EVALUATION METHOD AND SYSTEM FOR BLACK-START CAPABILITY OF GRID-FORMING ENERGY AND ENERGY STORAGE DEVICES

TECHNICAL FIELD

The present invention relates to the technical field of novel power systems and new energy, and in particular to an evaluation method and system for black-start capability of grid-forming energy and energy storage devices.

BACKGROUND

In the absence of external power sources, new energy devices (such as wind power or photovoltaic (PV)) or energy storage devices can start and provide initial power to support the start of critical facilities in the power grid. The black-start capability of new energy or energy storage devices ensures that even in the absence of traditional power sources, the device can play a role in restoring power supply and ensuring emergency recovery and stable operation of the power grid.

According to a patent application with a publication number of CN118487269A, by establishing and selecting key evaluation indexes, the black-start decision-making model is established and the input-output relationship is simplified. The black-start solutions are sorted by weighted evaluation and fuzzy evaluation methods, and the optimal solution is selected to evaluate the black-start capability of energy storage system after a large-scale blackout and ensure the rapid recovery of power supply to the power grid. According to patent application with a publication number of CN114862150A, an evaluation method for black-start capability of a distribution network based on distributed power sources is provided. By using the entropy weight fuzzy comprehensive evaluation model, the evaluation indicators are obtained and standardized, and the subjective and objective weights are calculated. Combined with the fuzzy evaluation method, the evaluation value of black-start capability of distributed power supply is finally obtained. According to a patent application with a publication number of CN115906615A, by analyzing the key technical factors of new energy participating in the initial black-start, the temporal and spatial support capability of black-start is defined, and the time series data is modeled by combining with long short-term memory (LSTM) neural network to evaluate the black-start capability of new energy system. This method takes into account the temporal and spatial fluctuations of new energy units, can optimize the black-start solution and improve the recovery efficiency of power grid.

The above research provides different technical paths and evaluation methods in the black-start capability evaluation of new energy and energy storage combined power generation systems. However, there are still some shortcomings for grid-forming new energy and energy storage devices. The above method mainly focuses on the single role of new energy and energy storage devices in black-start, but the complexity of the power grid structure is also one of the important factors affecting the black start capability. Factors including changes in grid topology, coordination of different types of distributed energy resources, load changes and distribution also have an impact on the black-start process. The black-start evaluation of grid-forming new energy needs to take into account the interconnection and collaborative work between different power sources to more comprehensively evaluate the black-start capability.

SUMMARY

To solve the shortcomings in the related art, the present invention provides an evaluation method and system for black-start capability of grid-forming new energy and energy storage devices, which can dynamically and accurately evaluate the black-start capability of each new energy and energy storage device. The method firstly detects faults of a power grid and reconstructs a power grid topology diagram. On the basis of reconstructing the topology, the recovery priority of load nodes and the real-time output capability of new energy/energy storage devices are calculated, and the recovery priority of load nodes and the real-time output capability of new energy/energy storage devices are synthesized with the path cost of intermediate nodes to form a weighted graph, and the optimal black-start path is searched based on the graph. Finally, the black-start is performed in the simulation environment, the running data of the device is recorded, and the start time, available power, voltage/frequency support capacity and influence intensity are calculated to generate a comprehensive score.

A first aspect of the present invention provides an evaluation method and system for black-start capability of grid-forming new energy and energy storage devices, and the method adopts the following technical solutions:

detecting fault nodes in a power grid by adopting a two-layer fault determination method in segmented load periods based on real-time operation status of the power grid; and updating a connection relationship of power grid nodes according to the fault nodes to obtain a reconstructed power grid topology diagram;

calculating a recovery priority score of each load node in the reconstructed power grid topology, and calculating real-time output capacity of each new energy and energy storage device;

converting the reconstructed power grid topology diagram into a weighted graph, and correcting edge weights and node weights of the weighted graph based on recovery priority, output capacity, and path cost of intermediate nodes; and searching for an optimal black-start path based on a corrected weighted graph; and

deploying the black-start path in a simulation environment to perform black-start simulation; recording operating data of each new energy and energy storage device in each simulation process; and evaluating black-start capability of a single new energy/energy storage device based on the operating data.

Further, the double-layer fault determination method includes the steps of:

performing preliminary detection of operating parameters for each power grid node in different load periods; and triggering fault detection when preliminary detection results exceed a trigger threshold;

calculating instantaneous change values of the operating parameters for power grid nodes that have triggered fault detection; and determining a power grid node as a fault node when the instantaneous change values exceed a fault detection threshold; and

taking a sum of an upper limit value of the trigger threshold and an offset as the fault detection threshold, taking a product of a standard deviation of operating parameters in a load period corresponding to fault detection and an offset weight as the offset, and taking a ratio of an instantaneous change value of a parameter to a sampling interval as the offset weight.

Further, the obtaining a reconstructed power grid topology diagram includes the steps of:

obtaining positions, equipment types, connecting lines and line attributes of all nodes in the power grid, and constructing a power grid topology diagram using an undirected graph structure;

taking a weighted sum of multiple factors as an edge weight of the power grid topology diagram, the multiple factors including line impedance, line capacity, line length, voltage level and recovery cost, and the reciprocal of line capacity and voltage level being taken in a weighted calculation; and

setting fault state markers for the fault nodes and marking edges connected to the fault nodes as disconnected; and in the power grid topology diagram, updating a topological connection relationship according to the fault state markers and disconnection markers to obtain the reconstructed power grid topology diagram.

Further, the recovery priority of the load node is calculated as a weighted sum of a recovery urgency, a power demand level, and a recovery difficulty of the load node;

the recovery urgency is assigned according to a load type; and the power demand level is expressed as a ratio of a maximum demand power of the load node to a maximum single-node demand power of all load nodes;

the recovery difficulty is a result of subtracting a weighted sum of three deduction items from a reference value of 10; and

the deduction items include equipment status score and available capacity of standby power supply of load node; and a time required for recovery is a ratio of an estimated time required for recovery of the load node to a longest tolerable outage time.

Further, the calculating real-time output capacity of the new energy and energy storage device in the reconstructed power grid topology diagram includes the steps of:

for wind power devices among new energy sources, using a wind speed-power conversion model based on power curves and meteorological parameter correction to calculate an instantaneous available power, and introducing grid operation state constraints for real-time correction;

for PV devices in new energy, calculating a theoretical output by a light intensity, and correcting the theoretical output according to a module temperature;

for energy storage devices, calculating an actual discharge power that an energy storage system may provide in real time based on real-time state of charge (SOC), rated capacity, and maximum charge-discharge power; expressing the actual discharge power as a minimum power constraint corrected by discharge efficiency; and

taking a minimum value between a maximum allowable discharge power and an available power determined by the SOC as the minimum power constraint; taking a product of a rated capacity and a fraction as a calculation method for the available power determined by the SOC; and taking a numerator of the fraction as a current available capacity and a denominator as a discharge time window.

Further, the discharge time window is dynamically corrected by combining load forecasting and safety constraints; and the corrected discharge time window is a weighted sum of a theoretical maximum discharge time window, an energy-load ratio and a temperature safety function; and

the energy-load ratio is a ratio of an available energy and a predicted load of the energy storage device.

Further, the weighted graph includes load nodes, power generation nodes, and intermediate nodes;

a weight of the load node is expressed as a reciprocal of the recovery priority, a weight of the power generation node is expressed as a reciprocal of real-time output capacity, and a weight of the intermediate node is expressed as a reciprocal of the path cost; and

for edges between the load nodes and the power generation nodes, edge weights are corrected using comprehensive values of endpoints; and based on the node weights in the weighted graph and the corrected edge weights, a shortest path is searched for as the optimal black-start path.

Further, the correcting edge weights using comprehensive values of endpoint includes the steps of:

calculating the comprehensive values of endpoints for the edges between the load nodes and the power generation nodes as a product of a node balance item and a path cost suppression item;

taking a weighted sum of a normalized value of recovery priority and a normalized value of real-time output capacity as a node balance item;

taking 1 minus a normalized value of path cost as a path cost suppression item; and

taking a ratio of an original edge weight in the power grid topology diagram to the comprehensive values of endpoints as the corrected edge weight; and adjusting the comprehensive value of endpoints through the influence intensity during calculation.

Further, in multiple simulated black-start processes, the operating data of new energy and energy storage devices are recorded in real time, for each new energy source and energy storage device, single-item evaluation indicators are calculated, including average start time, average available start power, voltage and frequency support capability, and impact intensity coefficient; and

a comprehensive score of the black-start capability of each new energy/energy storage device is calculated under the optimal black-start path according to the single-item evaluation indicators and single-item evaluation indicator reference values.

A second aspect of the present invention provides an evaluation and system for black-start capability of grid-forming new energy and energy storage devices, and operates the black-start capability evaluation method according to the first aspect of the present invention, and the system includes:

a topology reconstruction module, configured to detect fault nodes in a power grid by adopting a two-layer fault determination method in segmented load periods based on real-time operation status of the power grid; and update a connection relationship of power grid nodes according to the fault nodes to obtain a reconstructed power grid topology diagram;

a resilience evaluation module, configured to calculate a recovery priority score of each load node in the reconstructed power grid topology, and calculate real-time output capacity of each new energy and energy storage device;

a black-start path search module, configured to convert the reconstructed power grid topology diagram into a weighted graph, and correct edge weights and node weights of the weighted graph based on recovery priority, output capacity, and path cost of intermediate nodes; and search for an optimal black-start path based on a corrected weighted graph; and

a black-start capability evaluation module, configured to deploy the black-start path in a simulation environment to perform black-start simulation; record operating data of each new energy and energy storage device in each simulation process; and evaluate black-start capability of a single new energy/energy storage device based on the operating data.

Compared with the related art, the technical solution provided in the present invention includes at least one of the following beneficial effects.

1. In the present invention, by obtaining the real-time operation status of the power grid, two-layer fault determination is performed in segmented load periods, fault nodes are identified in time, and the connection relationship of power grid nodes is updated based on the fault nodes, and a reconstructed power grid topology diagram is generated. Through this dynamic topology, the actual connectivity and operational constraints of the power grid under different fault conditions can be accurately reflected, which provides a black-start capability evaluation closer to the real operating conditions for each new energy and energy storage device.

2. In the present invention, on the basis of reconstructing the power grid topology, the load node recovery priority, the real-time output capacity of power generation nodes and the path cost of intermediate nodes are integrated to form a weighted graph. By searching for the optimal black-start path, the key loads are recovered first and the output potential of each device is fully

exerted. This path optimization not only ensures the feasibility and stability of the black-start process, but also can more accurately evaluate the start capability and power support performance of each new energy or energy storage device under actual grid conditions.

3. In the present invention, in multiple black-start simulations, the start time, available power, voltage and frequency support ability of each new energy and energy storage device and the influence intensity on the system are recorded in real time, and the black-start capability of a single new energy or energy storage device under the optimal black-start path is comprehensively scored. By incorporating the reconstructed grid topology and path optimization results into the evaluation, the end-to-end quantified black-start capability can be obtained, which provides a scientific basis for power grid operation management and operation and maintenance decision-making, and at the same time provides an operational reference for black-start solution optimization.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic flow diagram of an evaluation method for black-start capability of grid-forming new energy and energy storage devices.

DETAILED DESCRIPTION

To make the objectives, technical solutions, and advantages of the present invention more clear, the technical solutions of the present invention will be clearly and completely described below with reference to the drawings in the embodiments of the present invention. The examples described herein are only some examples of the present invention, but not all examples. Based on the spirit of the present invention, all other embodiments obtained by those of ordinary skill in the art without creative effort are within the scope of protection of the present invention.

As an example of the present invention, a specific embodiment of an evaluation method for black-start capability of grid-forming new energy and energy storage devices is provided. Referring to FIG. 1, FIG. 1 is a schematic flow diagram of the evaluation method for black-start capability of grid-forming new energy and energy storage devices.

In step 1: real-time operation status of a power grid is obtained, and a fault position and status of the power grid are determined; and power grid topology is reconstructed according to the fault area.

1.1: edge equipment is deployed at each power grid node, the operating status of the power grid equipment is monitored, and the operating data of the power grid node is collected.

The edge equipment is deployed at each power grid node to collect parameter data at a collection frequency of 1 s, including current, voltage, power, and frequency under different loads. the power grid nodes include power generation nodes (new energy and energy storage devices), intermediate nodes (substations and distribution stations), and load nodes in the power grid.

According to the voltage and current data collected in real time, it is determined whether abnormal conditions including voltage and current drop and voltage loss occur. When the voltage or current exceeds the corresponding threshold, fault detection is triggered. The threshold values of current and voltage are set as follows.

The collected historical parameter data are classified according to load periods, including low load period (less than 40% of rated power), medium load period (40%-60% of rated power), medium and high load period (60%-80% of rated power) and high load period (greater than 80% of rated power).

On the edge equipment, statistical values of node parameter data, including mean and standard deviation, are calculated in segmented load periods. For each load period, the fault detection trigger threshold th_1 of current, voltage and frequency is $\mu \pm k \cdot \sigma$, μ represents a mean value and σ represents a standard deviation; k is a set multiple, which is set according to the requirements of load period. For example, in low load periods, because the load is low and the power grid stability is strong, k can be set to 0.5; and in high load periods, the power grid load fluctuates greatly and k can be set to 2 or 3.

When the real-time data of the power grid exceeds the upper and lower limits of the fault trigger threshold th_1, fault detection is immediately triggered, which includes voltage sudden change, current sudden change and frequency abnormality.

In an optional method of the present example, for the power grid node that triggers the fault warning, an instantaneous change value of the voltage and the current is calculated, and the instantaneous change value is a difference between the current voltage/current value and the voltage/current value before one sampling interval.

$$\Delta U = U(t) - U(t - \Delta t)$$

$$\Delta I = I(t) - I(t - \Delta t)$$

where ΔU and ΔI are instantaneous change values of voltage and current, and U and I are current voltage and current values; and Δt is a sampling interval.

When the instantaneous change value exceeds the fault detection threshold th_2, it is confirmed that the power grid node has failed. A fault detection threshold $th_2 = th_1^+ + \delta$; th_1^+ is an upper limit of the fault detection trigger threshold th_1; δ is an offset amount, which is set as a product of a standard deviation of current and voltage of a corresponding load period and an offset weight; and the offset weight is a ratio of the instantaneous change values of voltage and current to the sampling interval.

In this example, th_1 is a preliminary fault detection threshold, and the setting standard is relatively loose, while responding to the sudden change of current and voltage more quickly. However, because the power grid may experience short-term fluctuations or interferences under certain circumstances (including equipment switching or power fluctuations), once the parameter value exceeds th_1, it does not mean that a real fault has occurred. To ensure that the fault detection of power grid nodes will not trigger unnecessary fault response due to short-term fluctuations or errors, an offset δ is added in this example to set the criteria for fault confirmation more stringent, thereby reducing false alarms.

After the edge equipment completes fault detection, it can be confirmed that the specific power grid node where the edge equipment is located has a fault, which also confirms the fault location of the power grid.

1.2: the power grid topology diagram is constructed and the power grid topology is reconstructed according to the node fault situation.

1.2.1: the location coordinates, equipment types, connecting lines and attributes (such as impedance, voltage level, etc.) of all nodes of the power grid are obtained according to a geographic information system (GIS).

An undirected graph structure is used for constructing the power grid topology diagram. The nodes in the diagram represent power equipment (including substations, distribution stations, new energy devices, energy storage devices and load nodes, etc.), and edges represent connecting lines. Each edge is given a weight, and influencing factors of the weight include parameters including line impedance, line capacity, line length, voltage level and recovery cost. The smaller the edge weight, the more preferential the line is.

For nodes i and j, an edge weight $w_{i,j}$ of both are expressed as:

$$w_{i,j} = \alpha_1 \cdot Z_{i,j} + \alpha_2 \cdot \frac{1}{C_{i,j}} + \alpha_3 \cdot L_{i,j} + \alpha_4 \cdot \frac{1}{V_{i,j}} + \alpha_5 \cdot Cost_{i,j}$$

where $Z_{i,j}$ is an impedance amplitude of the line, $C_{i,j}$ is the line capacity, $L_{i,j}$ is the line length, and $V_{i,j}$ is a bit voltage level, and $Cost_{i,j}$ indicates the recovery cost of the line (related to the maintenance cost and maintenance time); α_1, α_2, α_3, α_4 and α_5 are weights, and in the present example, an objective of power grid topology reconstruction is adjusted; for example, when fast recovery is a priority objective, the weight configuration of recovery cost and path length is increased, and a line with low cost and easy recovery is preferentially selected for connection.

1.2.2: for the fault node determined in step 1, its location in the topology structure is retained in the power grid topology diagram, but a fault status flag is set to indicate that the node is currently unavailable. In addition, the edge connected to the failed node is also updated and marked as disconnected; and the topology structure is updated.

In an optional step of the present example, based on the updated power grid topology diagram, the alternating current (AC) power flow calculation method is used for performing steady-state simulation to verify that the updated power grid topology can operate normally.

In step 2: the recovery priority of load nodes, the output capabilities of new energy and energy storage equipment are evaluated.

2.1: priority is assigned to different load nodes based on the recovery needs of load nodes in the power grid.

For each load node in the updated power grid topology diagram, according to its recovery urgency, power demand level, and recovery difficulty, the priority score is calculated as follows:

$$prior_k = \lambda_1 \cdot E_k + \lambda_2 \cdot L_k + \lambda_3 \cdot R_k ;$$

where $prior_k$ is a priority score of a load node k; E_k, L_k and R_k are recovery urgency, power demand level and recovery difficulty of the load node k; λ_1, λ_2 and λ_3

weight coefficients for the recovery urgency, power demand level and recovery difficulty, which can be set and adjusted according to the actual situation.

Further, the recovery urgency is assigned a score according to the load type and the importance of the service object, and an instance of this example is shown in Table 1.

Table 1 Instance of recovery urgency score

Load point	Score range	Grading description
Medical premises, fire stations, and police	10	Types of life support
Water production and treatment, communication base station, and transportation hub	8	Important public services
Large industrial parks, ports, and logistics centers	6	Industry and economic pillar industries
Residential area, supermarket, and school	4	Resident life
General commercial, and non-critical production	2	General load

The power demand level is expressed according to the maximum load power ratio of the node, and the calculation method is as follows:

$$L_k = \frac{P_{k,\max}}{P_{\max,all}} \times 10$$

where $P_{k,\max}$ is the maximum demand power of the load node k, and $P_{\max,all}$ is the maximum demand power of a single node among all load nodes.

The difficulty of recovery takes into account the time required for recovery, equipment status and standby power supply; and the calculation method is as follows:

$$R_k = 10 - \left(w_t \cdot T_{\text{norm}} + w_s \cdot S_{\text{score}} + w_b \cdot B_{\text{score}} \right)$$

where T_{norm} is a standardized score of the time required for recovery, which is a ratio of an estimated time required for recovery of the load node to the longest tolerable power outage time; S_{score} is the equipment status score, which is obtained according to the diagnosis result of the load node, and the value is [0.10]. The worse the equipment status, the higher the score.

B_{score} is an availability of standby power supply, which is quantified by the available capacity of standby power supply of the load node. If there is no available standby power supply nearby, the availability of standby power supply is 0. w_t, w_s and w_b are weight coefficients of T_{norm}, S_{score} and B_{score}. It can be set and adjusted according to the actual situation.

2.2: the real-time output capabilities of new energy and energy storage devices in the updated power grid topology are calculated.

For wind turbines, PV arrays, and energy storage systems, operating status and environmental condition data are collected and preprocessed in real time. Partial instances of collected data are given in Table 2.

Table 2 Partial instances of collected data

Device	Operating state data	Environmental condition data
Wind turbine	Unit speed, and current output power	Wind speed and direction
PV array	Current output power and rated power	Light intensity and module temperature
Energy storage system	SOC, battery temperature, and charge and discharge power	/

The maximum available output capacity of each wind power and PV node is calculated by combining physical models with empirical models. Specifically:

2.2. 1: for wind power, an instantaneous available power is calculated by wind speed-power conversion model based on power curve and meteorological parameter correction, and dynamic constraints are introduced for real-time correction. Represented as:

$$P_{\text{avail}} = f_{pc}\left(V_{\text{wind}}\right) \times C_{\rho} \times C_{\theta} \times C_{dyn}$$

where P_{avail} is an instantaneous available power of real-time wind power, which represents the maximum active power that the wind turbine can output under current meteorological conditions; $f_{pc}\left(V_{\text{wind}}\right)$ is a wind turbine power curve function, provided by the wind turbine manufacturer, and a function output is a rated power ratio at a wind speed V_{wind}; C_ρ is an air density correction factor, $C_\rho = \rho/\rho_0$, ρ and ρ_0 are current air density and standard air density; C_θ is a wind direction deviation correction coefficient, $C_\theta = \cos(\theta_{dev})$, and θ_{dev} is an included angle between the current wind direction and the main axis direction of the fan.

C_{dyn} is a dynamic constraint correction coefficient, which is the minimum constraint included by multiple power grid operating state sub-constraints; and the dynamic constraint correction coefficient is expressed as:

$$C_{\mathrm{dyn}} = \min\left\{C_V, C_L, C_f, C_{\mathrm{iso}}, C_S\right\}$$

where C_V, C_L, C_f, C_{iso} and C_s are voltage constraints, line capacity constraints, frequency stability constraints, fault isolation constraints, and energy storage collaboration constraints.

It is to be noted that according to the actual situation of the power grid, the selection of sub-constraints can be adaptively adjusted.

2.2. 2: for PV, the theoretical output is calculated according to $P_{pv} = G \cdot \eta \cdot A$, and corrected by module temperature. where G is a real-time light intensity (unit W/m^2), η is an efficiency of PV modules, and A is a total area of the PV modules; and the theoretical output is corrected according to the module temperature as follows:

$$P_{pv}^{*} = P_{pv} \cdot [1 + \gamma(T_{ref} - T)]$$

where P_{pv}^{*} is a corrected PV output, γ is a temperature coefficient, and T_{ref} and T are a reference temperature and a current actual module temperature.

2.2. 3: for the energy storage system, the actual discharge power that the energy storage system can provide in real time is calculated according to the real-time SOC, rated capacity and maximum charge and discharge power, and represented as:

$$P_{\mathrm{output}} = \min\left(P_{\max}, \frac{\mathrm{SOC} - \mathrm{SOC}_{\min}}{t_{\mathrm{discharge}}} \times \mathrm{Capacity}\right) \times \eta$$

where P_{output} is a real-time actual discharge power, and $P_{\max}$ is a rated maximum discharge power of the energy storage system; SOC and $\mathrm{SOC}_{\min}$ are SOC and the minimum allowable SOC threshold; and $t_{\mathrm{discharge}}$ is a discharge time window, and $\mathrm{Capacity}$ and η are capacity and discharge efficiency of the energy storage device.

For the discharge time window, the traditional method is to use the manufacturer's rated value or a preset fixed duration. However, in the black-start phase of the power grid outage, the energy storage system faces challenges including large load fluctuations, complex operating environments, and variable equipment states. A fixed discharge time window may be difficult to meet the demand for continuous power supply when load demand surges or energy storage status declines. Therefore, in the present example, the energy storage state, load demand and power grid state are dynamically adjusted to avoid resource waste or power shortage caused by the fixed time window. The specific steps are as follows.

At the time of power recovery, a real-time SOC, state of health (SOH), a battery temperature T_{bat} and an ambient temperature T_{env} of the energy storage device are obtained.

Historical load and environmental parameters are used, and a time series model is applied to predict the load demand at the moment of power recovery; and a power recovery time is assumed to be t, the load demand $P_{load}(t)$ at this moment is based on the historical load data of previous k moments for prediction; and the process is expressed as:

$$P_{load}(t) = LSTM(\{P_{load}(t-k),\ldots,P_{load}(t-1),\},T_{env}(t))$$

where $LSTM()$ is a time series prediction model selected for this example.

In an optional method of the present example, the time series prediction model may select gated recurrent units (GRUs) or other neural network prediction methods.

The lowest safety SOC threshold is set as $SOC_{\min} \le SOC(t)$, and $SOC_{\min}$ is the lower safety limit of SOC. The temperature safety threshold value is $T_{bat}^{\min} \le T_{bat}(t) \le T_{bat}^{\max}$, and $T_{bat}^{\min}$ and $T_{bat}^{\max}$ are a lower temperature safety limit and an upper temperature safety limit, which are set according to the battery material.

The maximum discharge power of the energy storage device is assumed to be $P_{ESS}^{\max}$, the possible consumption is $E_{avail}(t)$, and the theoretical maximum discharge time window is

$T_{\text{window}}^{\text{theory}}(t)=\frac{E_{avail}(t)}{P_{ESS}^{\max}}$; where $E_{\text{avail}}(t)=\left(SOC(t)-SOC_{\min}\right)\times E_{\text{rated}}\times\eta$, and E_{rated} is a rated capacity of the energy storage device.

Combining load forecasting and safety constraints, weighted fusion is used for dynamically correcting the discharge time window; and represented as:

$$t_{\text{discharge}}^{*}(t)=\alpha\cdot T_{\text{window}}^{\text{theory}}(t)+\beta\cdot\frac{E_{\text{avail}}(t)}{P_{\text{load}}(t)}+\gamma\cdot f(T_{\text{bat}}(t))$$

where $t_{\text{discharge}}^{*}(t)$ is the corrected discharge time window, $f(T_{\text{bat}}(t)$ is a temperature safety function, and the discharge time is reduced when the temperature is close to the threshold; and α, β and γ are weight coefficients, $\alpha+\beta+\gamma=1$ is satisfied, and are adjusted according to the phased requirements of the black-start stage. For example, if the load power fluctuates violently at an initial stage of black-start, it is necessary to increase the value of β.

In step 3, according to the recovery priority of load nodes and the real-time output capabilities of new energy and energy storage devices, the power grid topology diagram is transformed into a weighted graph, and the edges and nodes in the weighted diagram are corrected.

3.1: in the weighted graph, nodes include load nodes P^{load}, power generation nodes P^{C} (new energy and energy storage) and intermediate nodes P^{u} (substations, distribution stations);

For the load node, it is assigned a weight $\omega_{P^{load}}$ according to the recovery priority $prior$, and expressed as $\omega_{P^{load}}=1/(prior+\varepsilon)$; and ε is a tiny constant to prevent zero.

For the power generation node, it is assigned a weight $\omega_{P^{C}}$ according to the real-time output capability C, and expressed as $\omega_{P^{C}}=1/[C(P)+\varepsilon]$; and $C(P)$ include the corrected instantaneous available power of wind power, the corrected PV output, and the actual discharge power that the energy storage system can provide.

For the intermediate nodes, it is assigned a weight $\omega_{P^{u}}$ according to the path cost $C(u)$, and expressed as $\omega_{p^u} = \frac{1}{C(u)+\varepsilon}$; where the path cost $C(u)$ is a comprehensive calculation value of the main transformer input cost, time cost, voltage overrun cost and power shortage cost of the intermediate node.

3.2: the edges in the weighted graph are consistent with those in the power grid topology graph; and the node weight correction is introduced into the edge weight of power grid topology diagram. The specific embodiment is as follows.

The recovery priority of load nodes, the real-time output capacity of power generation nodes and the path cost of intermediate nodes are normalized to [0, 1]; and the comprehensive value of the endpoint is calculated by the modification function, which is expressed as:

$\phi_{p,q} = [\xi \cdot \overline{prior_p} + (1-\xi) \cdot \overline{C(P)_q}] \cdot [1 - \overline{C(u)}],\quad \phi_{p,q} \in [0,1]$; where $\phi_{p,q}$ is the comprehensive value of the endpoint between the load node p and the power generation node q, $\overline{prior_p}$ is a normalized value of the recovery priority of the load node p, $\overline{C(P)_q}$ is a normalized value of the real-time output capacity of the power generation node q, and ξ is an adjustment factor for balancing the "supply capacity" and the "load value".

The edge weight representation of the weighted graph is corrected as $w_{p,q} = \frac{w_{p,q}^{\text{base}}}{1+\kappa \cdot \phi_{p,q}}$; where $w_{p,q}$ is a corrected edge weight between the load node p and the power generation node q; $w_{p,q}^{\text{base}}$ is an original edge weight in the power grid topology diagram of load node p and power generation node q; and κ is an influence intensity, and $\kappa \geq 0$ is used formeasuring the sensitivity of node characteristics to edge weight correction.

3.3: according to the node weight and the corrected edge weight in the weighted graph, the path with the lowest recovery cost is searched as the optimal black-start path through the shortest path search algorithm.

In an optional method of this step, a shortest path search algorithm such as Dijkstra shortest path algorithm can be selected to solve the optimal black-start path according to the weighted graph.

In the power grid topology diagram under conventional power recovery, the influencing factors of edge weight include line impedance, line capacity, line length, voltage level and recovery cost. However, in the black-start scenario of distribution network, path selection depends not only on the line conditions, but also on the value of path endpoints (i.e. load nodes and power generation nodes). For example, high-priority loads are worth recovering as soon as possible, and nodes with greater available power can drive more load recovery.

In this example, node weight correction is introduced into the edge weight definition of the weighted graph, high-value nodes can reduce the path search cost, and paths leading to high-priority loads or large-output power supplies can be given more priority in search, that is, black-start recovery "cost performance" is pursued.

In step 4, according to the optimal black-start path, the black-start strategy is executed in the simulation environment, and the black-start capability of the new energy and energy storage device is evaluated according to the recovery evaluation.

In an embodiment of this step, the start-stop sequence of the new energy (wind power, PV) and the energy storage device is determined according to the optimal black-start path. The power threshold and start conditions required for each equipment to start are clarified to ensure that the start process meets the safety and stability requirements of the power system.

In an embodiment of this step, multiple simulations are performed, a start-stop instruction is sent through the control system, the output power of each equipment is adjusted, and the power grid load is gradually restored until stability is achieved. In the black-start process, the start time, climbing process, and synchronization characteristics of new energy and energy storage devices are monitored in real time.

4.1: in multiple simulated black-start processes, the edge equipment is used forrecording in real time the operating data of each new energy and energy storage device, including but not limited to the actual output power curve, voltage deviation, frequency deviation, power margin, and start success status (i.e., whether it is successfully connected to the power grid).

After multiple simulations, for each new energy and energy storage device, a single evaluation index is calculated, including average start time, average available start power, voltage and frequency support capacity, and influence intensity coefficient.

Further, the average start time is $\overline{T_s} = \frac{1}{N_{sim}} \sum_{n=1}^{N_{sim}} T_{sim}^{(n)}$; $T_{sim}^{(n)}$ is a start time of a

n -th simulation, and $T_{sim}^{(n)} = t_{start} - t_{stable}$; and t_{start} represents a time point when the new energy or energy storage device receives the start command, and t_{stable} represents a time point when the output power reaches a stable grid connection level; and N_{sim} is the number of simulations.

Further, the average available starting power is $\overline{P_{\text{avg}}} = \frac{1}{N_{\text{sim}}} \sum_{n=1}^{N_{\text{sim}}} P_{\text{avg}}^{(n)}$; and $P_{\text{avg}}^{(n)}$ is the available starting power for the n -th simulation,

$$P_{\text{avg}}^{(n)} = \frac{1}{t_{\text{stable}}(n) - t_{\text{start}}(n)} \int_{t_{\text{start}(n)}}^{t_{\text{stable}}(n)} P(t)\, dt$$

.

Further, the voltage and frequency support capabilities are $S_{VF} = w_V \cdot S_V + w_f \cdot S_f$; where S_V is the voltage support capacity, $S_V = 1 / \overline{\Delta V_{\max}}$, and $\overline{\Delta V_{\max}}$ is an average value after summing the maximum deviation of all single simulation voltages; S_f is the frequency support capacity, $S_f = 1 / \overline{\Delta f_{\max}}$, and $\overline{\Delta f_{\max}}$ is an average value after summing the maximum deviation of all single simulation frequencies; and w_V and w_f are weight coefficients corresponding to the voltage support capability and the frequency support capability, and $w_V + w_f = 1$ is satisfied.

Further, an influence intensity coefficient is $\overline{k_q} = \frac{1}{N_{\text{sim}}} \sum_{n=1}^{N_{\text{sim}}} k_q^{(n)}$, that is, an average value of the influence intensity coefficient of the power generation node q in multiple simulations; and the influence intensity coefficient of the n -th simulation is $k_q^{(n)} = \Delta P_q^{(n)} / \Delta P_{other}^{(n)}$;

where $\Delta P_q^{(n)}$ is a power change amount during black-start, and $\Delta P_q^{(n)} = P_{stable}^{(q,n)} - P_{start}^{(q,n)}$; $P_{stable}^{(q,n)}$ is a power when the node q accepts the start instruction in the n -th simulation, and $P_{start}^{(q,n)}$ is a stable output power of the node q in the

n-th simulation; and $\Delta P_{other}^{(n)}$ is a sum of power changes of other new energy/energy storage nodes except nodes q in the best recovery path.

In an optional method of this step, the average start success rate of the new energy/energy storage node in all simulation times, that is, a ratio of the number of successful grid connections of the node to a total simulation coefficient, can also be counted.

4.2: According to the single evaluation index obtained in step 4.1, the comprehensive score of black-start capability of each new energy/energy storage device is calculated, which is expressed as:

$$B_q = \lambda_{\overline{T_S}} \cdot \left(1 - \frac{\overline{T_S}}{T_{\text{ref}}}\right) + \lambda_{\overline{P_{avg}}} \cdot \left(\frac{\overline{P_{avg}}}{P_{\text{ref}}}\right) + \lambda_{S_{VF}} \cdot \left(\frac{S_{S_{VF}}}{S_{\text{ref}}}\right) + \lambda_{\overline{k_q}} \cdot \left(1 - \frac{\overline{k_q}}{k_{\text{ref}}}\right)$$

where B_q is a comprehensive score of the black start capability of the node q; T_{ref}, P_{ref}, S_{ref} and k_{ref} are reference values of individual indexes, and are designed according to the system objectives; and $\lambda_{\overline{T_S}}$, $\lambda_{\overline{P_{avg}}}$, $\lambda_{S_{VF}}$ and $\lambda_{\overline{k_q}}$ are weight coefficients of each term in the formula, $\lambda_{\overline{T_S}} + \lambda_{\overline{P_{avg}}} + \lambda_{S_{VF}} + \lambda_{\overline{k_q}} = 1$ is satisfied.

4.3: according to the comprehensive score of the black-start capability of each new energy/energy storage device, a grade is assigned to each new energy/energy storage device. Table 3 shows instances of grading according to the threshold.

Table 3 Instances of grading

Grade	Comprehensive score	Description
A	$B_q \geq 0.8$	High black-start capability, as main start equipment
B	$0.6 \leq B_q < 0.8$	Black-start capability is at a medium level, with assisted start
C	$B_q < 0.6$	Low black-start capability, only available as backup equipment

In an optional example of the present invention, the comprehensive scoring grade provides quantitative black-start capability evaluation for each new energy/energy storage device, which can quickly identify high-capability and low-impact key equipment as starting or main nodes in the next black-start path selection, and at the same time assist in determining auxiliary positions of middle-grade equipment, avoiding low-grade bottleneck equipment from undertaking critical tasks, thereby optimizing path sequence, improving overall reliability, narrowing search space, and speeding up path planning decisions.

In the present invention, the optimal black-start path is searched according to the topology change of the power grid when the power grid fails and the demand difference of load nodes. The optimal black-start path can verify the start capability index of each new energy or energy storage device under actual system coordination conditions. It not only examines the average start time, maximum available start power, and voltage and frequency support capabilities of the equipment itself, but also reveals the interaction and power coupling effects between devices, and identify potential bottlenecks and key nodes in the path, thereby making the black-start capability evaluation more comprehensive, reliable, and close to actual operation. At the same time, the evaluation results can provide a scientific basis for equipment classification, start sequence optimization, auxiliary energy storage configuration and system-level black-start strategies, and provide reference for formulating high-reliability black-start solutions and improving the rapid recovery capabilities of microgrids or regional power grids.

As an example of the present invention, an evaluation system for black-start capability of grid-forming new energy and energy storage devices is provided, and implements the specific embodiment of the example of the evaluation method for black-start capability. The system includes:

a topology reconstruction module, configured to detect fault nodes in a power grid by adopting a two-layer fault determination method in segmented load periods based on real-time operation status of the power grid; and update a connection relationship of power grid nodes according to the fault nodes to obtain a reconstructed power grid topology diagram;

a resilience evaluation module, configured to calculate a recovery priority score of each load node in the reconstructed power grid topology, and calculate real-time output capacity of each new energy and energy storage device;

a black-start path search module, configured to convert the reconstructed power grid topology diagram into a weighted graph, and correct edge weights and node weights of the weighted graph based on recovery priority, output capacity, and path cost of intermediate nodes; and search for an optimal black-start path based on a corrected weighted graph; and

a black-start capability evaluation module, configured to deploy the black-start path in a simulation environment to perform black-start simulation; record operating data of each new energy and energy storage device in each simulation process; and evaluate black-start capability of a single new energy/energy storage device based on the operating data.

Finally, it is to be noted that the above examples are only used for illustrating the technical solutions of the present invention, rather than limiting the present invention. Although the present invention has been described in detail with reference to the examples, those ordinary skilled in the art will understand that modifications or equivalent substitutions can still be made to the specific embodiments of the present invention, and any modifications or equivalent substitutions that do not depart from the spirit and scope of the present invention are to be covered within the scope of the claims of the present invention.