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Regular paper

Evaluating Potential Benefits of Distributed Energy Resources for Improvement of Distribution System Resiliency

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This paper presents a comprehensive methodological framework to assess the contribution of distributed generation (DG) in smart buildings for improving the resilience of distribution power grids against extreme disasters. To achieve this, a new evaluation index, named energy supply reliability (ESR), is proposed to quantify the capability of DG in smart buildings to provide capacity support to the grid under extreme disasters, based on reliability analysis. The effects of multi-carrier energy demand and their interactions are explicitly considered in our index design. The mesh grid method and the Monte Carlo simulation are jointly used to calculate the power loss that presents after extreme disasters. A hybrid algorithm based on optimal scheduling technique is employed to examine the resilience of the distribution system with and without considering DG. The proposed framework is illustrated using a test case based on IEEE30 node systems, and the simulation results demonstrate that the appropriate utilization of DG in smart buildings can greatly improve the resilience and supply reliability of power grids against extreme disasters.

Keywords: distributed generation; energy supply reliability; mesh grid method; distribution system; resilience.

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1. Introduction

With the progress of human society, higher requirements have been raised for the secure and stable operation of modern power systems. In this context, the construction of resilient [1]-[2] power grid has gradually been a national strategy of many countries.

However, nowadays, the energy supply infrastructures are not adequately designed and prepared for unpredictable extreme disaster events. For example, the extreme events such as the earthquake and tsunami in Japan and the ice disaster in the south of China in 2008 severely damaged the power system, leading to large-scale power outages, which significantly endangered the public welfare. The resilient grid can better cope with the small probability high loss extreme events, minimize the effect of the event, and flexibly accommodate environmental changes. Besides, if the disaster damage cannot be avoided, it can also quickly recover the grid's power supply capacity. Therefore, establishing a resilient grid would greatly improve the robustness and efficiency of energy supply in future power systems.

Researchers are aware of the above facts, and the topic of the resilient grid has captured considerable research interests in the past decade. In [3], the main research directions and key points of distribution network resilience are detailed, including disturbance events, evaluation theory, and resilience promotion strategies. A novel evaluation framework for distribution system resilience is proposed in [4]. The influential factors of power grid resilience are characterized by four dimensions (technology, organization, society, and economy). Different indices are defined based on land usage, probability, and regulation cost; the corresponding solutions for improving the resilience of the distribution network

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are presented from both the planning and operating perspectives. Besides, some other quantitative metrics for defining the resilience of power grid have also been proposed in [5]-[8]. For example, in [5], the grid resilience is defined as the ratio of the system recovery portion after a disaster to the initial system loss before a disaster.

The above literature review shows that considerable work has been done about the resilience of the distribution system. However, in these researches, most proposed solutions aim to address the resilience issue by the reconstruction of the power network, such as the reinforcement of poles and towers and emergency repair after disasters [9]-[11]. Nevertheless, in real situations, such a scheme would normally incur extra investments to the distribution system owner.

Just because of such limitation, another alternative, distributed generation (DG), is increasingly popular in recent years [12]-[14]. In contrast to the supply-based solutions, DG is primarily committed to exploiting the flexibility from the demand side. As DG placed in smart buildings are under the protection of building walls, they are less vulnerable and more likely to survive in extreme disasters. In this light, for the grid operator, the massive amount of DG existed in smart buildings can be used as backup operating reserves and may potentially play a significant role in power restoration and grid resilience improvement under extreme disasters. Therefore, for long-term planning, it is critical to quantify and fundamentally demonstrate to what extent the flexible DG in smart buildings could be relied on to enhance the resilience target of the power grid. However, scarcely any current literature has studied this problem hitherto.

Therefore, an index of energy supply reliability is presented in this paper to analyze the ability to support the distribution network by the distributed power sources in smart buildings under extreme natural disasters.

In this paper, we present a new methodological framework to assess the contribution of DG in smart buildings to the resilience of distribution power grids against extreme disasters. To achieve this, based on the types of disasters, we first introduce a mesh-grid method to model the damage severity of distribution networks under different types of disasters. Then considering the multi-energy complementary characteristics of energy supply in smart buildings, based on reliability analysis, a new evaluation index named energy supply reliability (ESR), is proposed to quantify the capability of DG in smart buildings to provide capacity support to the grid under extreme disasters. A hybrid algorithm based on sequential Monte-Carlo simulation and an optimal dispatching method is utilized to quantify the potential resilience improvement of the system with and without considering DG under different disasters. Finally, the case study demonstrates the effectiveness of the proposed framework.

The rest of this paper is arranged as follows: Section 2 provides an overview of the smart building and its operation characteristics under study. Section 3 elaborates on the modelling of various DG technologies. On the above basis, in Section 4 and 5, the evaluation algorithm used for assessing the resilience of the distribution system is described. The numerical studies and the analysis of relevant results are provided in Section 6. Finally, Section 7 presents the conclusion of this work.

2. Overview of smart buildings

Nowadays, metropolitan cities have many smart buildings. With the development of science and technology, research on smart buildings and related technologies is increasing extensively. Smart building construction is a vital link in the practical application of the smart grid. It not only facilitates the grid to provide users with comprehensive and extended services but also achieves the two-way interactive function of grid users with low-carbon ratio and high energy efficiency. With the rapid development of science and technology, growing cross-industry and interdisciplinary results have been applied to smart buildings, a product of modernity, and their content and form have been improved accordingly.

The format of smart buildings involves transmission technology, quantification technology, control technology, and integrated wiring technology. Smart buildings have comprehensive management and control system for various technologies and integration applications, by which it can achieve many new functions such as two-way interaction, power consumption information collection, and distributed power access.

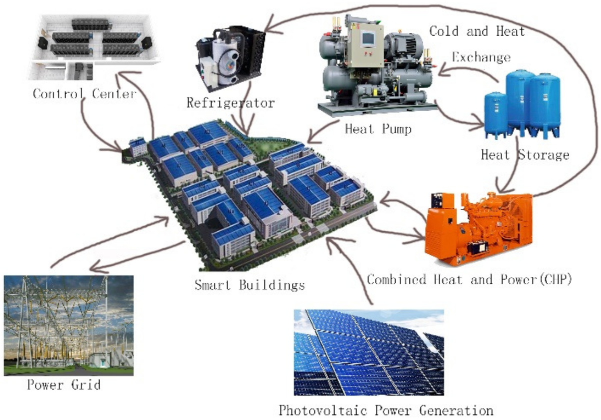

Figure 1 Schematic diagram of distributed energy system under study

As shown in Fig.1, differing from ordinary building constructions, the smart buildings add energy-efficient and automatic control equipment, while being connected to the grid, enabling two-way power transmission. More specifically, smart buildings contain various energy storage devices, such as combined heat and power (CHP), heat storage, electricity storage, distributed photovoltaic, heat pump, boiler, air conditioner, electric vehicle charging pile, and refrigerator. It is an integrated energy system for unified planning and unified dispatching of various energy sources such as power system, thermal system, renewable energy power generation system, and coupling system of power, heat, and cooling supply.

As shown in Fig.2, distributed energy resources in smart buildings can be used as production equipment or emergency energy supply equipment, so the intelligent control technology can automatically manage the load energy form distribution in the buildings, and it can be adjusted to satisfy different energy demands, ensuring the economy and reliability of the building operation.

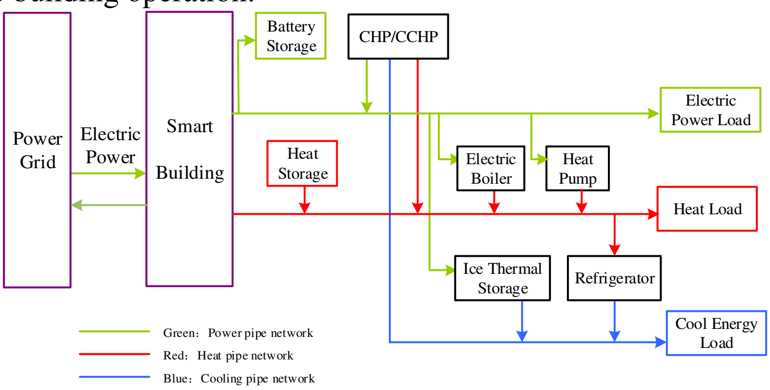

Figure 2 Energy flow diagram

3. Modelling of distributed energy sources

This section starts from the heat and energy storage characteristics in smart buildings, which includes solar PV generation units, heat storage tank, heat pump, electric boiler, and CHP equipment.

3.1. Solar PV

The generation capacity of a solar PV system is determined by many factors, such as the daily average radiation intensity of solar energy and the daily power consumption of the residents. The capacity of the photovoltaic power generation system can be determined by

$$A_{pv} = \frac{E_{Ld}}{\eta_{sys} \times E_{sd}} \tag{1}$$

$$P_{pv,stc} = E_0 \eta_{pv,stc} A_{pv} \tag{2}$$

where A_{pv} represents the surface area of solar cell, m^2; E_{Ld} denotes the daily average electricity consumption of customers, kWh/d; η_{sys} is total efficiency of solar power system; E_{sd} is daily average solar radiation, kWh/m^2·d; $P_{pv,stc}$ is output energy of the solar cell under standard test conditions, kW; E_0 is the solar radiation intensity, kW/ m^2; $\eta_{pv,stc}$ is efficiency of solar cell, usually 0.1~0.15.

3.2. Heat pipeline

The thermal equipment unit in the smart buildings mainly includes, but is not limited to, the heat pipeline network, the heat storage device, heat pump, and electric boiler. Thermal energy is transmitted and stored by the above devices.

The heat pipeline network is a crucial part of the heating system, which mainly consists of two parts: the heat pipeline and the circulating water pump. A typical physical model of a heat pipeline can be expressed as:

$$P_1 - P_2 = 1.15 \frac{\bar{\omega}}{2g\bar{v}} \left(\frac{\lambda}{D_1} L + \sum \xi \right) + \frac{H_2 - H_1}{\bar{v}} \tag{3}$$

$$t_{in} - t_{out} = \frac{3.6 Q_{loss}}{1000 G_L c_p} \tag{4}$$

$$Q_{loss} = \frac{\pi D_0 L K (t - t_a)}{R} \tag{5}$$

where P_1 and P_2 represent the pressure at the beginning and end of the pipeline, respectively; ω denotes the average flow velocity of the pipeline; v denotes the average specific volume of the pipeline; g denotes the acceleration of gravity; D_1 and D_0 represent the inner and outer diameters of the pipeline, respectively; λ denotes the process resistance coefficient; L denotes the length of the pipeline network; ξ denotes the local resistance coefficient; H_2 and H_1 represent the height of the beginning and end of the pipeline respectively; t_{in} and t_{out} represent the temperature at the beginning and end of the pipeline respectively; Q_{loss} denotes the heat loss of the pipeline; G_L denotes the flow rate of the pipeline; c_p denotes the pressure heat capacity of the hot water; K denotes the equivalent length coefficient of the heat loss component; R represents the thermal resistance of the pipeline; t represents the average temperature of the medium in the pipeline; finally, t_a represents the ambient temperature.

3.3. Electric boiler

An electric boiler is a typical electro-thermal coupling unit. The operation model of distributed power supply combined with the electric heating boiler can be given as:

$$Q_{EHB}(t) = \eta_{EHB}(1-\mu_{Loss})P_{EHB}(t) \tag{6}$$

where $Q_{EHB}(t)$ represents the heat supply of the electric heating boiler in time period t; $P_{EHB}(t)$ indicates the power consumption of the electric heating boiler in time period t; η_{EHB} represents the electrothermal conversion efficiency; μ_{Loss} stands for the heat loss in time period t.

3.4. Heat pump

The typical operation model of a heat pump can be expressed as:

$$q_{HP} = k\frac{V_{HP}(t_h - t_c)\rho_r}{3600T_{HP}} \tag{7}$$

where q_{HP} represents the heating power of the heat pump unit; V_{HP} represents the water consumption of the heat pump unit; ρ_r represents the hot water density; t_h and t_c respectively indicate the hot water set temperature and the cold water hydration temperature; k is the safety factor; T_{HP} stands for the heat pump unit operating hours.

4. Assessment of resilience of power grid under extreme disasters

After an extreme disaster (such as hurricanes, blizzards, and lightning strike), the outdoor equipment could be more vulnerable in extreme disasters, which may cause equipment failures, thus affecting power supply reliability. Therefore, there is an urgent need to transfer power to the main loads in the power grid. Compared with the traditional way of using the thermoelectric power supply, since the thermal power plant unit is shut down during the disaster and it takes time to restart, there is a shortage of time required for power transmission. Therefore, the use of DG in the smart building's power grid for faster recovery is more efficient. For these reasons, under the premise of ensuring the energy supply reliability in smart buildings, how to pre-set the optimal scheduling mode to guarantee the maximum speed of power grid recovery has become an urgent problem to be solved.

4.1. Modelling of power grid under extreme disasters

Natural disasters such as typhoons, line icing, and lightning strikes, which are destructive to power grid equipment, are presented in spatial geography so that the power system connection can be rasterized. Natural disasters that occur at specific geographic grid locations can cause the tower to collapse or the ice cover of the line to be too large to power properly. Therefore, the mesh grid method is used to characterize the extent of damage resulted by natural disasters to the grid.

Taking the IEEE 30-node power system as an example, as shown in Figure 3, when a typhoon disaster occurs, the dark region is used to represent the areas in strong destructive power, considering the collapse of the tower and the interruption of the transmission line in this area. The surrounding light colour areas have a corresponding probability of being destroyed. A matrix is used to model the latitude and longitude of each grid, and the grid matrix is generated multiple times by the Monte Carlo method, which can eliminate the error caused by randomness and simulate the damage of various natural disasters. The grid method is used to analyze the location of damaged outdoor equipment in the power grid, classify the disasters, and combine historical data to calculate the probability of tower collapse and equipment damage under different disaster levels. Then the disaster situation of the power grid can be analyzed to address power losses under extreme disaster conditions.

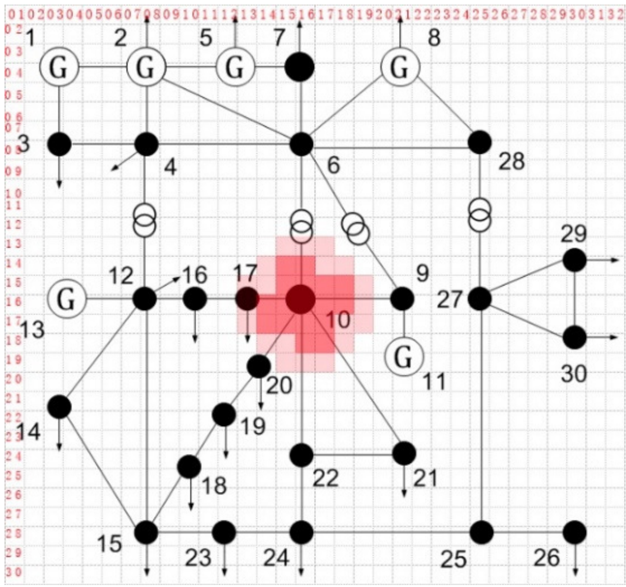

Figure 3 Network grid method to simulate the damage of IEEE 30-node system caused by natural disasters

4.2. Index of energy supply reliability

After extreme disasters, the power grid outdoor equipment is damaged, resulting in power loss. In smart buildings, distributed power sources are survived. Under the premise of ensuring the reliability of its loads, using surviving distributed power sources can reverse the power supply to the grid and reduce grid recovery time. The energy supply reliability index (ESR) is proposed to evaluate the effectiveness of pre-disaster dispatching and ensure the normal energy supply of users in the buildings. After satisfying the energy supply reliability and the relevant energy distribution constraints, the optimal supply scheduling is sought to transmit energy to the power grid. If the supplied energy is lower than the load demand in the current period, it is assumed that power supply or heating or cooling failure occurs, and the energy supply reliability is not satisfied.

The energy supply reliability (ESR) is defined as follows:

$$ESR = \alpha * \frac{P_F^L - \Delta P_F^{LOSS}}{P_N^L} + \beta * \frac{H_F^L}{H_N^L} + \gamma * \frac{C_F^L}{C_N^L} \tag{8}$$

where P_F^L, H_F^L, C_F^L are the electrical, thermal, and cold energy loads in the original state of the building; P_N^L, H_N^L, C_N^L are the electrical, thermal, and cold energy loads after optimal scheduling, ΔP_F^{LOSS} is the power loss when the smart building transmits electrical energy to the grid. α, β and γ are weight coefficients, which are respectively 0.5, 0.3, and 0.2.

The energy supply reliability is characterized by the ratio of electric, thermal, and cooling loads in smart buildings before and after optimized scheduling. Based on the optimal distribution of heat and cold loads, the supply of electric energy is preferentially ensured. When the maximum energy supply reliability cannot satisfy the power supply requirements of the power grid, and the power loss cannot be filled, the energy supply reliability index can be reduced temporarily, and the power grid is supplied preferentially.

5. An optimization model for smart building scheduling

5.1. Formulation

Extreme weather causes severe damage to much outdoor equipment in the power grid. By isolating the damaged equipment in the grid, distributed power sources are utilized in the smart buildings to transfer electric energy so that the main load of the power grid can continuously run during major disasters. Part of the power supply is replaced by heat and cold energy to maximize the transmission power of smart buildings to the power grid.

The objective function is max P_t^L, and the optimization variables are H_t^L, C_t^L, P_t^L, where H_t^L, C_t^L, P_t^L represent the electrical, thermal and cold energy real-time loads in the smart buildings.

Smart buildings operation must meet electrical, thermal, and cold power balance constraints, as follows:

$$\begin{aligned} & P_t^{PG} + P_t^{PV} + P_t^{CCHP} = P_t^L + P_t^{AC} \\ & \sum_{i=1}^{N_{AC}} \Delta P_{t,i}^{AC} + \sum_{i=1}^{N_{EV}} \Delta P_{t,i}^{EV} + P_t^{BSS} \end{aligned} \tag{9}$$

$$H_t^{GB} + H_t^{CCHP} = H_t^L \tag{10}$$

$$C_t^{CCHP} + Q_t^{AC} = C_t^L \tag{11}$$

where P_t^{PV} 、 P_t^L 、 H_t^L , and C_t^L are photovoltaic output, basic electric load, basic heat load, building cooling load.

As for power grid, the constraints to be met include the power balance of the node, the power flow limitation of the line and the connection relationship of the network, the active and reactive power limits of the distributed power supply, and the node voltage constraints.

$$\begin{cases} \sum_{j|i\in\Omega_B} P_{i,t} = \sum_{j|i\in\Omega_B} P_{j,t} - P_{j,t}^g - (1-u_{j,t})P_{j,t}^L \\ \sum_{j|i\in\Omega_B} Q_{i,t} = \sum_{j|i\in\Omega_B} Q_{j,t} - Q_{j,t}^g - (1-u_{j,t})Q_{j,t}^L \\ 0 \le P_{i,t} \le (1-u_{j,t})P_{j,t}^{g,\max}, \forall i \in \Omega_B \\ 0 \le Q_{i,t} \le (1-u_{j,t})Q_{j,t}^{g,\max}, \forall i \in \Omega_B \\ 0 \le P_{j,t}^g \le P_{j,t}^{g,\max}, \forall j \in \Omega_N \\ 0 \le Q_{j,t}^g \le Q_{j,t}^{g,\max}, \forall j \in \Omega_N \\ |V_j^{\min}| \le |V_{j,t}| \le |V_j^{\max}|, \forall j \in \Omega_N \end{cases} \tag{12}$$

where Ω_N represents the set of distribution network nodes; $u_{j,t}$ represents the fault state of line j at time t, the fault is 1, and the normal operation is 0. After the solution is completed, the power supply of the DG to the critical loads in the island under different fault scenarios can be obtained.

5.2. Solution procedure

This paper proposes the objective function based on pre-disaster energy optimization scheduling model, including constraint conditions and decision variable set. The model is built on the random mixed-integer linear programming problem, discussing the extreme disasters with different influence ranges and maximizing the transmission capacity of distributed energy to the main load of the grid. In the MATLAB environment based on the YALMIP solution platform, the problem can be solved by programming in the currently developed CPLEX business solver to get the optimal global solution.

Step 1: Use the mesh grid method to generate a set of disaster scenarios caused by multiple different types of extreme weather.

Step 2: Analyze the photovoltaic power generation, heat storage tank, heat pump, and CHP in the smart buildings to obtain the models of electrical and thermal energy generation and storage.

Step 3: Combine the historical power data of load in the building to establish the smart buildings energy consumption model, consider the random variables and determine the energy consumption model per unit time, and get the energy supply reliability in the case of satisfying the fundamental power and heating demand of the smart buildings.

Step 4: Establish a prediction model for the damage of the power grid under a specific disaster and determine the power loss in the situation of disaster.

Step 5: Consider the situation of smart buildings power delivery after the power grid is damaged and solve the power transmission range under the premise of ensuring the energy supply reliability of smart buildings.

Step 6: Determine whether the solved transmission power can satisfy the grid power loss. If no, reduce the energy supply reliability requirement (ESR) index and return to step 4; if yes, end the iteration and output the results.

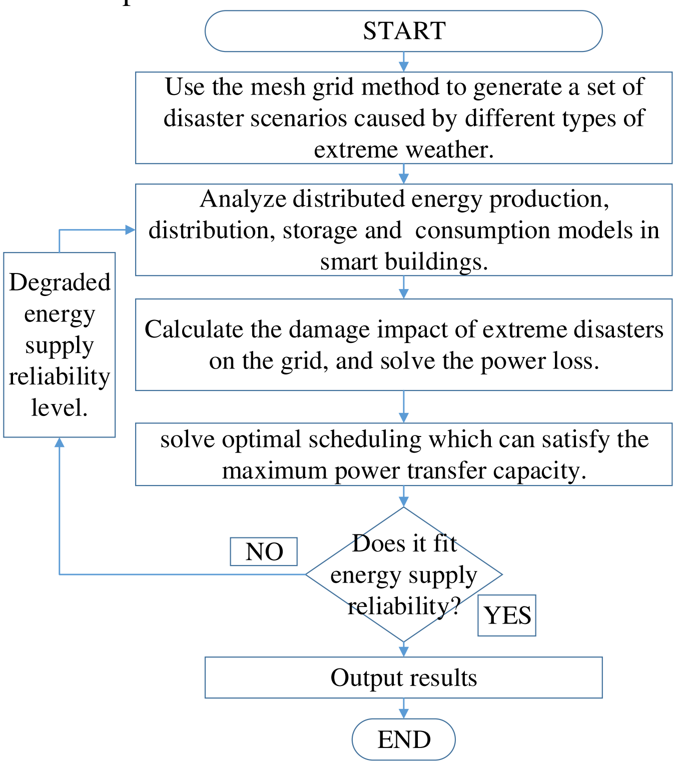

Figure 4 Flowchart of optimal dispatch of energy delivery after natural disasters

6. Case study

6.1. Comparative analysis of energy supply reliability (ESR) before and after optimization

A classic smart building model is illustrated in this section to verify its effectiveness in achieving the fast start mode of power transmission to the power grid.

Various natural disasters are considered to achieve this, including but not limited to insulator ice coating, lightning strikes, typhoons, and earthquakes, to calculate their impact on the reliability of IEEE 30-node power system. The mesh grid method is used to divide the distribution power system into 32*30 grids, and each grid is represented by matrix elements. Then Monte Carlo method is used to imitate the damage of the extreme disasters to the grid and solve the grid power loss. After the extreme disasters, the distributed power sources at the end of the smart building are still alive and can be distributed to the power grid to improve the efficiency of restarting.

DG considered in this paper mainly includes PV roofs, electric boilers, heat pumps and other production equipment. The maximum available power is shown in Table 1.

Table 1: Energy input parameters in smart buildings

Types of energy input parameters	**Output(kW)**	**Form of energy flow**
Photovoltaic power generation	0~60	Electricity
Heat pump	0~30	Heat energy
Electric boiler	0~20	Heat energy
CHP1	0~80	Electricity
CHP2	0~70	Heat energy
Compression refrigerator	0~25	Cold energy

By optimizing the distribution of electricity, heat energy, and cold energy flow in smart buildings, part of the power supply load in the buildings is replaced by heat and cold sources. While ensuring the normal supply of buildings and maximizing energy supply reliability (ESR), the grid power provided to compensate for the power loss of the island grid is expected to be maximized.

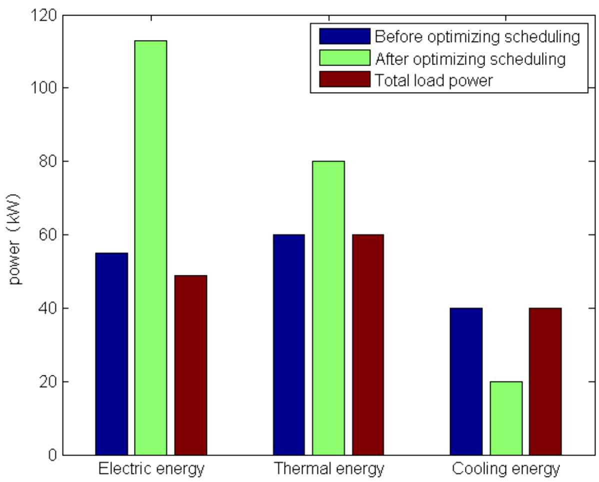

Figure 5 Comparison of energy supply and demand before and after disasters

6.2. Sensitivity analysis

To more accurately quantify the degree of improvement of DG for disaster recovery, a sensitivity analysis was conducted to increase the maximum available power of DG in Section 6.1 and to explore the effect of different proportions of DG's maximum available power on energy supply reliability (ESR), as shown in Fig.6.

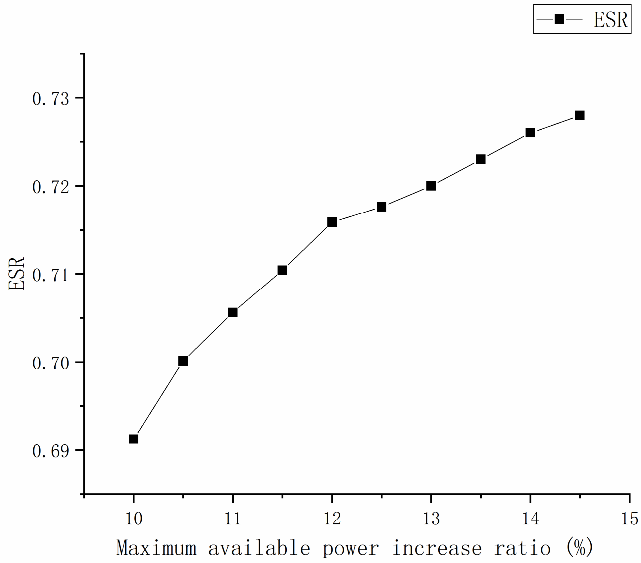

Figure 6 Effect of DG's maximum available power on ESR

Figure 6 shows that when the maximum available capacity of DG increases by 10% - 15%, the energy supply reliability (ESR) also increases accordingly, but the growth trend is relatively slow. It is because there are certain electricity, heat, and cold loads (such as building lighting, heating, and computer room cooling) in the smart building, and only part of the additional capacity is used for load recovery of the distribution network after a disaster. Therefore, to improve the recovery capability of the resilience of the distribution network, under the premise of meeting the fundamental comfort requirements of smart building users, a certain amount of load shedding can be considered to supply more power to the island grid and to help to resume after disasters.

6.3. DG's impact on energy supply reliability (ESR) under different disasters

Simultaneously, the energy supply reliability (ESR) is calculated under each natural disaster condition. The results, as shown in Table 2, indicate that under the current building scale after the power is delivered, it has different effects on the reliability of its load operation. In the icing and lightning strike disasters, the building itself can maintain the normal operation. After ending the optimal operation of the energy, the building can return to the original state and achieve normal and stable operation.

By rigorous calculation, of the given condition, the grid forms an island, and the energy flow in the smart buildings can effectively fill the power loss of the island grid and ensure the energy supply reliability.

Table 2: Impact on ESR caused by different disasters

Types of extreme disasters	**Power loss(kW)**	**Energy demand(kW)**	**ESR**
Typhoons	189	143	0.49
Earthquakes	196	139	0.53
Ice-coating	167	153	0.89
Lightning strikes	173	158	0.81

7. Conclusion

This paper aims to research the enhancement of distribution system resilience using surviving distributed power sources in smart buildings after extreme disasters. Moreover, energy supply reliability indicators and analysis frameworks are proposed. By using the mesh grid method to simulate a variety of extreme weather damages, the power distribution of smart building energy supply and load is optimized to satisfy the grid power loss. Through the analysis of the case study, the following conclusions can be obtained:

1) The surviving distributed power sources of smart buildings after extreme disasters can support the resilience of the power grid to a certain degree and can be used as backup power for the power grid to improve its reliability.

2) By adjusting the energy supply structure and load energy using forms in the smart buildings, the power delivery capability can be increased, and the grid resilience can be improved.

3) The maximum available power of various types of DG in a smart building has a specific impact on post-disaster load recovery and promotion. Appropriately increasing the maximum available power of DG can effectively improve energy supply reliability (ESR) and the efficiency of load recovery.

The future of this proposed paper should be pointed out. It does not focus on small-scale disaster situation of smart buildings, but only simulates the damage process of the power grid. We next will analyze the disaster situation of the distributed power sources inside the smart buildings. The research of this paper will provide some ideas and reflections for further studies on the research of power grid recovery and its resilience.

Acknowledgement

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