SPECIFICATION

DYNAMIC FREQUENCY REGULATION CONTROL SYSTEM AND METHOD FOR DISTRIBUTED PHOTOVOLTAIC EDGE INTELLIGENT CONTROLLER

Technical Field

The invention belongs to the technical field of distributed photovoltaic control, and particularly relates to a dynamic frequency regulation control system and method for a distributed photovoltaic edge intelligent controller.

Background Art

A dynamic frequency regulation control system for a distributed photovoltaic edge intelligent controller is based on the principle of distributed consensus control, achieving stable regulation of power grid frequency under photovoltaic output fluctuations through intelligent algorithms at the edge side, it is widely used in microgrid scenarios with high penetration of renewable energy. However, existing dynamic frequency regulation control systems have two core problems: firstly, insufficient coordination in the control architecture, where centralized architectures are prone to single-point failures and excessive computational burden, and decentralized architectures lack effective coordination mechanisms leading to conflicting adjustments among photovoltaic units, making them difficult to adapt to the distributed layout characteristics of photovoltaic units; secondly, weak adaptive capability of the controllers, where traditional PID or fixed-parameter FOPID controllers cannot dynamically adapt to nonlinear operating conditions such as photovoltaic output fluctuations and load mutations, and intelligent controllers often suffer from blind parameter initialization and slow convergence speed, resulting in lagging frequency regulation response, large overshoot, and significant steady-state error.

Summary of the Invention

In view of the hereinabove situation, and to overcome the deficiencies of the prior art, the invention provides a dynamic frequency regulation control system for a distributed photovoltaic edge intelligent controller. To address the problem of insufficient coordination in existing systems, this solution constructs a "leader-follower" distributed consensus architecture, each edge intelligent controller makes independent decisions and exchanges information in real time through a low-latency communication network, eliminating the need for a central control node, this not only avoids the single-point failure risk of centralized architectures but also solves the lack of coordination in decentralized architectures, thereby enhancing system scalability and fault tolerance; to tackle the problem of weak adaptive capability of the controller, this solution integrates fuzzy logic and a recurrent neural network (FRNN) to design a self-adaptive tuning fractional-order PID (FOPID) controller. Control parameters are precisely initialized through a fuzzy rule base, and then an RNN optimizes the parameters in real time based on a Lyapunov energy function, adapting to photovoltaic output fluctuations and complex disturbances, simultaneously, frequency regulation is coordinated with an energy storage execution module to further improve frequency stability.

The technical solution adopted by the invention is as follows: the dynamic frequency regulation control system for a distributed photovoltaic edge intelligent controller provided by the invention comprises a distributed photovoltaic unit, an edge intelligent controller cluster, a communication network, an energy storage execution module, and a monitoring center;

the distributed photovoltaic unit is configured to convert solar energy into electrical energy, output the electrical energy to a power grid, and provide energy support for frequency regulation;

the edge intelligent controller cluster is a core control unit. Each distributed photovoltaic unit is correspondingly configured with an edge intelligent controller. Each edge intelligent controller integrates an FRNN-FOPID control module, a local data acquisition module, and a communication module, implementing local data processing and real-time control decisions;

the communication network is configured for information interaction among the edge intelligent controllers, supporting a distributed consensus collaborative mechanism;

the energy storage execution module is connected in parallel with the distributed photovoltaic unit, receiving instructions from the edge intelligent controller, and suppressing photovoltaic output fluctuations through charging and discharging to assist frequency regulation;

the monitoring center is configured to monitor the system operating status in real time and store operating data, without participating in real-time control.

Furthermore, the FRNN-FOPID control module specifically comprises:

a fuzzy logic initialization unit: having a built-in fuzzy rule base, inputting power grid frequency deviation (Δf) and deviation change rate (Δf'), and generating initial proportional gain (Kp), integral gain (Ki), derivative gain (Kd), and fractional-order parameters (λ, μ) for the FOPID controller by mapping using trapezoidal membership functions;

an RNN dynamic optimization unit: constructing an optimization model based on a Lyapunov energy function, employing a stochastic gradient descent (SGD) algorithm to update FOPID control parameters in real time, balancing convergence speed and stability;

an FOPID execution unit: generating an active power regulation instruction based on the optimized parameters and outputting the instruction to the distributed photovoltaic unit and the energy storage execution module.

Furthermore, the local data acquisition module specifically comprises:

a data acquisition unit: acquiring output data of the distributed photovoltaic unit, power grid frequency deviation (Δf), and deviation change rate (Δf') in real time, with a sampling frequency of 100 Hz;

a data preprocessing unit: performing filtering and noise reduction processing on the acquired data and eliminating outliers to ensure data accuracy.

Furthermore, the communication network specifically comprises:

a transmission unit: employing industrial ethernet or a wireless local area network (WLAN), with a transmission delay of ≤50 ms;

a consensus coordination unit: implementing control instruction calibration among edge intelligent controllers based on a "leader-follower" mechanism, supporting a "plug-and-play" function, allowing newly added photovoltaic units to automatically join.

Furthermore, the energy storage execution module specifically comprises:

a battery energy storage system: employing a lithium battery pack, with a rated power between 20% and 30% of the rated power of a corresponding distributed photovoltaic unit;

a bidirectional converter: implementing bidirectional conversion between direct current and alternating current, with a charging and discharging response time of ≤10 ms, configured to receive and execute charging and discharging instructions from the edge intelligent controller.

The beneficial effects achieved by the invention using the aforementioned solution are as follows:

(1) to address the problem of insufficient coordination in existing systems, this solution constructs a "leader-follower" distributed consensus architecture, each edge intelligent controller makes independent decisions and exchanges information in real time, eliminating the need for a central control node; this not only avoids the single-point failure and computational burden of centralized architectures but also solves the lack of coordination in decentralized architectures. System scalability is improved, supporting flexible access of 100+ photovoltaic units.

(2) to address the problem of weak adaptive capability of the controller, this solution employs a two-stage parameter adjustment mechanism of "fuzzy initialization + RNN dynamic optimization", the fuzzy rule base ensures initial parameters precisely adapt to operating conditions, and the RNN optimizes parameters in real time based on a Lyapunov energy function; compared with traditional PID controllers, the frequency regulation settling time is shortened by over 29%, overshoot is reduced, and absolute error is decreased, significantly improving frequency regulation accuracy and dynamic response speed.

(3) through coordinated frequency regulation between the energy storage execution module and the distributed photovoltaic unit, combined with the low-latency transmission of the communication network and the consensus coordination mechanism, the system can maintain stable performance under complex operating conditions such as ±20% parameter fluctuations, load mutations, and short-circuit faults. Verified by hardware-in-the-loop (HIL) testing, the system possesses strong robustness and engineering practicality.

Brief Description of the Drawings

The drawings are provided to further understand the solution and constitute a part of the specification, together with the embodiments of the invention, they are used to explain the invention and do not constitute limitations to the invention.

Fig. 1 is an overall flowchart of a dynamic frequency regulation control system for a distributed photovoltaic edge intelligent controller according to the invention.

Fig. 2 is a core workflow diagram of an FRNN-FOPID control module according to the invention.

Specific Embodiment of the invention

The technical solutions in the embodiments of the invention will be described clearly and completely hereinafter with reference to the accompanying drawings in the embodiments of the invention, obviously, the described embodiments are only a part of the embodiments of the invention, not all of them; based on the embodiments of the invention, all other embodiments obtained by a person of ordinary skill in the art without creative effort shall fall within the protection scope of the invention.

Embodiment 1: referring to Figs. 1-2, the dynamic frequency regulation control system for a distributed photovoltaic edge intelligent controller provided by the invention comprises a distributed photovoltaic unit, an edge intelligent controller cluster, a communication network, an energy storage execution module, and a monitoring center;

the distributed photovoltaic unit comprises a plurality of photovoltaic inverters, each photovoltaic inverter having a rated power of 600 kW, configured to convert solar energy into electrical energy and output the electrical energy to a power grid;

each photovoltaic inverter in the edge intelligent controller cluster is correspondingly configured with an edge intelligent controller, employing an ARM Cortex-A9 processor with an operating frequency of ≥1 GHz, and integrating an FRNN-FOPID control module, a local data acquisition module, and a communication module;

the communication network employs industrial ethernet, with a transmission delay of ≤30 ms, supporting a "leader-follower" consensus coordination mechanism;

the energy storage execution module comprises a battery energy storage system (rated power 120 kW) and a bidirectional converter, connected in parallel with the photovoltaic inverters to access the power grid;

the monitoring center employs an industrial computer, communicating with each edge intelligent controller via ethernet, monitoring and storing operating data in real time.

Embodiment 2: this embodiment is based on the aforementioned embodiment, the local data acquisition module is the foundation for ensuring the accuracy of frequency regulation control, requiring real-time and accurate acquisition of power grid frequency and photovoltaic output data, specific operations comprise:

data acquisition unit: employing high-precision frequency sensors and power sensors to acquire power grid frequency deviation (Δf), deviation change rate (Δf'), and photovoltaic inverter output data in real time, the sampling frequency is set to 100 Hz to ensure capturing rapidly changing operating conditions;

data preprocessing unit: employing a mean filtering algorithm to perform noise reduction processing on the acquired data and eliminating outliers caused by sensor interference, the analysis frequency of the processed data is once every 10 ms, providing reliable data support for control decisions.

Embodiment 3: this embodiment is based on the aforementioned embodiment, the FRNN-FOPID control module is the core for achieving adaptive frequency regulation, by combining fuzzy initialization and RNN dynamic optimization, it solves the problem of poor parameter adaptability of traditional controllers, specific operations comprise:

fuzzy logic initialization unit: having a built-in set of 25 fuzzy control rules, input variables Δf and Δf' are both divided into five fuzzy subsets: "negative medium (NM)", "negative low (NL)", "zero (Z)", "positive large (PL)", and "positive medium (PM)", mapping is performed using trapezoidal membership functions; for example, when Δf=NM and Δf'=NM, initial control parameters of PM level are output, ensuring initial parameters adapt to different operating conditions;

RNN dynamic optimization unit: constructing an optimization objective based on a Lyapunov energy function, with minimizing frequency regulation error as the core, employing a stochastic gradient descent (SGD) algorithm to update network weights, the learning rate is set to 0.03, and parameter optimization is completed once every 10 ms, balancing convergence speed and stability;

FOPID execution unit: generating an active power regulation instruction based on the optimized parameters Kp, Ki, Kd, λ, and μ, the instruction output resolution is 0.01 kW, ensuring regulation accuracy.

Embodiment 4: this embodiment is based on the aforementioned embodiment, the communication network and the distributed consensus coordination mechanism are key to achieving multi-unit coordinated frequency regulation, specific operations comprise:

transmission unit: employing industrial ethernet for data transmission, using the TCP/IP communication protocol, setting the transmission port to 8080, ensuring data transmission stability and low latency (≤30 ms);

consensus coordination unit: selecting the edge intelligent controller of photovoltaic unit 1 as the leader, and the others as followers, the leader controller collects local control instructions from each follower, calibrates instruction deviations based on a consensus algorithm, and then feeds back to each follower, ensuring coordinated adjustment actions of all edge intelligent controllers; supporting a "plug-and-play" function, when a new photovoltaic unit is added, communication pairing and role assignment are automatically completed without the need to reconstruct the control network.

By executing the above operations, to address the problem of insufficient coordination in existing systems, this solution constructs a "leader-follower" distributed consensus architecture, each edge intelligent controller makes independent decisions and exchanges information in real time, not only avoiding the single-point failure and computational burden of centralized architectures but also solving the lack of coordination in decentralized architectures, system scalability is significantly improved.

Embodiment 5: this embodiment is based on the aforementioned embodiment, the energy storage execution module is used to suppress photovoltaic output fluctuations and assist the distributed photovoltaic unit in completing frequency regulation. Specific operations comprise:

battery energy storage system: employing a lithium iron phosphate battery pack, with a rated voltage of 380 V and a capacity of 200 Ah, supporting deep charge-discharge cycles, with a service life of ≥3000 cycles;

bidirectional converter: employing a two-level topology structure, with a switching frequency of 10 kHz and a charging/discharging response time of ≤8 ms, it receives charging and discharging instructions from the edge intelligent controller, it charges when photovoltaic output is excessive, and discharges when photovoltaic output is insufficient or when increased frequency regulation power is needed, thereby suppressing output fluctuations.

Embodiment 6: this embodiment is based on the aforementioned embodiment, the overall workflow of the system is as follows:

after system startup, the local data acquisition module begins to acquire power grid frequency deviation (Δf), deviation change rate (Δf’), and photovoltaic inverter output data in real time, after preprocessing, the data is transmitted to the FRNN-FOPID control module;

the fuzzy logic initialization unit generates initial parameters for the FOPID controller based on the acquired Δf and Δf' through the fuzzy rule base, ensuring initial control stability;

the RNN dynamic optimization unit takes frequency regulation error as the objective, updates FOPID parameters in real time via the SGD algorithm, completing one optimization every 10 ms;

each edge intelligent controller exchanges control instructions through the communication network, the leader controller calibrates instruction deviations to ensure coordinated actions;

the FOPID execution unit outputs control instructions, adjusting the active power output of the photovoltaic inverter, and simultaneously controlling the charging and discharging of the energy storage execution module to suppress photovoltaic output fluctuations and quickly respond to power grid frequency deviations;

when disturbances such as load mutations or short-circuit faults occur, the RNN dynamic optimization unit rapidly adjusts parameters to suppress frequency deviations and ensure system stability;

the monitoring center stores operating data in real time for later analysis and does not participate in real-time control.

Regarding parameter adjustment:

Step 1: parameter adjustment for fuzzy rule initialization (highest priority)

targeted parameter tuning:

if initial frequency regulation overshoot is large: reduce the output gain corresponding to the "positive large (PL)" level in the fuzzy rule base, with each adjustment amplitude of 10%;

if initial response is lagging: increase the output gain corresponding to the "negative medium (NM)" and "positive medium (PM)" levels, with each adjustment amplitude of 8%;

verification: continue until initial frequency regulation shows no significant overshoot and response is timely, then fix the fuzzy rule parameters;

Step 2: parameter adjustment for RNN optimization (second priority) targeted parameter tuning:

if parameter convergence is slow: increase the learning rate of the SGD algorithm (by +0.01 each time, upper limit 0.05);

if parameters oscillate: decrease the learning rate (by -0.005 each time, lower limit 0.01);

verification: continue until parameters converge to stable values within 50 ms with no significant oscillation;

Step 3: parameter adjustment for communication and energy storage (third priority)

targeted parameter tuning:

if coordinated instruction delay is large: check industrial ethernet connections, optimize routing configuration to ensure transmission delay ≤50 ms;

if energy storage suppression effect is poor: adjust the energy storage charging/discharging power threshold (by ±5% each time) to adapt to photovoltaic output fluctuation characteristics;

verification: continue until the system controls frequency deviation within ±0.001 p.u. under operating conditions with photovoltaic output fluctuations of ±20%.

By executing the hereinabove operations, to address the problem of weak adaptive capability of the controller, this solution employs a two-stage parameter adjustment mechanism of "fuzzy initialization + RNN dynamic optimization", combined with the energy storage execution module and distributed consensus coordination; this significantly improves frequency regulation accuracy, dynamic response speed, and system robustness, verified by hardware-in-the-loop (HIL) testing, the settling time can reach 4.19 s, overshoot is 0.0007 p.u., absolute error is 1.017×10^{-5}, and all performance indicators are superior to those of traditional controllers.