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Research on droop control strategy for interconnection ports of two-level energy routers

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In the context of the "dual carbon" goal, energy routers are increasingly widely used. To address the challenge of controlling multi-level energy routers across various operating states, this paper proposes a bidirectional droop control strategy for their interconnection ports. The control system uses the DC bus voltages on both sides of the interconnection port to assess the electricity demand of the upper and lower-level energy routers. It then derives the required magnitude and direction for both the transmission power and the loss power. The control architecture includes two droop links: the upper level DC voltage active power and the lower level DC voltage active power, and the difference between their outputs is used as the power reference value for the interconnection port. This dual variable droop control can more accurately coordinate the energy transfer between upper and lower level energy routers, achieving full utilization of electrical energy. A simulation model was built using Matlab/Simulink and compared with the power transmission of a two-stage energy router without interconnection ports to verify the correctness and rationality of the control method.

KEYWORDS
bus voltage, droop contro, energy router, interconnection port, power distribution

1 Introduction

Under the background of the "dual carbon" goals (Jiang and Raza, 2023), with the continuous increase of DC loads such as new energy vehicles, AC/DC hybrid micro-grids have developed rapidly, and the energy routers designed based on this are also constantly evolving. The energy router topology consists of six ports: energy storage DC port, distributed photovoltaic port (Yang et al., 2025), AC grid-connected port, interconnection port, AC load port and DC load port (Deng et al., 2023; Zhang et al., 2025). The numbers and types of ports can be increased or decreased as needed based on the actual situation. DC power and AC power can supply both AC and DC loads simultaneously, enhancing distribution flexibility and making full use of energy. Due to the complex operation mode of energy routers (Liu et al., 2019), they are quite different from traditional power systems in terms of control and simulation modeling, among which, in order to facilitate the full utilization of energy in energy routers, multiple levels of energy routers are usually connected in series to achieve the transmission of active power between different energy routers, The ports that connect two levels of energy routers for energy conversion are called interconnect ports. The interconnect port needs to balance the bidirectional flow of power between the two levels of energy routers and coordinate the energy transfer between the two levels. For the energy routers on both sides of the interconnect port, the interconnect port has to present both power and load characteristics simultaneously at every moment. The effective control of the interconnect ports directly affects the stable operation of the two-level energy router and the coordinated distribution of DC power.

Interconnect port control methods (Li et al., 2025) include constant voltage control (Gao et al., 2025), droop control, and control of current flow, among others. Constant voltage control strategies are simple and easy to implement, but they make the power size and direction of the interconnect ports uncontrollable, which can easily cause damage to the devices in the energy router. Controlling the flow of current through interconnected ports requires regular operations and is rather complex. The bivariate voltage control strategy, based on the two-stage energy router's DC bus, enables rational load distribution between both stages while maintaining operational simplicity. As the physical core and intelligent hub of the power supply system, the multi-energy router undertakes multiple functions (Yue and Cai, 2020) such as multi-energy conversion, power distribution, and energy management. Therefore, the rational power distribution of multi-energy routers has become a prerequisite for the safe and reliable operation of emerging systems.

At present, domestic scholars have conducted in depth research in this field. References (Jiayi et al., 2014) propose a segmented sagging control strategy for AC/DC bidirectional converters applicable to AC/DC hybrid micro-grids, reducing the frequent actions of the converters. Reference (Eghtedarpour and Farjah, 2014) presents a bidirectional droop control method for interface converters, but the control process is cumbersome and does not consider the DC bus voltage drop caused by droop control, reducing the reliability of its control strategy. The research subjects of the above-mentioned studies were mostly single routers, and the power transmission when multiple routers were connected was not taken into account, as well as the economic application and the transmission of loads between the upper and lower levels.

This paper first constructs the basic topology of the energy router and connects the two-level energy routers through interconnect ports. While considering the control strategy of the interconnect ports for the rational flow of interconnect port power, and taking into account the economy in practical applications, the optimal path of energy was explored with the goal of educing network loss. A corresponding simulation model was built to verify the rational allocation of power at the interconnect ports of the two-level energy router under different operating conditions.

The bidirectional sag control strategy proposed in this paper is not only applicable to general AC/DC hybrid microgrids, but can also be extended to other power supply systems with the requirement of coordinated operation of multi-level energy routers, such as railway traction power supply systems. In such systems, the station routers, traction substation routers and line routers can achieve dynamic mutual assistance of power and voltage support through interconnection ports, thereby enhancing the economic efficiency and reliability of the overall system operation.

2 Basic topology structure of the energy router

A power router is a Power conversion system (PCS) composed of multiple levels of converter modules. In combination with the application scenarios and corresponding working conditions of multi-port power routers in real production and life, the following basic functions need to be achieved: flexibly and effectively connect different distributed generation devices and different loads, can also achieve mutual conversion between AC and DC power forms and bidirectional energy flow, and can autonomously realize off-grid and grid-connected conversion according to system requirements.

To fulfill the basic functional requirements mentioned above, build the basic architecture of a multi-port power router as shown in Figure 1. The three-phase AC/DC converter, the single-phase AC/DC converter, the DC boost converter, the energy storage and its bidirectional power converter, the AC/DC load, and the bidirectional power converter of the interconnection port are combined through a common DC bus to form the topology of the power router.

The interconnect ports of the energy router are the core components for achieving intelligent scheduling and conversion of multi-source, multi-network, and multi-load energy, and they undertake the key functions of power input and output. Interconnect ports enable the two-way flow of energy between two levels of energy routers, support the interaction of multi directional energy such as photovoltaic, battery, and grid, and also play a role in power quality management, harmonic suppression, voltage and frequency stabilization, and ensuring energy safety.

3 Optimal path analysis of energy

3.1 Power balance analysis

As described in the previous section, since the upper-level energy router is a first-level critical load with the highest power supply reliability requirements, the analysis and strategies of the energy router in this article are based on the operating state in grid-connected mode.

The stable operation of each port of the energy router is a key prerequisite for achieving upper-level optimized scheduling. The energy router described in this paper is a typical multi-terminal DC system, and each unit of the energy router is connected to the DC bus through the corresponding power electronic converter, so the bus voltage is a key indicator reflecting the stable operation of the system. Maintaining the stability of the bus voltage requires a power balance among the ports, and an analysis of the power balance of the energy router is needed.

3.1.1 Power analysis of the upper-level energy router

In grid-connected mode, the energy router stabilizes the voltage through the battery energy storage port. The power output by the photovoltaic port should be prioritized to ensure that the internal load demand of the DC microgrid is met. When there is surplus or shortage of photovoltaic power, the energy storage port or interconnection port will absorb or supplement the energy accordingly to achieve dynamic power balance within the system.

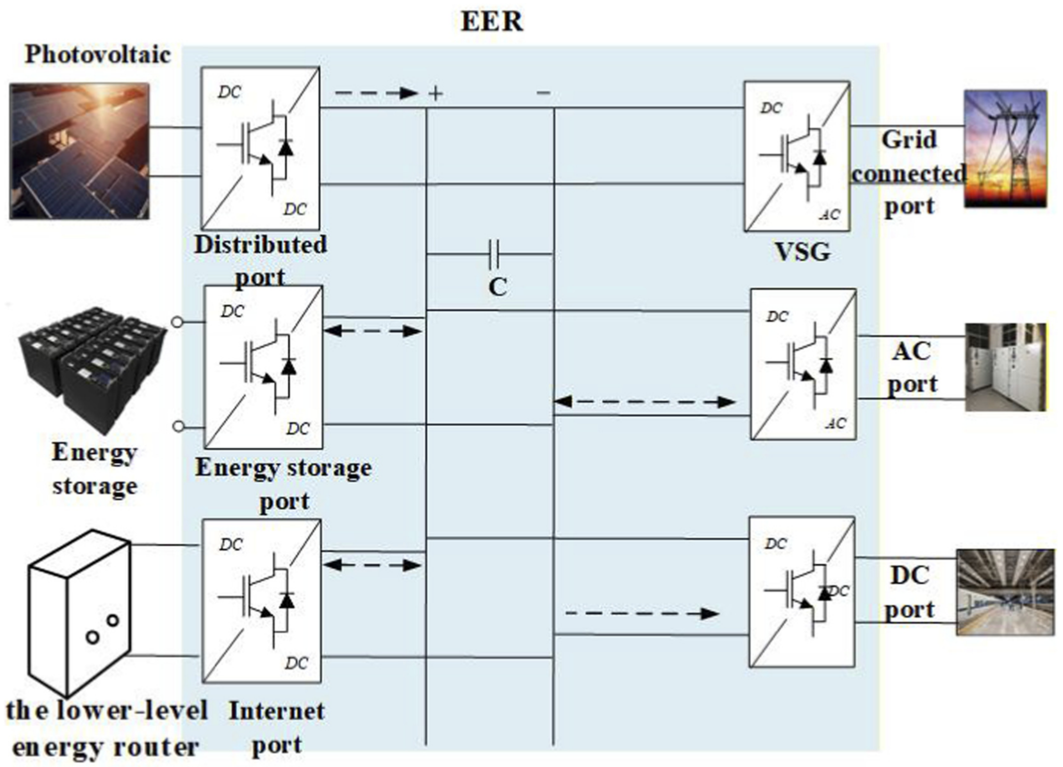

FIGURE 1
Basic topological architecture of the power router.

It is specified that the power direction from the DC bus to the interconnect port is positive. At this time, the internal power balance formula of the energy router is:

$$P_{upper1} = P_{load} + P_{grid} + P_{Bat} - P_{PV} \tag{1}$$

In the Formula 1, P_{PV} is the photovoltaic output power, P_{load} is the AC/DC load consumption power, P_{Bat} is the energy storage consumption power, P_{grid} is he power flowing into the main grid, and P_{upper1} is the power received by the upper-level energy router through the interconnection port. The power transmission will be verified through simulation.

Although the interconnect ports are bidirectional power ports, they are generally considered uncontrollable ports because their own power direction is determined by the load power changes of the upper and lower energy routers and the size is often uncontrollable.

3.1.2 Power analysis of the lower-level energy router

In the lower-level energy router, which is not directly connected to the main grid but has an additional interconnection port connected to the upper-level energy router, the internal power balance formula for the lower-level energy router should be:

$$P_{upper2} = P_{PV} + P_{Bat} - P_{load1} - P_{load2} \tag{2}$$

In the Formula 2, P_{upper2} is the power output to the upper-level energy router, P_{PV} is the photovoltaic output power, P_{load} is the AC/DC load consumption power, and P_{Bat} is the energy storage consumption power. The power transmission will be verified through simulation.

3.2 Analysis of power allocation principles

To maximize the rationality and economy of system operation, consider the goal of achieving bidirectional energy flow at interconnection ports to balance power and minimize network loss as the optimal energy path. The port interconnection of the cooperative power supply system based on two-level energy routers is shown in the following (Figure 2).

Interconnection lines and AC grid lines, due to their longer length, have greater resistance, and the network loss rate is much greater than the line loss inside the energy router. Therefore, only the line loss should be considered during the analysis. The line power loss on the AC side is Formula 3:

$$\Delta P_{AC} = \left(\frac{P_{grid}^2 + Q_{grid}^2}{U^2}\right) \cdot R_{line\_AC} = \left(\frac{P_{grid}}{U\cos\varphi}\right)^2 \cdot R_{line\_AC} \tag{3}$$

The power loss on the DC side is Formula 4:

$$\Delta P_{DC} = \left(\frac{P_{upper}}{(U_2 - U_1)}\right)^2 R_{line\_DC} \tag{4}$$

In order to make the system run economically, it is necessary to reduce the line network loss, so the power transmission on

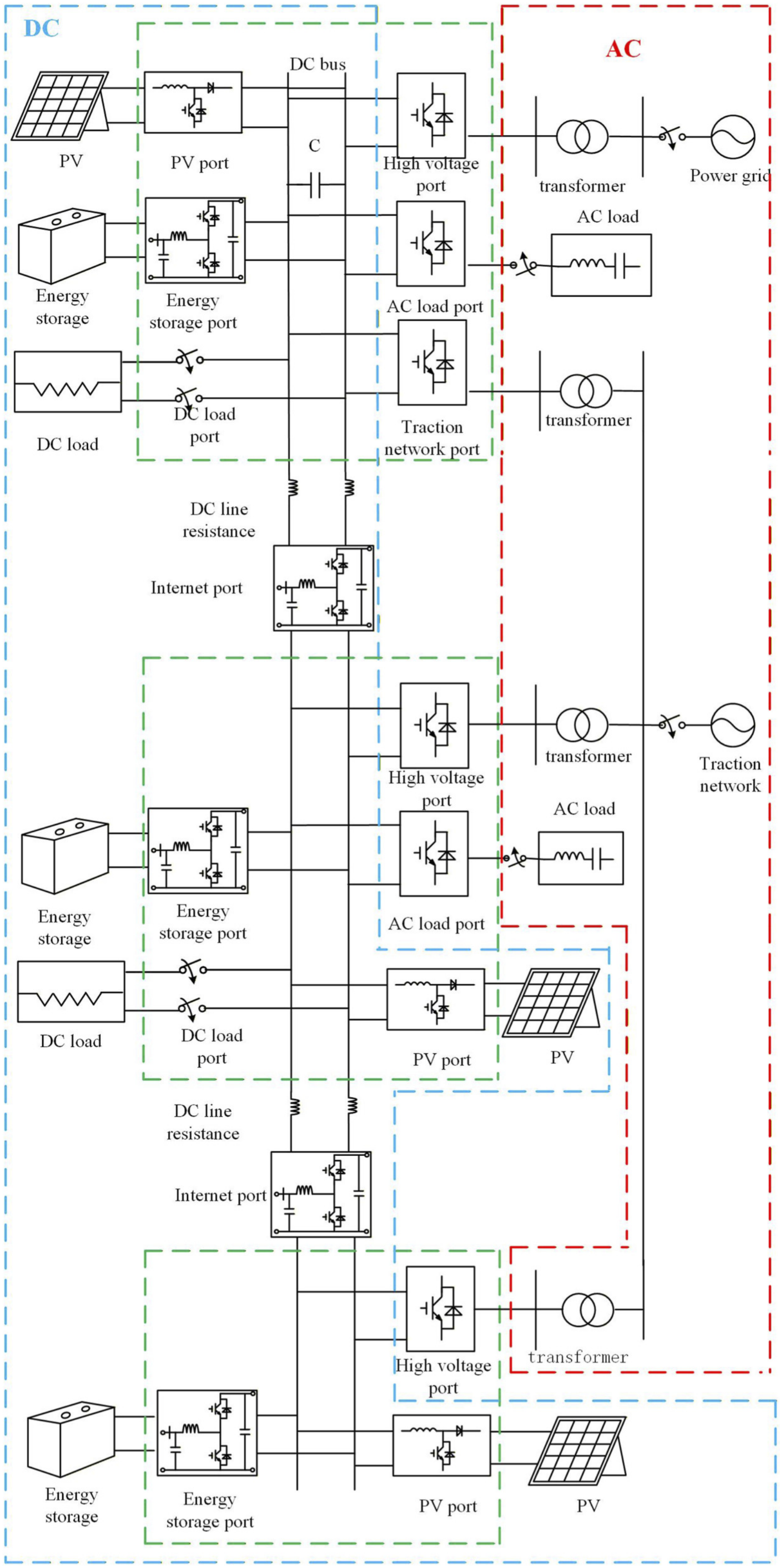

FIGURE 2
Serial energy router topology scheme.

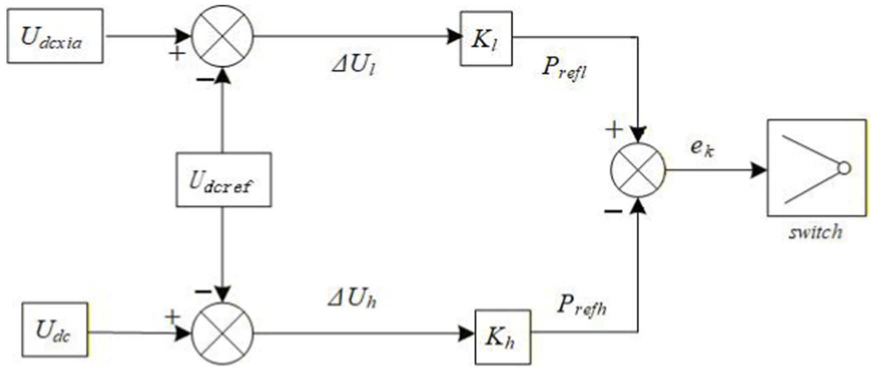

FIGURE 3
Structure diagram of bidirectional droop control at interconnected ports.

the line should be reduced, and local photovoltaic consumption should be given priority. When the local node energy storage can no longer consume the excess power, power consumption is carried out through the interconnection port.

For the internal power balance of the energy router, the bidirectional power port regulation of the two-level energy router should prioritize energy storage. When the energy storage SOC reaches the specified limit or the regulated power reaches the limit, it is necessary to participate in the regulation through the interconnection port.

For the external power balance of the energy router, if the energy storage regulation capacity of both levels of the energy router reaches the upper limit, the network presents radiation network characteristics and the line transmission power cannot be regulated. The power of the upper-level energy router is balanced by the grid, and the power of the interconnected lines is determined by the power shortfall or balance of the lower-level energy router.

3.3 Bidirectional droop control of interconnect ports

U_{dc}-P is an active power droop control method that takes into account the effect of the DC bus voltage on the active power of the interconnect ports. Based on this, the influence of the DC bus voltage of the upper and lower energy routers on power flow can be considered simultaneously, allowing the interconnect ports to control power transmission more precisely and achieve full utilization of energy. For this purpose, this paper proposes a method of bidirectional drooping control, with reference to the two-stage DC bus voltage for the distribution of active power.

$$P_{upper1} = P_{upper2} - \Delta P \tag{5}$$

In the Formula 5, P_{upper1} represents the power received by the upper-level energy router through the interconnection port, P_{upper2} represents the power released by the lower-level energy router through the interconnection port, and ΔP represents the power loss of the interconnection line. P_{upper1} and P_{upper2} plus or minus determine the power flow direction of the interconnect ports. When the power supply and load change, the system power flow changes, causing the DC bus voltages of the two stages to change. Therefore, adjust P_{upper1} and P_{upper2} based on the changes in the voltages of the two stages to bring the two-stage energy routers to a new stable state.

Interconnect port bidirectional droop control takes the two-stage DC bus voltage as input to control the active power flowing through the interconnect port (positive direction is from the upper level to the lower level). For the interconnect, the control structure is shown in the figure. Bidirectional droop control consists of a U_{dc}-P-U_{dcxia} control droop loop and a power double loop.

U_{dc} is the upper-level DC bus voltage, U_{dcxia} is the lower-level DC bus voltage, U_{dcref} is the reference DC bus voltage, K_l and K_h are the droop coefficients of the lower-level energy router and the upper-level energy router respectively, P_{ref_l} and P_{ref_h} are the reference power components obtained from the two levels of voltage through the droop link, and the energy flow direction of the interconnect port is determined by the positive or negative of the reference power component after the difference, The reference value of reactive power set in this paper is 0. Power sag control enables the output power of interconnected ports to track the reference power.

The following types can be seen from the Figure 3.

$$\Delta U_l = U_{dcxia} - U_{dcref} \tag{6}$$

$$\Delta U_h = U_{dc} - U_{dcref} \tag{7}$$

$$P_{refl} = \left(U_{dcxia} - U_{dcref}\right) * K_l \tag{8}$$

$$P_{refh} = \left(U_{dc} - U_{dcref}\right) * K_h \tag{9}$$

$$e_k = P_{refl} - P_{refh} \tag{10}$$

$$e_k = K_l * \left(U_{dcxia} - U_{dcref}\right) - K_h * \left(U_{dc} - U_{dcref}\right) \tag{11}$$

$$K_n = \left(P_{dcmax} - P_{dcmin}\right) / \left(U_{max} - U_{min}\right) * \left(\frac{S_n}{S_{total}}\right) \tag{12}$$

In the Formulas 6–12, ΔU_h and ΔU_l are respectively the difference between the upper and lower DC bus voltages and the reference voltage, and e_k is the difference of the reference power. ΔU_h and ΔU_l respectively represent the extent to which the voltages of the two stages of the DC bus deviate from the rated reference value to

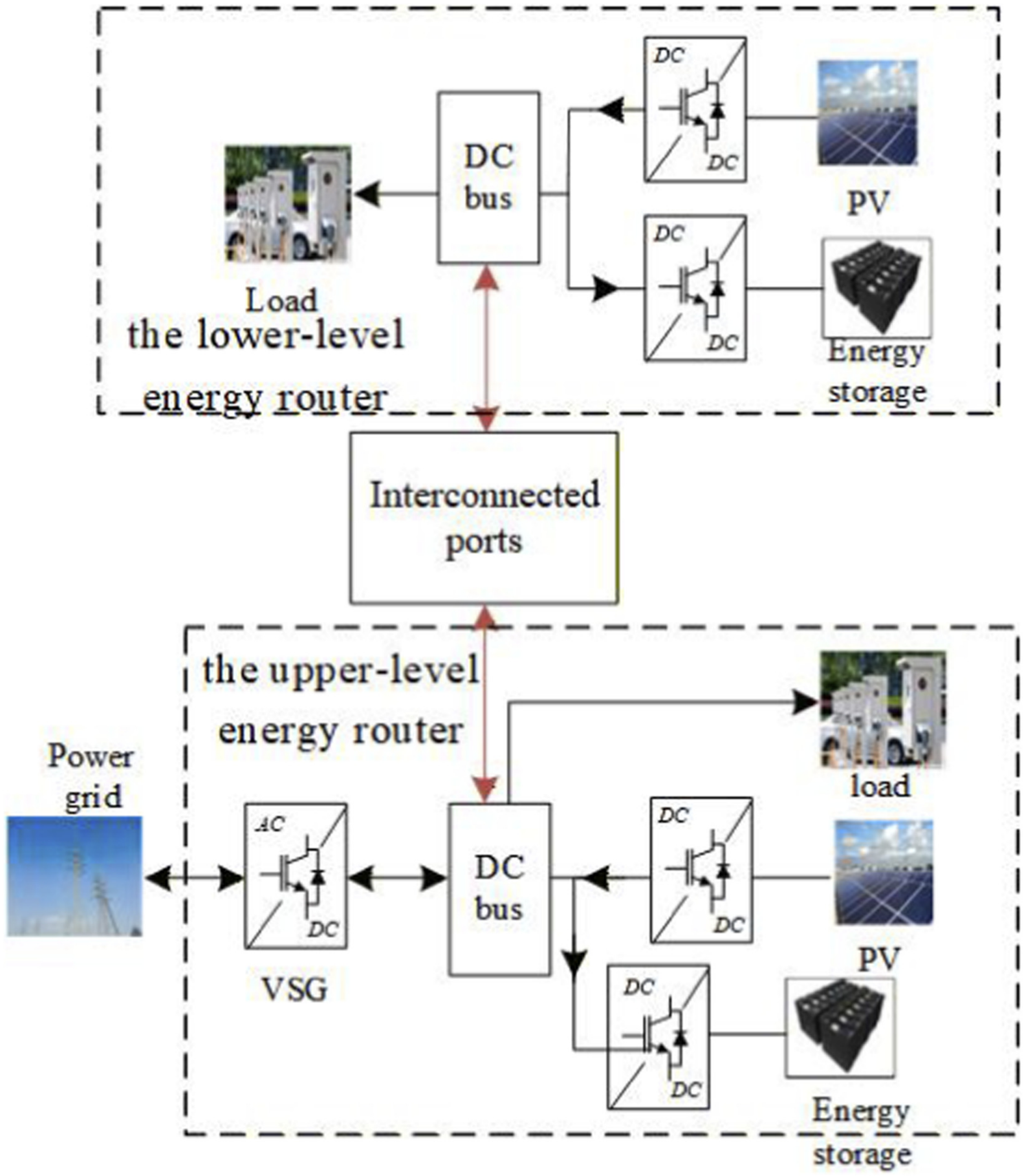

FIGURE 4
Model of the energy router.

TABLE 1 Key parameters in the example.

Parameter	Quantitative value	Unit
DC side voltage U_{dc}	750	V
Rated reference voltage on the DC side U_{ref}	750	V
Rated frequency f	50	Hz
Filter capacitor C	2.5	mF
Measure the DC voltage of the storage device U	400	V
Filter inductance L	1	mH

determine P_{refl} and P_{refh}, the value of P_{refl} and P_{refh} reflect the level of variation in the power demand of the two-stage energy router. The difference e_k of reference power reflects the relative level of change in power demand on both sides of interconnected ports. Bidirectional droop control determines the size of the power delivered through e_k. The value of U_{dcref} directly affects the determination of the interconnect port reference power, so an appropriate reference value needs to be selected.

When e_k>0, the power is positive and the energy flows from the lower-level energy router through the interconnection port to the upper-level energy router, and there is power redundancy in the lower-level energy router; When e_k<0, power is negative, energy flows from the upper-level energy router through the

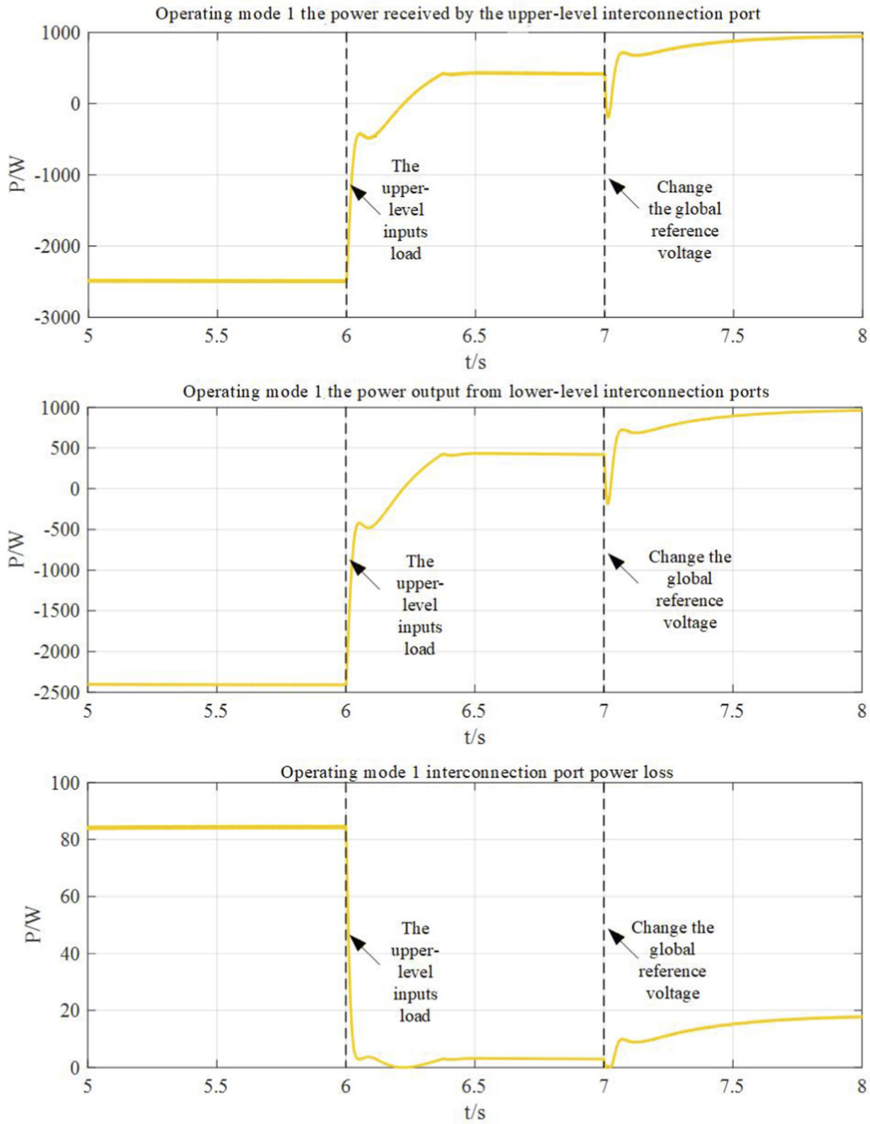

FIGURE 5
Power waveform diagram of the interconnected port under Condition 1.

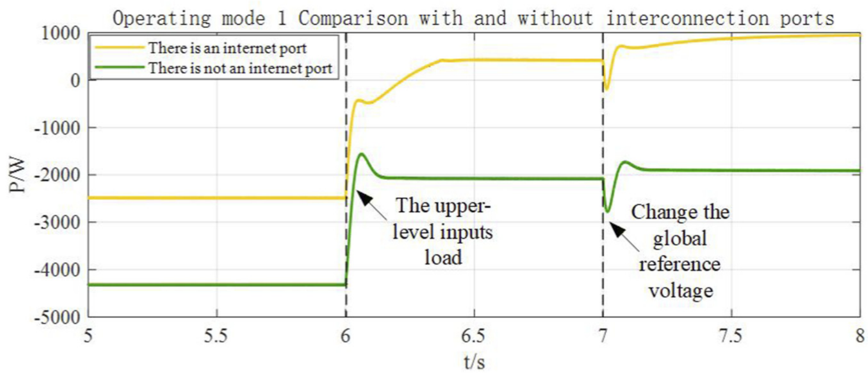

FIGURE 6
Comparison of power with and without interconnected ports in operating Condition 1.

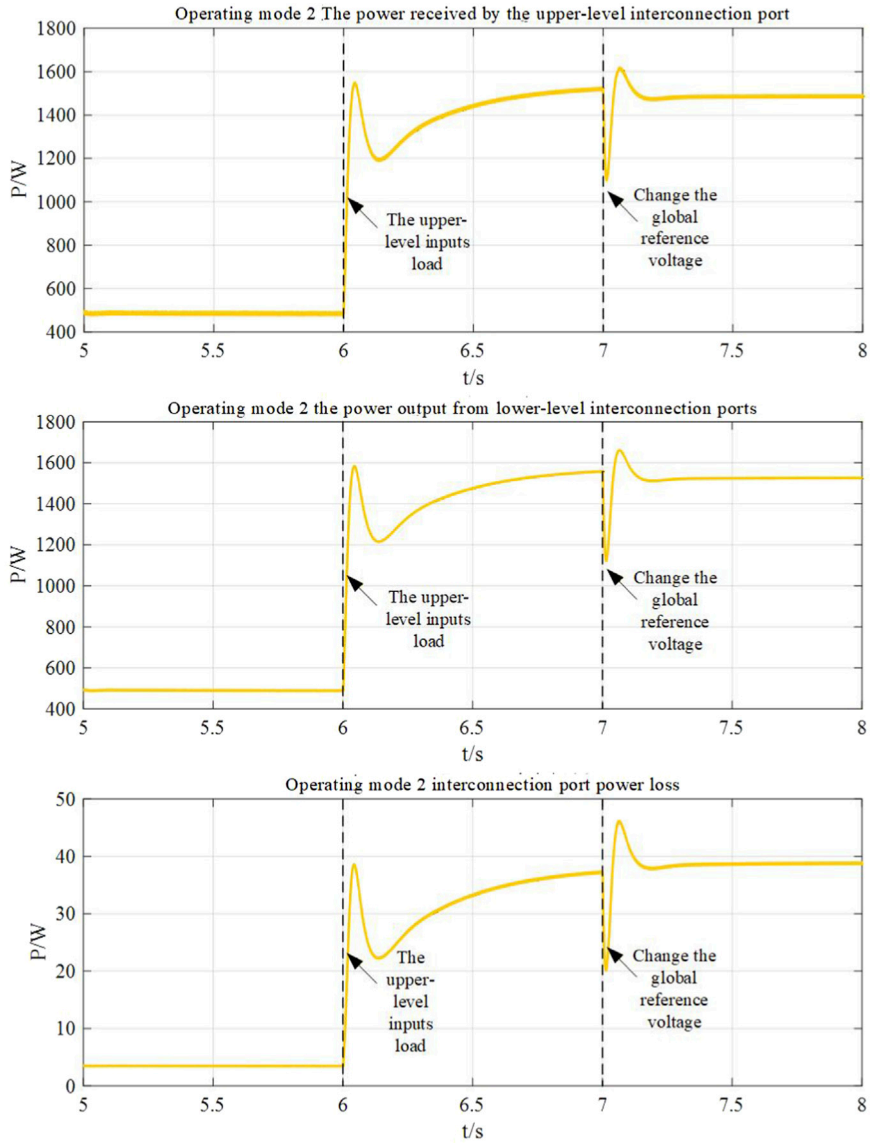

FIGURE 7
Power waveform at the interconnect port of work Condition 2.

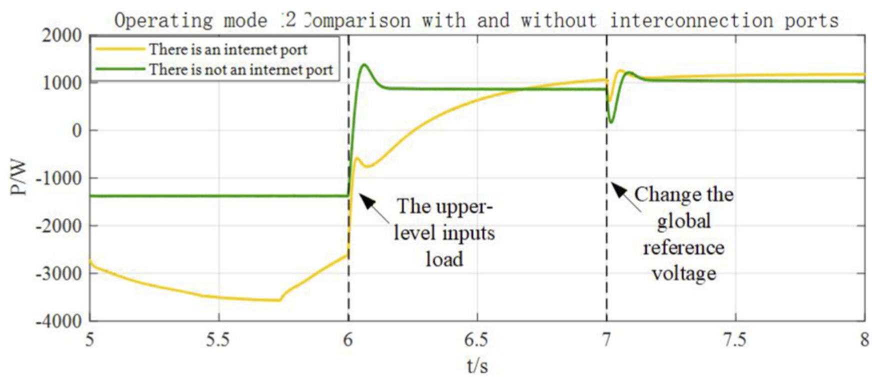

FIGURE 8
Comparison of power with and without interconnected ports in operating Condition 2.

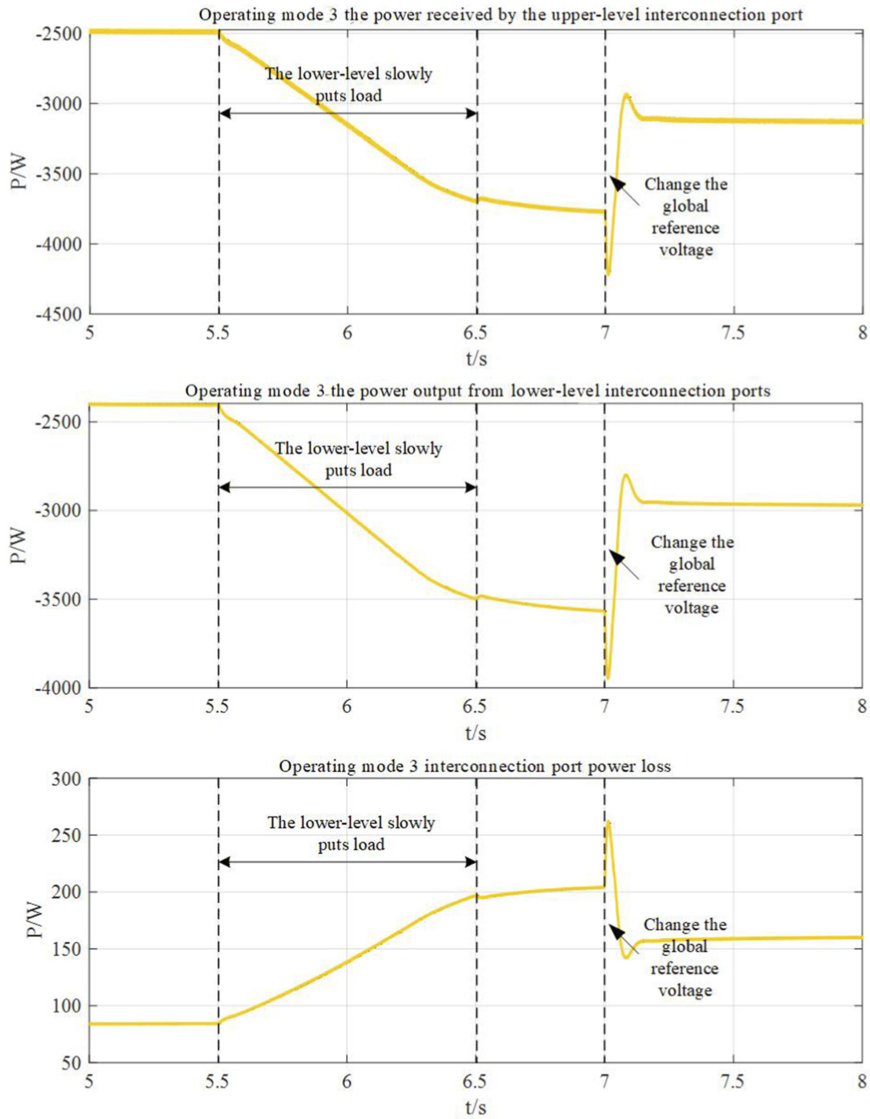

FIGURE 9
Power waveform at the interconnect port of work Condition 3.

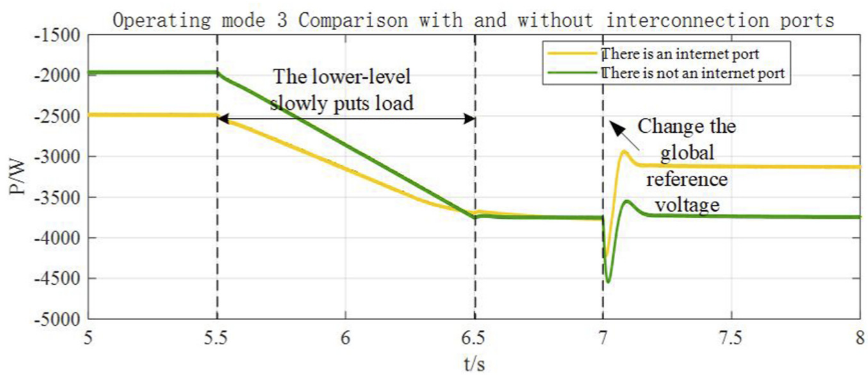

FIGURE 10
Comparison of power with and without interconnected ports in operating Condition 3.

interconnection port to the lower-level energy router, and there is a power deficit in the lower-level energy router; When $e_k = 0$, the energy demand levels on both sides of the interconnect ports are equal, and there is no power flow on the interconnect line. By using bidirectional droop control to regulate the transmission power of the interconnect ports, energy always flows to the level of energy router with a greater load demand, so that regardless of which level of energy router the load fluctuation occurs, the two levels of energy routers will share the load fluctuation together, effectively achieving the rational use of energy.

4 Energy flow simulation analysis

Build a single five-port simplified two-stage energy router model in Matlab/Simulink as shown in Figure 4.

The model simulates the situation of two-level energy routers and verifies the ability of the interconnection ports of the parallel energy router system to maintain normal operation in different working scenarios based on the system and environmental disturbances that often occur in actual situations. The operating conditions of the system under different grid fluctuations were simulated at different times respectively.

To verify the bidirectional flow of energy at the interconnect ports of the two-stage energy routers based on the required size, DC loads were respectively applied to the two-stage energy routers under the conditions of power redundancy and deficiency, as shown in Table 1 for simulation to verify the energy flow at the interconnect ports.

4.1 Operating mode 1

In Condition 1, the upper-level energy router is connected to the grid, and there is a power deficit in the lower-level energy router. The upper-level energy router transmits energy to the lower-level through the interconnection line to achieve power balance. Simulation: When a 5 kW DC load is put into the upper-level energy router at 6 s, the global DC voltage reference value drops by 50 V at 7 s, and the simulation time is 8 s.

As shown in Figure 5 is the power waveform of the interconnection line. Under this condition, the power balance of the interconnection ports is manifested as the power emitted by the lower interconnection port minus the power loss of the interconnection line is equal to the power received by the upper interconnection port. It can be seen from the figure that before the simulation 6 s, due to the power deficit of the lower-level energy router, the power flow direction of the interconnection port is negative, that is, the energy flows from the upper level to the lower level. At 6 s, the upper-level energy router puts in a 5 kW DC load, the energy required by the upper level increases, the energy of the interconnection port continuously decreases until it reverses, at this time the energy flows from the lower level to the upper level, At 7 s, the global voltage reference value is changed, and the power flowing to the upper-level energy router increases, achieving a reasonable distribution of power.

As shown in Figure 6, it is a comparison diagram of power on and off interconnected lines under Condition 1. At this time, the power flowing on interconnected lines without interconnected ports is significantly more than that with interconnected ports, indicating that the effect of local energy consumption is not obvious, and the power distribution is not as reasonable as with interconnected ports.

4.2 Operating mode 2

In condition 2, the upper-level energy router is connected to the grid. The power of the lower-level energy router is redundant and is output to the upper-level energy router through the interconnection line to achieve power balance. Simulation: When a 5 kW DC load is put into the upper-level energy router at 6 s, the global DC voltage reference value drops by 50 V at 7 s, and the simulation time is 8 s.

Figure 7 shows the power waveform of the interconnect port in Condition 2. Under this condition, the power balance of the interconnect port is manifested as the power emitted by the lower interconnect port minus the power loss of the interconnect line is equal to the power received by the upper interconnect port. Before 6 s, due to the power redundancy of the lower-level energy router, the power flow direction of the interconnection port is positive, that is, energy flows from the lower-level to the upper-level. At 6 s, the upper-level energy router puts in a 5 kW DC load, and the energy required by the upper-level increases. Considering that there are energy storage components at this stage that can provide some energy for it, therefore, the energy through the interconnection port increases but is less, With less power loss on the interconnection line, local storage and consumption of photovoltaic and energy storage batteries were achieved, and economic efficiency was improved. When the reference voltage is changed at 7 s, the energy at the interconnection port does not change much and does not affect its normal operation.

As shown in Figure 8, when the power of the lower-level energy router is redundant and the load is put into the upper-level energy router, the power fluctuation on the interconnection line without the interconnected port is significantly greater than that with the interconnected port, which also indicates that the power of this level cannot be well absorbed locally and requires a large amount of power from the lower-level energy router. It can be concluded that the power distribution is more reasonable when there are interconnected ports.

4.3 Operating mode 3

In Condition 3, the upper-level energy router is connected to the grid and there is a power deficit in the lower-level energy router. The upper-level energy circuit is connected through the interconnection line The device transmits energy to the lower level to achieve power balance. The simulation shows a slow input of 3 kW DC load into the lower-level energy router at 5.5–6.5 s, a 50 V drop in the global DC voltage reference at 7 s, and the simulation time is 8 s.

Figure 9 shows the power waveform of the three interconnect ports under working condition. Before 5.5 s, due to the power deficit in the lower-level energy router, the power flow direction of the interconnect ports is negative, that is, energy flows from the upper level to the lower level. At 5.5 s, a 3 kW load is slowly put into the lower-level energy router. At this time, the power required by the lower-level energy router increases. The energy flowing through the interconnect port increases, and so does the power loss on the interconnect line. At 7 s, the reference voltage is changed. At this

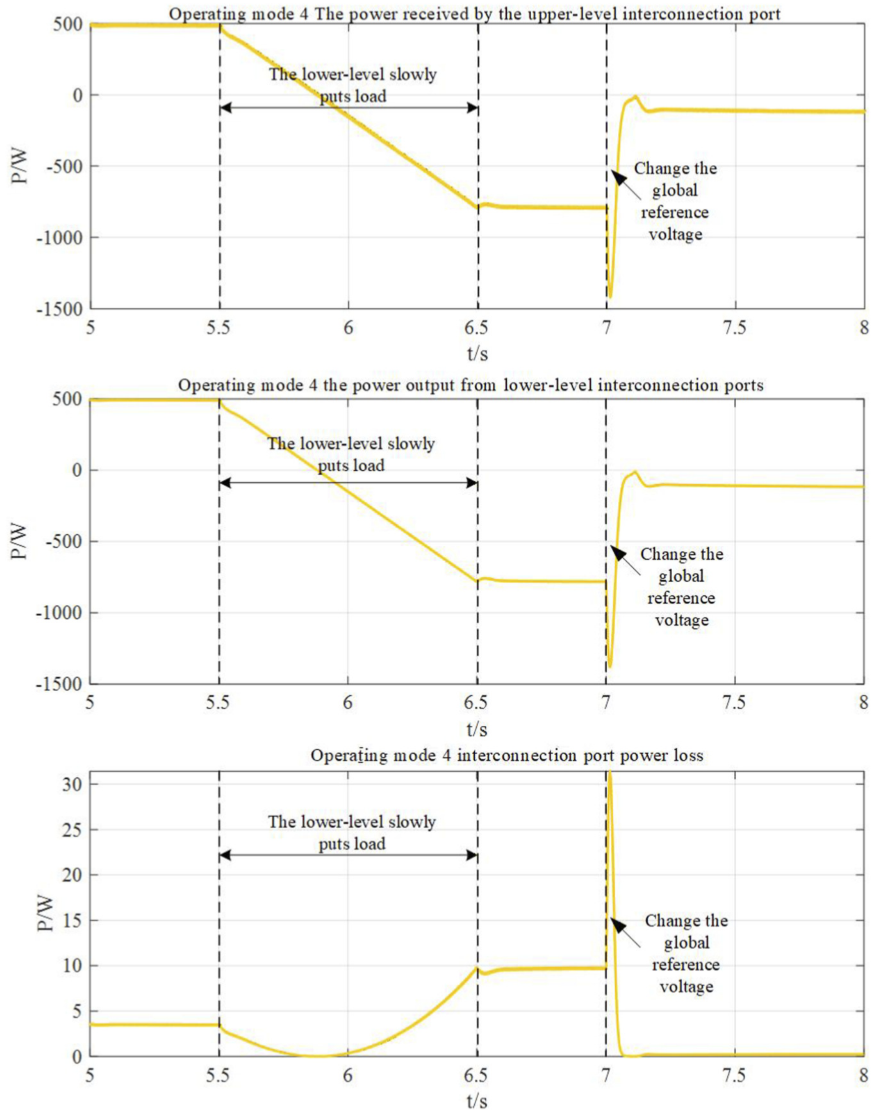

FIGURE 11
Power waveform at the interconnect port of work Condition 4.

time, the power of the interconnect port decreases, and so does the power loss on the interconnect line.

As shown in Figure 10, it is a comparison diagram of power on and off interconnected lines under working condition 3. Compared with the situation with interconnected ports, when the global reference voltage is changed at 7 s, the power of the non-interconnected ports remains almost unchanged, the power on interconnected lines is larger, the loss is also larger, and the power distribution is not reasonable enough.

4.4 Operating mode 4

In condition 4, the upper-level energy router is connected to the grid for operation, and the power of the lower-level energy router is redundant. Energy is transmitted from the upper-level energy router to the lower-level through the interconnection line to achieve power balance. The simulation shows that a 3 kW DC load is slowly loaded into the lower-level energy router at 5.5–6.5 s, and the global DC voltage reference drops 50 V at 7 s. The simulation time is 8 s.

Figure 11 shows the power waveform of the interconnect port under condition four. Before 5.5 s, due to the power redundancy in the lower-level energy router, the power flow direction of the interconnect port is positive, that is, the energy flows from the lower level to the upper level. At 5.5 s, a 3 kW load is slowly put into the lower-level energy router, and at this time the flow power of the interconnect port is reverse (from the upper level to the lower level). And the power is increased to meet the energy requirements of the lower-level energy router, allowing the system to run stably. At 7 s, the reference voltage is changed to reduce the power on the link line, and the loss is also reduced, making the operation more economical.

As shown in Figure 12, it is a comparison diagram of power on and off interconnected lines under Working condition 4. Compared with the situation with interconnected ports, when the global reference voltage is changed at 7 s, the power of the non

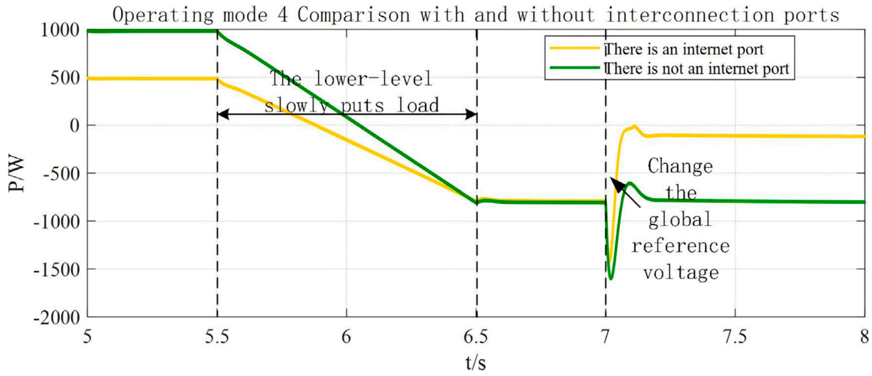

FIGURE 12
Comparison of power with and without interconnected ports in operating Condition 4.

interconnected ports remains almost unchanged, the power on interconnected lines is larger, the loss is also larger, and the power distribution is not reasonable enough.

It can be seen from the above working condition diagram that while power balance has been achieved inside the energy router, the interconnected ports can achieve bidirectional energy flow according to the requirements of the two-stage energy router. The two energy routers have achieved power distribution and compared with the non-interconnected ports, the power distribution is more reasonable.

5 Conclusion

This paper takes the two-level energy router as the research object, studies its topological structure, briefly analyzes the power balance within each level of the energy router, deeply analyzes the bidirectional droop control with the dual variables of the two-level DC bus voltage at the interconnection ports, clarifies that the two-level energy router distributes power according to the demand and compares it with the two-level energy router without interconnection ports, and verifies its rationality through modeling. This dual-variable droop control can more accurately coordinate the energy transmission between the upper and lower-level energy routers, and achieve the full utilization of electrical energy.

The ports of the router work together to achieve multiple functions such as multi-energy conversion, power distribution, and energy management. At the same time, each level of energy router's photovoltaic power is preferentially consumed locally by the energy storage section to reduce power transmission on the line. When the energy storage of different scenario routers is saturated, control strategies are adopted for energy transmission at interconnected ports to ensure the power balance of the entire system and meet the demand. Bidirectional power flow at the interconnect ports is achieved by controlling the voltages of the two levels of DC buses. The modeling simulation results verified the aforementioned interconnect port energy flow, enabling the two-level energy router to transfer energy and balance power through the interconnect port as required, achieving reasonable power transmission.

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 authors.

Author contributions

PL: Software, Project administration, Methodology, Formal Analysis, Resources, Writing – original draft, Data curation, Visualization, Writing – review and editing, Conceptualization, Validation, Funding acquisition, Investigation, Supervision. HM: Formal Analysis, Conceptualization, Writing – original draft, Data curation. JZ: Methodology, Investigation, Funding acquisition, Writing – review and editing. RW: Writing – original draft, Software, Resources, Project administration. SY: Visualization, Validation, Supervision, Writing – review and editing.

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Conflict of interest

Authors PL, HM, JZ, RW, and SY were employed by China Electric Power Research Institute Co., Ltd.

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