x}_s,\ddot{x}_s) - \tau^{*}_{\Phi s} = u_s \end{aligned} \tag{24}$$

where

$$\begin{aligned} A_s(x_s,\dot{x}_s,\ddot{x}_s) = &\sum_{\substack{r=1 \\ r\neq s}}^{n} N_{sr}(x)\left[(UE\ddot{x}_s)_r + \left(\dot{U}E\dot{x}_s\right)_r + \dot{I}_r\right] \\ &+N_{sr}(x)\left[(UE\ddot{x}_s)_r + \left(\dot{U}E\dot{x}_s\right)_r \quad +\dot{I}_s\right] - N_s(x_r)\ddot{x}_s \\ &+\sum_{\substack{r=1 \\ r\neq s}}^{n} D_{rs}(x_s,\dot{x}_r)\left((UE\dot{x}_s)_r + I_r\right) + D_{sr}(x,\dot{x}_s) \\ &\left((UE\dot{x}_s)_r + I_r\right) - D_s(x_s,\dot{x}_s)\dot{x}_s \\ &+\left(\overline{H_s}(x) - H_s(x_s)\right) + \left(\tau^{*}_{\Phi s} - \tau_{\Phi s}\right) \end{aligned} \tag{25}$$

3 Dynamic grid partitioning model of the EES

When considering the energy balance support requirements of nodes in the EES, the set of node state variables in the EES can be expressed as follows:

$$X = \{x_s \mid x_s \in \Omega,\ s \in S\} \tag{26}$$

where Ω can reflect the energy requirement of node s in the EES.

When the energy balance requirement of node s is Ω, the EES is divided into Λ grid regions, $\Lambda = \{0, 1, \cdots, L\}$, and the energy field matrix formed by injecting energy into each grid region is expressed as follows:

$$Y = \left\{y_s \,\middle|\, y_s \in \Lambda,\ s \in S\right\} \tag{27}$$

where y_s is the injected energy of node s.

Under the given operating state variable X, the probability of each scheme for energy partition of energy field Y (this energy field is the Markov random field) is given as follows:

$$P(Y \mid X) = \frac{P(X \mid Y)P(Y)}{P(X)} \tag{28}$$

In the process of constantly changing the operating state variable X, the energy field matrix also changes accordingly. Therefore, the energy partitioning problem can be converted to solve the minimization of energy imbalance in the EES by calculating the global optimal estimation solution Y^{*}, that is, dynamically solving the minimization of energy imbalance in the EES:

$$\begin{aligned} Y^{*} &= \arg\max_{Y} P(Y \mid X) \sim \arg\min_{Y} E_g(X,Y) \\ &= \arg\min_{Y} \{E_d(X,Y) + E_s(Y)\} \end{aligned} \tag{29}$$

where $E_g(X,Y)$ represents the energy supply and demand balance condition in Y; $E_d(X,Y) = -\lg P(X \mid Y)$ represents the still present energy requirement after dividing the system; $E_s(Y) = \sum_{s,r\in N(s)} \delta(y_s, y_r)$ represents the battery energy that can be called within the dividing scope; and $N(s)$ refers to all neighboring nodes within the grid partition where node s is located.

4 Identification model of the weak partition area for transient energy balance in the EES

4.1 Identification model of the weak partition area

We establish an energy correlation model for adjacent nodes in the EES, namely, the degree of topological overlap $c_{sr}(x_s, x_r)$:

$$c_{sr}(x_s, x_r) = \frac{b_{sr}}{1 - b_{sr}} \tag{30}$$

$$b_{sr} = \left|\exp\left\{\frac{-2 \times \left(\|x_s - x_r\|_2\right)^2}{\left(\rho \max\limits_{r \in N_s} \|x_s - x_r\|_2\right)^2}\right\}\right|^{\gamma} \tag{31}$$

where x_s and x_r are the state variables of two adjacent nodes which provide direct energy exchange to each other, $s \neq r$; b_{sr} represents the energy exchange level; $\|x_s - x_r\|_2$ represents the Euclidean distance of adjacent nodes; ρ refers to the homogenization element of heterogeneous nodes connected to hybrid energy; and γ is the penalty element for the energy interaction exceeding limit.

Let w_s represent a set of nodes within the partition area where node s is located that has direct energy injection or cascading energy interaction, and $\vartheta_s(y_s)$ is the set of adjoining nodes that provide direct energy exchange with set w_s. Then, the energy interaction degree with high-order topological prior for nodes $c_{w_s}(x_s, x_{\vartheta_s})$ is as follows:

$$c_{w_s}(x_s, x_{\vartheta_s}) = c_{N1}(x_s, x_{N1}) + c_{N2}(x_s, x_{N2}) + \cdots + c_{Ni}(x_s, x_{Ni}), \tag{32}$$

where $c_{w_s}(x_s, x_{\vartheta_s})$ represents all energy correlation values c_{Ni} related to node s added together in the partition area where node s is located; $c_{N1}, c_{N2}, \ldots, c_{Ni}$ indicates the energy correlation between node s and all adjacent nodes that have an energy interaction.

In summary, we establish a high-order prior energy model for node energy correlation:

$$E_h(x_w|\Upsilon) = \sum_{s\in S, r\in N_s}\left[\frac{b_{sr} + \sum\limits_{u\neq s,r} b_{su}b_{ru}}{\min\left\{\sum\limits_{u\neq s} b_{su} \sum\limits_{u\neq r} b_{ru}\right\} + 1 - b_{sr}}\right], \tag{33}$$

where $E_h(x_w|\Upsilon)$ is the prior energy of higher-order topological structures in the grid region where node s is located; $\Upsilon = \{\rho, \gamma\}$ is the higher-order prior parameters for network partitioning.

Based on this, a Gaussian likelihood estimation model for the partition area is constructed to identify the degree of energy imbalance in each partition area:

$$\begin{cases} P(X|Y,\theta) = \prod_{s=1}^{N}\left[P\left(x_s|y_s,\theta\right)\prod_{r\in\vartheta_s}P\left(x_r|y_r,\theta\right)^{\frac{w(y_r)}{w_r}}\right] \\ w(y_r) = \sum_{s\in S}\sum_{r\in\vartheta_s}\|x_s - x_r\| = \sum_{s\in S}\sum_{r\in\vartheta_s}(x_s + x_r - 2x_s x_r) \end{cases} \tag{34}$$

where $x_r = \{x_r|r \in \vartheta_s\}$ is the neighborhood node state variable set of node s; $\theta = \{\mu_l, \sigma_l^2\}_{l\in\Lambda}$, where μ_l, and σ_l^2 are the probability distribution mean and variance of energy imbalance within a partition area; w_r is the probability calculation weight of energy imbalance within the partition area, and $w_r = \sum_{r\in\mathcal{N}_s} w(y_r)$. The smaller the w_r, the larger the estimated value Y^* of the energy imbalance within its corresponding partition area, and the weaker the energy balance ability of the partition area.

4.2 Identification process of the weak partition area for transient energy balance in the EES

The specific steps for identifying EES energy balance weak grids based on a prior knowledge model are as follows:

Step 1: Initialize the parameter node set w_s, the homogenization element of heterogeneous nodes connected to hybrid energy ρ, and the penalty element for the energy interaction exceeding limit γ.

Step 2: Calculate the energy correlation between node s and all adjacent nodes with the energy interaction $c_{sr}(x_s, x_r)$ in the partition area where node s is located.

Step 3: Calculate the prior energy of the topological structure $\gamma E_h(x_{w_s}\,|\,\gamma)$ of the partition area where node s is located.

Step 4: Repeat steps 2 to 3 until $s = S$.

Step 5: Sort the estimated values Y^* of the energy imbalance within the partition area by adopting the Gaussian likelihood estimation model and identify the weaker energy balance ability partition area.

The flow chart for grid identification with weak energy balance capability is shown in Supplementary Figure S1.

5 Example analysis

Consulting the actual operating EES data, this article designs a simulation system, as shown in Supplementary Figure S2: the add-up load of the sending-end power grid at node 1 is 10,000 MW, the AC transmission is 2,000 MW, and the DC transmission is 3,000 MW. The total load of the node 2 receiving-end system is 60,000 MW, and the DC is 3,000 MW from the sending-end system. The total load of the node 3 receiving-end system is 50,000 MW, and the AC 2,000 MW is connected from the sending-end system.

The internal equivalent network structure of the new energy transmission terminal grid is shown in Supplementary Figure S3. G1, G5, and G8 are three photovoltaic converging power nodes with capacities of 3,000, 2,000, and 3,000 MW, respectively. G2 is the wind power-gathering power node with a capacity of 4,000 MW. G13 is a hydropower power node with a capacity of 6,000 MW; G11 is a thermal power node with a capacity of 2,000 MW; B1, B5, B6, B14, and B24 are battery energy storage units with capacities of 1,500, 1,000, 1,600, 1,100, and 900 MW·h, respectively.

We built a system transient stability simulation model based on MATLAB, with a limit cutoff time of 0.3 s set for simulation. Aiming at testing and verifying the effectiveness of the EES weak grid identification method for transient energy balance proposed in this paper, two simulation scenarios are set. Scenario 1 does not consider the energy support role of energy storage devices in the transient energy equilibration, and scenario 2 considers energy storage to adjust the energy balance.

5.1 Energy storage devices do not participate in energy balance

Supplementary Figure S4 shows the equivalent power angle instability curve and its corresponding transient stability margin index change curve at node 1 of the sending-end system shown in Supplementary Figure S3, without considering the participation of energy storage in regulation, when a fault occurs at node 1 with a three-phase short circuit, and this fault is not removed within the limit removal time.

As shown in Supplementary Figure S4, when the fault occurs along the output line of channel 1 of the sending-end system and the system becomes unstable, the power angle of the system at node 1 exceeds the power angle stability limit after the first swing and the sending-end system loses synchronization with the receiving-end system. During the instability process of the sending-end system, the equivalent power angle change curve of the system at node 1 is a continuously increasing oscillation process. Meanwhile, as shown in the variation curve of the stability margin index of the system in Supplementary Figure S4, the curve shows that the stability margin index of the sending-end changes significantly during the first swing of the power angle swing of node 1, indicating that the system will lose synchronization with the receiving-end system.

According to the EES dynamic grid partitioning model, as mentioned earlier, the grid partitioning of the sending-end power grid shown in Supplementary Figure S2 is carried out, and the partitioning results are shown in Supplementary Figure S5.

Supplementary Figure S5 is shows that when a transient fault happens in the output channel of the sending-end system, due to the large startup methods of new energy sources, such as photovoltaic and wind power in the system, and the lack of energy storage, when dividing the grid of the sending-end network, the new energy sources are all divided in the same grid as hydroelectric or thermal power units to ensure that the transient energy balance characteristics within the grid meet the system stability requirements as much as possible.

When the sending-end system loses stability under the scenario of the three-phase short circuit fault at node 1 in Supplementary Figure S3, the energy balance weak grid identification method put forward in this article is adopted to calculate the estimated energy imbalance of each grid. This article mainly calculates the estimated value of energy imbalance within the grid and ranks the calculation results of multiple grids in order to identify the grid with the largest energy imbalance and the weakest energy balance ability. The comparison between the calculation results and the maximum frequency deviation of each grid during the fault time period can be seen in Supplementary Table S1.

Supplementary Table S1 shows that except for partition area 1, where the fault point is located, the variation pattern of the estimated value of energy imbalance calculated using the method put forward in this article is mostly consistent with the variation pattern of the maximum grid frequency deviation during the fault time period, which verifies the effectiveness of the energy balance weak partition area identification method mentioned earlier. In addition, when the sending-end system becomes unstable, the frequency deviation of each partition area in the system is relatively large. This also indicates that when the energy storage system is not configured, the sending-end system will not only lose synchronization with the receiving-end system when facing large transient energy injection but also cause significant energy oscillations inside the sending-end system. If the startup mode of thermal and hydroelectric units existing in the power grid is small at this time and the response speed can hardly reach the requirement level of suppressing transient energy propagation within an effective time, the sending-end system is likely to undergo splitting or even collapse.

5.2 Energy storage devices participate in energy balance

Considering the involvement of multi-energy storage equipment involved in energy regulation, at the time the fault occurs at node 1 of channel 1 of the sending-end system in Supplementary Figure S2, the equivalent power angle instability curve and its corresponding transient stability margin index change curve at node 1 are shown in Supplementary Figure S6.

Supplementary Figure S6 shows that at the time of fault occurrence to channel 1 in the sending-end system, the system protection and safety control devices do not cut off the fault within the limit cutting time. The power angle of node 1 in the system exceeds the power angle stability limit after the first swing. However, due to the rapid absorption of transient energy by the energy storage device configured in the sending-end system after the system's transient energy exceeds the limit, the amplitude of the power angle swing in the system decreases rapidly during the second swing and makes the subsequent oscillation process converge quickly.

Meanwhile, the variation curve of the stability margin index in Supplementary Figure S6 shows that the stability margin index in the sending-end system quickly decreases to within the stability threshold after a jump in the first swing of the power angle swing at node 1. It can be seen that after configuring battery energy storage, the ability of the sending-end system to maintain transient stability has been significantly improved, but the system will still enter an unstable state, causing significant energy impacts on the synchronous power supply, new energy power supply, and load of the sending-end system.

The grid division results when considering the participation of energy storage devices in regulation are shown in Supplementary Figure S7.

Supplementary Figure S7 shows that compared to the grid division in Supplementary Figure S5, the transient energy balance grid division results shown in Supplementary Figure S7 not only consider the support role of traditional hydropower and thermal power units for new energy sources but also consider the support role of energy storage systems for new energy sources and loads.

The energy balance weak grid identification method proposed in this article is used to calculate the estimated energy imbalance values of each grid after re-partitioning. The comparison between the calculated results and the maximum frequency deviation of each grid during the fault time period is shown in Supplementary Table S2.

Supplementary Table S2 shows that compared with the estimated energy imbalance value in Supplementary Table S1, after considering the participation of energy storage devices, the estimated values of energy imbalance within each grid have been reduced, and the energy balance ability has been improved. This once again verifies the effectiveness of the energy balance weak grid identification method mentioned previously. Moreover, when the sending-end system is unstable due to the transient energy support effect of the energy storage system, the frequency deviation of each grid area of the sending-end system increases and decreases significantly. On the other hand, the simulation results also indicate that although the energy storage system could improve the transient energy balance ability of the system to a certain extent, relying on the energy absorption or release characteristics of a simple energy storage system still cannot effectively maintain the stability circumstance of the sending-end system during serious transient fault at the outlet of the sending channel.

6 Conclusion

To improve the stability of transient faults in EESs with battery energy storage, this paper proposes a weak partition area identification method for transient energy balance in an EES based on a high-order prior energy model with energy correlation.

(1) This article studies the transient energy propagation mechanism of ports during faults in EESs, establishes an unconstrained propagation model that reflects the transient energy propagation characteristics of ports, and adds actual multiple constraints to establish a system model that describes transient energy transfer.
(2) Considering the energy balance support requirements in EESs, this paper proposes an EES dynamic partitioning model and an energy balance weak partition area identification method based on a prior model of node energy correlation, achieving the identification of areas with weak energy balance capabilities in EES.
(3) This article is based on actual operating data and verifies the proposed method through numerical simulation. The simulation results verify the effectiveness of the proposed

transient energy balance weak grid identification method (QIN, 2015; Hu et al., 2021; Cheng et al., 2022).

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 SQ, who carried out the design and data analysis of the main research, KZ led the writing of the article, ZuC and SC proofread all the drafts, ZeC gave guidance to the paper, and YZ objectively proofread the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author YZ was employed by State Grid Liaoning Electric Power Co., Ltd.

The remaining 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1204960/full#supplementary-material

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