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RELIABILITY ASSESSMENT OF RURAL CLEAN ENERGY SUPPLY SYSTEM BASED ON ACCURATE MODELING OF USER DEMAND

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ABSTRACT

The popularity of electric heating equipment in rural areas has led to an increase of the peak load of electricity. In order to ensure the reliability of the system, the indoor building heat balance and the flexible comfort requirements of users can be comprehensively considered. So we propose a reliability assessment method of rural clean energy supply system based on accurate modeling of user demand. Firstly, the rural clean energy supply system framework is constructed, including the system-side equipment model and user-side building heat balance model. Secondly, we model the user's flexible comfort requirements, which derive indicators of the reliability of energy supply considering flexible comfort requirements. Thirdly, the method of fault impact analysis of rural clean energy supply system is proposed, and the load reduction strategy at failure time and the process of reliability assessment are formulated. Finally, through practical examples, we compare the reliability indicator whether considering the user's flexible comfort requirements and the building heat balance characteristics or not, which prove the improvement of the reliability of energy supply of the whole system of the proposed method.

Keywords: Building heat balance, Customer comfort, Clean energy supply system, Load reduction, Reliability assessment

NONMENCLATURE

Symbols	
K_i	total number of inner surfaces of different enclosures in the room
α_k	Convective heat transfer coefficient of envelope structure k(W/m²·℃)
C_w/C_n	Air specific heat of indoor and outdoor
ρ_w/ρ_n	Air density of indoor and outdoor
V_o	Outdoor air penetration(m³/h)
β	Cold air permeability
K_d/F_d	Heat transfer coefficient and area of door
$V(t)$	Ventilation volume at time t
$T_n(t)/T_w(t)$	calculated temperature of indoor and outdoor
V	Air volume
η	Heat dissipation efficiency of radiator
$Q(t)$	Total heating power input by the heat source device at time t
$PMV(t)$	PMV indicator value at time t
M	the body's metabolic rate
I^{cl}	Thermal resistance of clothes
$H_{hg,I}/U_{hg,i}$	Average heat load and annual average heating stop time at the load point i under rigid comfort demand
$H_{hr,I}/U_{hr,i}$	Average heat load and annual average heating stop time at the load point i under flexible comfort demand
N_i	Number of users at the load point i
$P^j_{PV}(t)$	The real-time output of distributed photovoltaic j at time t
$P^i_d(t)$	Discharge power of power storage device i at time t
$N_{PV}/N_d/N_L$	Total number of distributed photovoltaic, power storage device and load
t_{st}/t_{end}	The start and end moment of island
$L_t^k(t)$	The Real-time load of load k at time t
L_{con}	Transfer capacity of feeder during transfer period
$X(k)$	The reduction state of load point k

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1. INTRODUCTION

With a number of national policies to promote the development of clean heating[1], electric heating equipment has gradually become popular. Electric heating equipment, the component of connecting the distribution network and the heat network, has promoted the transformation of the traditional rural distribution network to the clean energy supply system. For the building, it has a certain thermal inertia, so the temperature change in the room lags behind that of heating power. On the other hand, residents' comfort demands are reflected in the temperature range, not a fixed temperature value. Therefore, it is an urgent problem to be solved to establish a suitable building thermal balance model and a flexible comfort demand model for users in rural areas to ensure the reliability of the rural clean energy supply system.

At present, reliability research is mostly concentrated in power system field. Reference [2] adopts the regional failure mode impact analysis method, and proposes a method to evaluate the reliability of distribution systems with distributed power sources by using Monte Carlo simulation method. With the development of multi-energy systems, the reliability research of power systems has evolved into multi-energy systems. In [3], based on the operating mechanism of microgrid system and the difference of energy taste, a reliability evaluation of microgrid with energy storage considering multi-energy coupling and grade difference is proposed.

In addition, the actual experience of the end-users is an important part, which refers to the actual demand of the users during the winter heating period. The user's comfort demands is reflected in the temperature interval. The thermal inertia of the building also affects the user's thermal demands. Literature [4] converts the user's thermal demand into a fixed temperature range, and applies it to the new energy consumption research of the heat network. Literature [5] proposes a rural micro-energy network electric heat joint scheduling method considering the indoor building thermal balance and the users' flexible comfort. The above studies did not consider the impact of end-user demand on reliability.

If the users' flexible comfort demands can be considered, combining the energy storage characteristics of the building and formulating a reasonable operation strategy of the electric heating equipment, the reliability level of the combined electric and heat system will be improved. To this end, this paper proposes a reliability assessment of rural clean energy supply system based on accurate modeling of user needs. The contributions of this paper are mainly included in the following aspects. Firstly, this paper constructs the rural clean energy supply system framework, and proposes the energy supply reliability indicator considering the flexible comfort demand. Secondly, considering the building heat balance model and the user flexible comfort demands, the load reduction strategy of the island operation and transference area after failure is proposed, and the reliability evaluation method of the rural clean energy supply system is improved. Thirdly, the enhancement of building heat balance model and user flexible comfort demand model to reliability is analyzed by examples.

2. RURAL CLEAN ENERGY SUPPLY SYSTEM FRAMEWORK AND USER-SIDE BUILDING HEAT BALANCE MODEL

2.1 Rural clean energy supply system framework and equipment energy efficiency model

The rural clean energy supply system framework is shown in Figure 1.

Distributed photovoltaic are in low permeability levels[6]. The model of electricity storage device is in [6], the heat storage device uses the model in [7]. For electric heating equipment, the relationship between the heating coefficient and the heating capacity of the air source heat pump is as shown in [8].

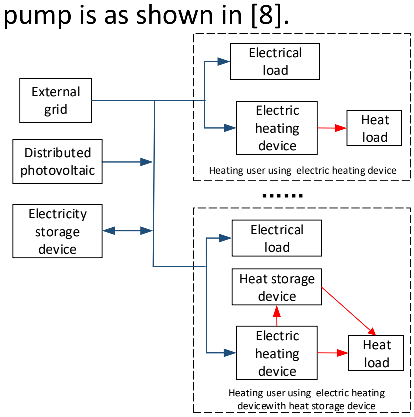

Fig 1 The framework of rural clean energy supply system

2.2 User-side building heat balance model

Due to the thermal inertia of the building, the change of indoor temperature will lag behind the change of heat power of electric heating equipment. The air heat balance model in the building can more accurately analyze the user heat demand. After reasonable simplification, the indoor thermal system balance equation can be shown in equation (1)[12].

$$\left(\sum_{k=1}^{N_i} F_k \alpha_k + 0.278 \times c_w \rho_w V_0 + \beta K_d \mathrm{F}_d + 0.278 \times c_w \rho_w V(t)\right) \quad (1)$$

$$\left[T_n(t) - T_w(t)\right] + 0.278 \times c_n \rho_n V \frac{\partial T_n(t)}{\partial t} = 3.8A + \eta Q(t)$$

3. MODEL OF FLEXIBLE COMFORT DEMAND AND ENERGY SUPPLY RELIABILITY INDICATOR

3.1 Model of flexible comfort demand

Taking into account the user's schedule of work and the impact of flexible comfort requirements on the user thermal demands, model of flexible comfort demands can reduce the user's thermal demands while ensuring user comfort.

The user's requirement for comfort in the building is not to make the indoor temperature constant, but to maintain the indoor temperature within a certain range. This paper uses the estimated average thermal sensation indicator PMV to measure the user's comfort requirements for the building[9], the calculation formula is shown in equation (2).

$$\mathrm{PMV}(t) = 2.43 - 3.76 \times \frac{33.5 - T^{in}(t)}{M(I^{cl} + 0.1)} \qquad (2)$$

The conditions that must be met to form a comfortable thermal environment are given by the ISO7730 New Standard. The recommended range of PMV indicator is shown in equation (3).

$$-0.5 \le PMV \le 0.5 \qquad (3)$$

By calculation, temperature comfort interval for the user in winter is 20~24 °C. The standard also indicates that the indoor temperature for maintaining the user's most comfortable thermal environment during the winter is 22 °C. It is noteworthy that the user does not require indoor temperature while nobody is at home.

3.2 Energy reliability indicator considering differentiated comfort demands

The energy supply reliability indicators of rural clean energy supply systems can be divided into power supply reliability indicators and heat supply reliability indicators. The power supply reliability indicator uses the indicator in the literature [6], including the system total power shortage indicator *ENS* and the System average power outage time indicator *SAIDI*.

The heat supply reliability indicator can be derived from the power supply reliability indicator, and the system total heat shortage indicator ENS_h, the system average heating shortage time indicator $SAIDI_h$ and the average heating availability indicator $ASAI_h$ are represented. The calculation formula are is as follows.

$$ENS_{hg} = \sum H_{hg,i} U_{\mathrm{hg},i} \quad (4) \qquad ENS_{hr} = \sum H_{hr,i} U_{\mathrm{hr},i} \quad (5)$$

$$SAIDI_{hg} = \frac{\sum U_{hg,i} N_i}{\sum N_i} \quad (6) \qquad SAIDI_{hr} = \frac{\sum U_{hr,i} N_i}{\sum N_i} \quad (7)$$

$$ASAI_{hg} = 1 - \frac{SAIDI_{hg}}{8760} \quad (8) \qquad ASAI_{hr} = 1 - \frac{SAIDI_{hr}}{8760} \quad (9)$$

4. RELIABILITY ASSESSMENT OF RURAL CLEAN ENERGY SUPPLY SYSTEM CONSIDERING ACCURATE MODELING OF USER DEMANDS

4.1 Component state model

Before using Monte Carlo simulation for system reliability evaluation, the state of each component needs to be sampled. In this paper, the two-state Markov model[6] is used to set up the component's failure rate λ and repair rate μ to sample the trouble-free working time and fault repair time of the components in the rural clean energy supply system.

4.2 Failure impact analysis

After the component failure, the fault impact analysis needs to be carried out. In this study, distributed photovoltaics and tie switches are involved. The fault impact analysis method in [6] is used to divide the system into nine regions. Only the single fault condition is considered.

4.3 Load reduction strategy considering accurate modeling of user demands

The heating power and indoor temperature of the air source heat pump satisfy the building heat balance constraint (1). When the system is in normal operation, the indoor temperature is maintained at an ideal value by adjusting the air source heat pump. After the system fails, the air source heat pump needs to be adjusted to reduce the user's heat demand while satisfying the user's heat comfort.

After the system fails, the contact switch is closed to form an island or area to be transferred. For the fault area in the operation of the island, when the distributed photovoltaic output is insufficient, the storage device is used to discharge. If the full load cannot be supplied, the load in the island needs to be reduced, and the mathematical expression for determining whether the load is needed is determined is shown in equation (10).

$$\sum_{j=1}^{N_{PV}} P_{PV}^{j}(t) + \sum_{i=1}^{N_d} P_d^{i}(t) < \sum_{k=1}^{N_L} L_t^{k}(t), \quad t \in [t_{st}, t_{end}] \quad (10)$$

For the fault area to be transferred, when the load transferred is greater than the contact capacity, the storage device is used to discharge. If the total load cannot be supplied, the load needs to be reduced. The mathematical expression is shown in equation (11). The objective function of load reduction is shown in (12).

$$L_{con} + \sum_{j=1}^{N_{DG}} P_{PV}^{j} + \sum_{i=1}^{N_d} P_d^i(t) < \sum_{k=1}^{N_L} L_t^k \quad (11)$$

$$\max \sum_{t=t_{st}}^{t_{end}} \sum_{k=1}^{N_L} L_t^k(t) X(k) \quad (12)$$

The detailed process of the load reduction strategy is shown in Figure 2.

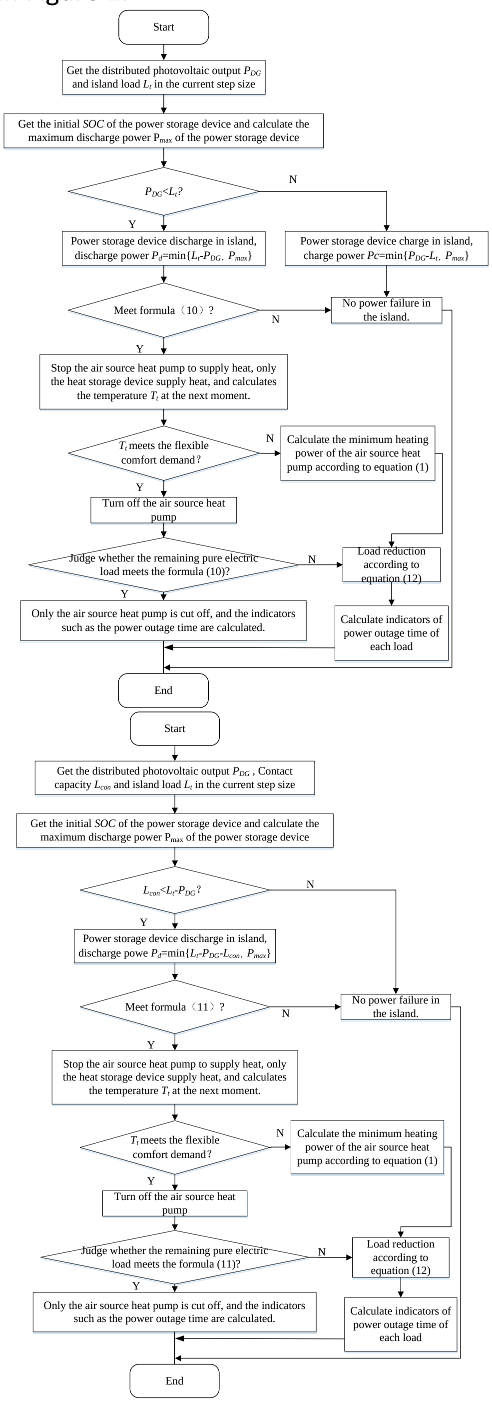

Fig 2 Load Reduction Strategies for island operationt and areas to be transferred

4.4 Reliability assessment process

For the rural clean energy supply system including distributed photovoltaic, air source heat pump and storage device, the process of Monte Carlo simulation reliability assessment is shown in Figure 3.

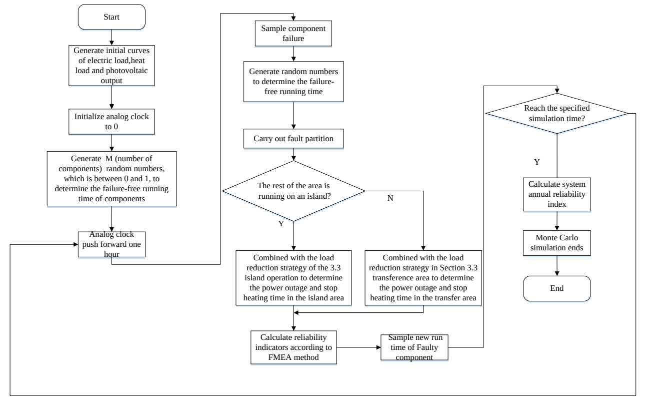

Fig 3 Reliability evaluation process

5. CASE ANALYSIS

5.1 Case parameter

In this paper, a modified multi-branch feeder IEEE RBTS Bus6 is taken as an example to analyze, and adds air source heat pump (HP), distributed photovoltaic (PV) and storage device. The example structure is shown in Figure 4. The specific parameters are as follows.

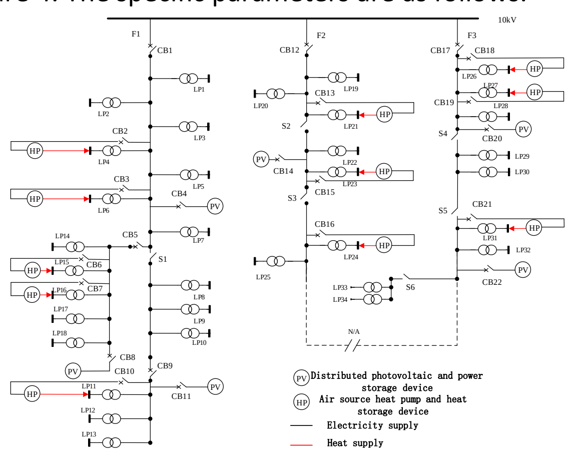

Fig 4 The structure of the example system

The specific light intensity R_c and the rated light intensity G_{std} are 0.15 kW/m^2 and 1 kW/m^2, the photovoltaic rated power P_{sn} is 0.9 MW. The COP of air source heat pump is 3. The electrical storage device rated capacity is 3 MWh, the maximum charge and discharge power is 0.25MW, the charge and discharge efficiency is 0.85. The rated capacity of the heat storage device is 2MW·h, and the maximum charge and discharge power is 0.2MW. The electrical load data is collected in [3].The heat load data is calculated by the relationship between the indoor temperature and the heating power in [10], that is, the formula (13), and the indoor temperature is set to 22 ℃. The capacity of the feeder F1, F2 and F3 are 13.5 MW, 6MW and 6 MW, separately. The indoor temperature is selected to be 20 to 24 °C. According to the law of the villagers' work schedule, it is stipulated from 7:00 am to 11:00 am and from 3:00 pm to 17:00 pm, there is no demand for thermal demand.

$$Q_{l,t} = \frac{1}{R}\left(\frac{T_{in,t+1} - kT_{in,t}}{1-k} - T_{out,t}\right) \qquad (13)$$

5.2 Reliability assessment

In order to analyze the impact of flexible comfort demands and building heat balance model on the reliability, the following two cases are set.

Case 1: Do not consider the building heat balance of indoor buildings.

Case 2: Consider the building heat balance of indoor buildings

When calculate the reliability index under the rigid comfort demand, the indoor heating mode is used to maintain the indoor temperature at 22 °C. When calculating the reliability index under the flexible comfort demand, the indoor temperature meets the required temperature in the section 4.1.

5.2.1 The comparison of energy supply reliability

The reliability evaluation process of Section 3.2 is used to evaluate the reliability of the two cases. The system reliability indicators are shown in Table 1.

Table 1 System reliability index under different schemes

Case	Power supply reliability		Heat supply reliability			
	ENS/ MWh/a	SAIDI/ h/(user·a)		ENS_h/ MWh/a	$SAIDI_h$/ h/(user·a)	$ASAI_h$/ %
1	91.266	8.165	Rigid comfort demand	31.348	6.864	99.9216
			Flexible comfort requirements	15.436	4.841	99.9447
2	91.266	8.165	Rigid comfort demand	25.346	5.872	99.9329
			Flexible comfort requirements	13.768	2.894	99.9669

For power supply reliability, since the building heat balance and the flexible comfort demands all affect the user's heat demand, the power supply reliability of the system is not affected. For heat supply reliability, considering the building heat balance and adopting flexible comfort demands can effectively improve the reliability of the rural clean energy supply system. Compared with the reliability index under the flexible comfort demand and the rigid comfort demand, it can be seen that the energy supply reliability improvement brought by only the flexible comfort demand is more than it brought by the building heat balance. According to case 2, it can be seen that considering the building heat balance and flexible comfort demands, the energy supply reliability can be further improved.

5.2.2 Impact on reliability assessment considering building heat balance

Figure 5 shows the temporal variation of the outdoor air temperature and the air source heat pump heat power considering the building heat balance or not under rigid comfort demand.

It can be seen from Figure 5 that when considering the building heat balance, the indoor temperature changes have time delay characteristic, and the peak time of the air source heat pump heat power is slightly earlier than the outdoor temperature lowest point, so the heat power at the outdoor temperature lowest point is reduced. The maximum heat power without considering the building heat balance is 0.6MW, the maximum heating power considering the building heat balance is 0.565MW, and the peak value of the heat power is reduced by 5.83%, which improves the electricity load curve. In some fault scenarios, the areas that cannot be transferred or the islands cannot be operated can be transferred and run. So it can reduce the time to stop heating and improve the reliability of heat supply.

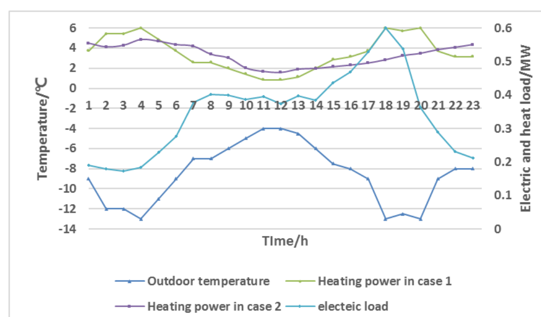

Fig 5 Outdoor temperature and electric heat load curve

5.2.3 Impact on reliability assessment considering flexible comfort demands

To demonstrate the impact of flexible comfort requirements on energy supply reliability, compare the reliability indicator of case 1 considering flexible comfort demands or not.

When the isolation switch S3 is faulty, the contact transfer area in the fault division of the distribution network is the area composed of the air source heat pumps at LP24, LP25 and LP24. After the fault occurs, the downstream contact switch is closed, and supply power to the contact transfer area through the feeder F3. If the load reduction determination condition formula (11) is satisfied, the load is reduced. The electric heating load curve is shown in Figure 4.

When S3 fails at 19 o'clock, the electric load under feeder F3 is 0.545 MW and the heat load is 0.59 MW. At this time, the discharge power of the electrical storage device is maximum 0.25 MW, and the heat release power of the heat storage device is also the maximum 0.2 MW, and the maximum contact transfer capacity of the feeder F3 is calculated to be 1.205 MW. Considering the rigid comfort demands, LP25, LP24 and the air source heat pump at LP24 need to be reduced in load. And the electric load of air source heat pump at LP24 needs to be reduced, leaving electric of LP25 and LP24, while the heat load needs to be cut off. If the flexible comfort demand is adopted, the heat load required by the user can be reduced. So the air source heat pump at the LP24 can be transferred, thereby improving the system heat supply reliability. The load reduction plan at 19 o'clock is shown in Table 2.

Table.2 Load reduction scheme in case of failure at 19 o'clock

comfort demands	The time of stopping heat supply in HP (h)	The heat load value of HP (MW)	The heat release of heat storage device (MW)
Rigid	2	0.39	0.2
flexible	0	0.335	0.2

It can be seen from Table 3 that whether adopting the flexible comfort demand will change the user's heat demand value. So the heat load of the air source heat pump can be transferred, which improves the heat supply reliability.

6. CONCLUSION

Based on the consideration of the building heat balance model and the user flexible comfort demands, Monte Carlo simulation is used to evaluate the reliability of the rural clean energy supply system. Through the analysis of the example, the following conclusions can be obtained:

(1) Considering the heat balance characteristics of the building, the heat power of the air source heat pump can be increased when the outdoor temperature is high, and the heat demand can be reduced using the heat storage characteristics of the building when the outdoor temperature is low, and the curve of the energy consumption of the air source heat pump can be improved, which improves the reliability of energy supply;

(2) Compared with the indoor constant temperature heating, the user's flexible comfort demand can reduce the user's thermal demand when the heat load cannot be transferred. So the load can be transferred or the heat loss can be reduced when the supply cannot be transferred, which improves energy supply reliability;

(3) Considering the heat balance characteristics of the building and the user's flexible comfort demands, the improvement of the reliability index is more obvious. And it can play a role in improving the reliability of energy supply. The promotion has practical value.

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