Performance analysis of IoT-enabled hydro-photovoltaic power systems considering electrical power mission chains

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Abstract: Synergistically and complementarily managing the operation of hydropower plants and other weather-dependent renewable energy generation plants (e.g., solar energy plants) provides an effective measure to improve the performance efficiency (PE) of renewable energy. However, environmental uncertainty and physical system unavailability pose challenges in assessing the PE of the power generation. This paper proposes an approach to synergistically and complementarily managing the operation of hydro-photovoltaic (HPV) power systems in IoT under uncertain environments and develops a mission chain-based PE model for quantifying the capacity of the fulfilment of a power supply mission to satisfy users' demand for power. An importance measure-based restoration strategy is then proposed to enhance the PE of an HPV power system (PEPS). The approach is examined by taking a large-scale HPV in China in the case study. The results show that, in winters and in summers, the PEPS is higher than PE of a photovoltaic power system and a hydropower system, respectively, and the PEPS with the importance measure-based restoration strategy is higher than that under the random restoration strategy, respectively. The findings not only lay the foundation for the complementary operation of hybrid renewable energy power systems but also provide a reference for the restoration in case of power cuts.

Keywords: Hydro-photovoltaic power system; Performance; Mission chain; Restoration

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1 Introduction

1.1 Background

With the growth of population and rapid economic development, the world's energy demand is increasing [1]. However, the exploitation and use of traditional energy resources (e.g., coal, oil, natural gas…) has brought serious environmental problems. There is a growing preference for renewable energy resources (RES) [2]. As the two most mature forms of RES, hydropower and photovoltaic (PV) power have been widely applied in smart power systems. Hydropower systems convert hydro energy into electrical energy. PV power systems directly convert solar energy into electrical energy using PV cells based on PV effect [3]. Both hydropower systems and PV power systems have the characteristics of long service life and little pollution to the environment. They can be smart. Smart hydropower systems achieve intelligent scheduling by monitoring parameters such as water level and flow velocity and smart PV power systems realise intelligent control and management by monitoring parameters such as light intensity and panel temperature. Nevertheless, both hydropower and PV power are affected by the seasonal factor and weather, showing randomness, intermittence, and seasonality. For safety and cost saving, power system managers are reluctant to accommodate large-scale PV power due to the poor power quality of solar energy [4]. Moreover, energy waste is also a serious problem. Synergistically and complementarily managing the operation of hydro-PV (HPV) plants is therefore vital, which can improve the stability of power systems. More importantly, HPV power systems have high economic and environmental benefits. It can not only reduce energy waste and has an exemplary role for achieving the target of decarbonisation in the energy sectors, but also make a more efficient use of energy and contribute to the development of RES.

1.2 Literature review

A power system is a network composed of some electrical equipment for power transmission, transformation & distribution, and usage. Many authors have done research on the analysis of power demand and supply [5]. Zhou et al. [6] proposed a optimisation operation framework for a pumped-storage power plant driven by the peak-shaving and valley-filling operation method. Park et al. [7] presented a multi-objective optimisation-based framework for managing solar powered green hydrogen systems to balance the trade-off between economic cost and productivity. Narasimman et al. [8] evaluated real time performance of a grid-connected PV plant to identify the impact of various environmental parameters on the PV power generation. Considering the weather and climate driven RES, one of the most common solutions to overcome the mismatch between demand and supply is a hybridisation of two or more energy resources into a single power plant. The operation of hybrid energy resources is based on the complementary nature of RES [9]. Adefarati et al. [10] proposed a method to manage a hybrid energy system consisted of wind turbines, fuel cells, PVs and utility grids to meet users demand for energy. Chen et al. [11] proposed a method for managing a PV-natural gas integrated energy system to optimise the energy, environmental and exergo-environmental parameters in power systems. Mansoor et al. [12] developed two new hybrid models for forecasting the amount of power generated by a wind-PV power system. Hamza et al. [13] forecasted the amount of power generated by a renewable energy system in hybrid wind-PV power systems. Shams et al. [14] predicted and analysed the oversupply of wind and solar energy in power systems. However, the inherent fluctuation and intermittence of wind power and PV power pose great difficulties for stable power system operation [15]. Li et al. [16] considered the difference in the methods of supplementing the variable and intermittent output of wind and PV power and outlined five consumption modes. He et al. [17] proposed a method for managing a wind-PV-battery-thermal energy storage system with a multi-objective planning-operation co-optimisation. Javed et al. [18] claimed that hybridisation of pumped hydro storage can increase the system reliability when renewable energy systems are off-grid. Bhayo et al. [19] optimised power management of hybrid solar PV-battery integrated with a pumped-hydro-storage system for standalone electricity generation. Fang et al. [4] explored the complementary HPV operation with the purpose of improving the power quality of PV and promoting the integration of PV into the system. To summarise, more authors study power systems related wind and PV now. But the few focus on synergistically and complementarily managing the operation of the two energy resources including hydro and PV.

For power system performance, Fan et al. [20] evaluated the influence of renewable energy uncertainty on power system dynamic performance. Li et al. [21] constructed a multi-state model to quantify the time-varying performance of the battery energy storage system. Yuan, Wang and Chen

[22] presented a self-optimisation droop control strategy for microgrid considering operation cost and efficiency to improve the overall operation performance. Yuan, Xia and Li [23] proposed an energy dispatch model for grid-connected microgrids to trade off the economic efficiency and operational risk. Chakraborty, Modi and Singh [24] presented a reliable, resilient, real-time, rule-based energy management scheme for microgrid to improve the efficiency. Zhang et al. [25] modelled the fragility of an energy-delivery system and integrated to assess critical power equipment performance. Poudel, Manwell and McGowan [26] developed a stochastic model for downscaling of streamflow and an empirical model of a micro hydropower system for performance analysis. Zamora-Juárez et al. [27] assessed the performance of a micro hydropower plant integrated into a rainwater harvesting system. Gopi et al. [28] analysed the weather impact on the performance of a solar farm by comparing of different machine learning techniques. Wang et al. [29] proposed a real-time dispatch method for a hybrid HPV system to minimise the negative effects of PV power generation fluctuations on the performance of hydro units. Alqahtani, Yang and Paul [30] assessed the performance of a pumped hydro power energy storage connected to a hybrid system of PV and wind turbines. In summary, most articles concerned about the performance of traditional power systems and new power systems with single RES, while little research on performance efficiency of hybrid power systems has been done. Furthermore, the exploration about the performance efficiency of hybrid HPV power systems is scant.

A power system is highly susceptible to various hazards such as natural disasters, instabilities, and extreme weather [31,32]. The vulnerabilities of a power system can cause huge losses of power supply with sever social and economic consequences [33]. Sperstad, Kjolle and Gjerde [34] provided a comprehensive framework for vulnerability analysis of extraordinary events in power systems. Mohammadi and Sahraei-Ardakani [35] developed a multidimensional scenario selection method, which made use of failure features as well as network features of the elements that may fail, to achieve a superior performance of a power system. Shuvro et al. [36] developed a Markov-chain model to capture the dynamics of cascading failures in power grids. Xie et al. [37] improved performance of distributed optimal frequency control under communication failures of a power system. Amiri et al. [38] proposed a method to detect and diagnose the faults of PV systems based on a machine learning. Aghaei et al. [39] connected the degradation phenomena and failure modes to the module component, and its effects on the PV system. Faced with all kinds of risks and failure, ensuring the reliability of power systems is vital for assuring the quality of the power supply by taking definite restoration measures [40]. Yan et al. [41] proposed a novel restoration rule set for scheduling the power system equipment repair after the occurrence of extreme events. Shankar, Inkollu and Nithyadevi [42] offered accurate predictions, proactive decision support, and efficient restoration strategies. Bosisio et al. [43] presented a tabu-search-based algorithm to restore the energy supply after permanent faults. Nahi, Zare and Faghihi [44] designed a short-term estimation model of wind power delivery to variable loads for rapid restoration of power systems during the self-healing service process. Qiu et al. [45] explored the potential benefits of RES in restoration and potential ways for variable RES to participate in system restoration. Fotis, Vita and Maris [46] presented a novel restoration strategy focused on the fast and reliable power supply after a blackout. Vita et al. [47] suggested a restoration technique using distributed generation for the restoration of important loads after a blackout to maximise the number of critical loads that are restored following the catastrophic incident. In short, many have studied the failure and restoration of power systems, while relatively few consider the importance measure-based restoration strategy of power systems under different equipment failures.

1.3 Research gaps and contributions

According to the above review, even though there is a relatively well-developed knowledge of performance evaluation, failure analysis and restoration technique, it is noted that most studies mainly focused on conventional power systems, single-RES power systems and complementary wind-PV power systems. However, little research is done on considering the performance efficiency enhancement and novel restoration strategy of hybrid power system with variable RES (e.g., solar energy) and stable RES (e.g., hydro energy). More importantly, in addition to relying on the energy storage system to make up for the shortcomings of variable RES, synergistically and complementarily managing variable RES power systems and stable RES power systems is a feasible solution. Managing a PV power system with a hydropower system to form an HPV power system and thus studying its performance efficiency are scant. Performance improvements can increase the efficiency of a power system. Performance efficiency improves not only system performance, but also the efficiency of operation and maintenance (O&M). Therefore, this paper focuses on HPV power systems and the objective is to enhance the performance efficiency of the HPV power system based on power supply missions. A performance efficiency model of HPV power systems is developed based on electric mission chains. An importance measure-based restoration strategy is proposed to enhance the performance efficiency of the HPV power system.

In conclusion, the novelty and contributions of this paper can be described as follows.

- A mission chain model of HPV power systems for power supply mission is developed by holistically considering the power generation, transmission, transformation and distribution, and usage process.
- A performance efficiency model for HPV power systems considering different types of power equipment is established from the perspective of social power service.
- Restoration importance is proposed to enhance the performance efficiency of power systems. The equipment restoration strategy in the order of importance measures can improve the performance efficiency of HPV power systems under the limited resources.

1.4 Overview

The remainder of this paper is organised as follows. Section 2 develops a mission chain model and a heterogeneous network model of HPV power systems in IoT. Section 3 establishes a performance model considering different nodes' electric power. Section 4 enhances the performance of HPV power systems based on restoration importance. Section 5 studies a case and discusses the results. Section 6 concludes the paper.

Nomenclature

Abbreviations

HPV	Hydro-photovoltaic
HV	High voltage
IoT	Internet of Thing
LV	Low voltage
O&M	Operation and maintenance
PV	Photovoltaic
RES	Renewable energy resources

Symbols

D_k	The k-th ($k = 1,2, \ldots, K$) power transformation and distribution node
e_{mi}	Edge connecting the m-th ($m = 1,2, \ldots, M$) load node and the i-th ($i = 1,2, \ldots, I$) power generation node
e_{ij}	Edge connecting the i-th power generation node and the j-th ($j = 1,2, \ldots, J$) transmission node
e_{jk}	Edge connecting the j-th power transmission node and the node D_k
e_{km}	Edge connecting the node D_k and the m-th load node
G_i	The i-th power generation node
I_a^p	Restoration importance of the node a
L_m	The m-th load node
m_0	Number of satisfied users whose demand for power are met
P_a^{PEM}	Performance of the node a
P_i	Electric power of the node G_i
P_j	Electric power of the j-th power transmission node
P_k	Electric power of the node D_k
P_m	Input electric power of the node L_m
PE	Performance efficiency of an HPV power system
PEM	Performance efficiency of multiple users
PES_m	Performance efficiency of the m-th single-user
Q_m	Demand for power of the node L_m
T_j	The j-th power transmission node
λ	Failure rate
μ	Restoration rate
τ	Mission baseline

2 Electric mission chains modelling of HPV power systems in IoT

2.1 HPV power systems in IoT

In the HPV power system studied in this paper, the IoT technology plays a crucial role. The IoT realises the digitalisation and intelligence of power systems by connecting various equipment to the Internet, which provides a technical guarantee for realizing two-way interaction between users and the power system and improving power supply reliability. HPV power systems are seriously affected by internal and external hazards, so it is vital to study the methods of enhancing the performance efficiency of power systems in complex and dynamic environments. Under the IoT, the physical layer of HPV power systems is composed of complex subsystems such as hydropower generation subsystems, PV power generation subsystems, energy storage subsystems, power transmission subsystems, and power transformation and distribution subsystems. All subsystems cooperate to complete the operation of a power system. The core equipment of those subsystems can be simplified into power plants, high voltage (HV) towers, distribution stations with transformers, and loads. Each equipment in the physical layer can be connected through electric mission chain. A typical IoT-enabled HPV power system is shown in Fig.1.

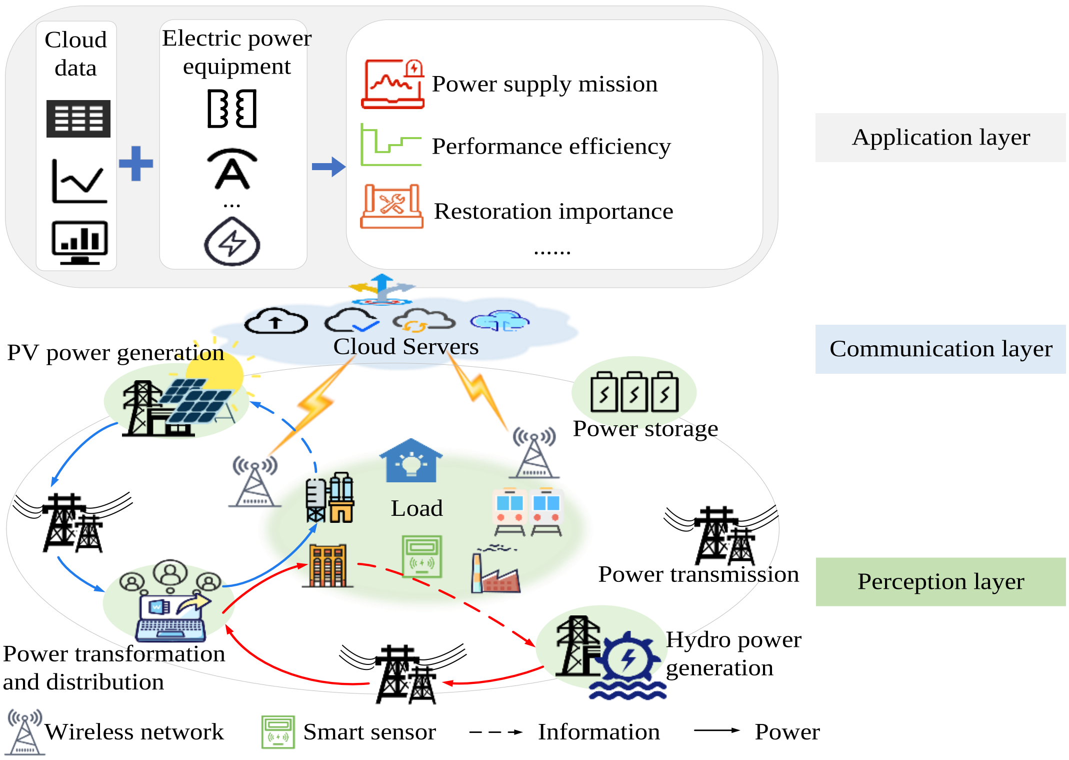

Fig.1. An IoT-enabled HPV power system.

In the IoT-enabled HPV power system, the real-time operating dynamics of the system are captured by the perception layer. The perception layer then transmits the captured data to the communication layer. The data further reaches the application layer. The application layer drives the O&M of the power system to meet the users' demand for power based on the analysis of data. First, the PV power plant and the hydropower plant generate power together to meet the total demand for power. Since the PV power plant is greatly affected by seasonal changes and weather changes and the hydropower plant is greatly affected by drought, the IoT schedules the capacity of the two power plants based on the scale of power plants and external natural conditions. Further, hydro- and solar-energy complement each other and jointly constitute a safe and stable green energy supply system.

The “HPV complementary operation” means that the power generated by the PV plant can be transmitted to the hydropower plant through HV lines. Then according to the total power generating capacity and the real-time PV power generating capacity, the hydropower plant adjusts the hydropower to shave peaks and fill valleys. Eventually, the total power is connected to the grid for transmission. The HPV plant in an uncertain environment is manifested as: the PV power plant works during the sunny day and the hydropower plant works at night and during the non-sunny day. Faced with bad weather, users in HPV power systems are also powered by the hydropower plant. But during nights with droughts, they need to be powered by the energy storage system. Besides, adverse weather conditions, such as high temperatures, may also cause certain damage to PV panels, so is hydropower plants. For seasonal shifts, longer daylight hours in summers and shorter daylight hours in winters will lead to more power generating capacity. Therefore, the PV plant produces more power during the day when the sun is shining brightly. During this period, the PV plant’s power generation can meet the use’s demand for power and may even exceed it. Excess power is delivered to the hydropower plant via transmission lines. The hydropower plant regulates the flow of water to adjust the amount of power generated. When more power is delivered from the PV plant, the hydropower plant can reduce the water level in the reservoir and release the water flow to reduce power generation to meet the demand of the system. This allows for “peak shaving”. While, at night or during bad weather the PV plant produces less power, or even no power. During this period, as the PV plant cannot meet the demand of the system, the hydropower plant can make up for the shortfall in the system by increasing the water level in the reservoirs and storing water in order to increase the power generation. In this way, “valley filling” has been achieved. Through synergistically and complementarily managing the operation of PV and hydropower plants, a more stable and reliable power supply and a more efficient use of renewable energy can be achieved.

Power supplied by the power plants is transmitted along with HV lines through HV towers to the distribution stations with transformers. During the transmission process, natural disasters (e.g., snowstorm, lightning, hurricane, etc.) and internal degradation (e.g., aging, wear, tear, loose, etc.) can cause the HV towers to fail. When a HV tower fails, it is replaced by a nearby HV tower to work. However, the current flowing through every HV tower is limited by its rated current. If the actual current through a HV tower is greater than the rated current, the tower will fail due to overloading. Its load is transferred along the power transmission lines to the neighbouring HV tower that operates normally. The neighbour work in place of the failed HV tower. Meanwhile, the failed one enters the maintenance state. If the transfer of power causes an overload of a neighbouring HV tower, the neighbouring one fails. Power will continue to be transferred to surrounding HV towers that are in a normal operating condition. A cascading failure of the transmission process does not stop until the actual current of one of the HV towers is less than the rated current or until all HV towers within the power system fail. During the cascade failure, various smart sensors in the perception layer can detect the situation of the failed HV tower and transmit it to the cloud servers in the communication layer. After cloud computing, data is transmitted to the application layer. The application layer selects a working HV tower and the nearest failed one to work alternatively. Additionally, the power supply from the power system and the users' demand for power are registered by the perception layer and transmitted to the communication layer, further to the application layer. The application layer combines the data with the actual operating status of the system to transform voltage and distribute power through the distribution stations with transformer. During the distribution process, natural disasters and internal degradation can cause the equipment to fail.

The nodes and edges abstracted by HPV power systems, as shown in Table 1.

Table 1. Nodes and edges abstracted by systems

Systems	Abstracted by
Core equipment in the HPV power systems	Nodes
Hydropower plants and PV power plants	Power generation nodes
Distribution stations with transformers	Power transformation and distribution nodes
Electric appliances of users	Load nodes
Information flows or power flows between two nodes	Edges

Suppose that the heterogeneous network model is used to represent the topology of the HPV power system. The heterogeneous network is defined by $W = (A, V, E)$. V represents the set of all nodes, defined by $V = G \cup T \cup D \cup L$. G is the set of power generation nodes, denoted by $G = \{G_1, G_2, \dots, G_i, \dots, G_I\}$, where $1 \le i \le I$. T is the set of power transmission nodes, denoted by $T =$

$\{T_1, T_2, \dots, T_j, \dots, T_J\}$, where $1 \le j \le J$. D is the set of power transformation and distribution nodes, denoted by $D = \{D_1, D_2, \dots, D_k, \dots, D_K\}$, where $1 \le k \le K$. L is the set of load nodes, denoted by $L = \{L_1, L_2, \dots, L_m, \dots, L_M\}$, where $1 \le m \le M$. E is the set of all edges, defined by $E = E_{L \to G} \cup E_{G \to T} \cup E_{T \to D} \cup E_{D \to L} = \{e_{mi}, e_{ij}, e_{jk}, e_{km}\}$. $A = \{A_{GT}, A_{TD}, A_{DL}, A_{LG}\}$ represents the set of matrices connected between different nodes, where $A_{GT} = [x_{ij}]_{I \times J}$, $A_{TD} = [x_{jk}]_{J \times K}$, $A_{DL} = [x_{km}]_{K \times M}$, and $A_{LG} = [x_{mi}]_{M \times I}$ represent the connection state between two nodes. There are two connection forms of nodes, including the transmission line connection (e.g., x_{ij}, x_{jk}, and x_{km}) that transmits power and the IoT connection (e.g., x_{mi}) that transmits information. In actual power supply scenarios, different types of nodes are limited by their own attributes, operation resources, and external environments. Random failures occur in an unpredictable manner, causing failed nodes to be removed from the power network. $x_{ij} = \begin{cases} 0, G_i \xrightarrow{no} T_j \\ 1, G_i \xrightarrow{yes} T_j \end{cases}$. Same for x_{jk}, x_{km}, and x_{mi}.

2.2 Electric mission chains of HPV power systems

HPV power systems perform specific power supply mission, completing power generation, transmission, transformation and distribution, and power usage in turn. In this paper, a "mission cycle" is defined as the whole power supply process, including power generation, transmission, transformation & distribution of HPV power systems and power usage of lodes. In a mission cycle, the mission chain of a power system is denoted by $L_m \to G_i \to T_j \to D_k \to L_m$. The mission chain is a closed loop. Being formed for L_m, a closed loop is a mission chain tailored for the user. To ensure the reliability of a power system, the number of closed loops formed for each L can be more than one. $L_m \to G_i$ refers to the information flow that user's demand for power is transmitted to a power plant through the IoT. The information here is the user's demand for power, e.g., electricity consumption per unit time for each user. $G_i \to T_j$ refers to the power flow that the electric power is transmitted from a power plant to HV towers along with transmission lines. $T_j \to D_k$ refers to the power flow that the electric power from an HV tower is transmitted along the transmission lines until power reaches a distribution station with transformer. $D_k \to L_m$ refers to the power flow from a distribution station with transformer to user demand area, which includes that the conversion of HV power into low voltage (LV) power and the distribution of power to users' area.

The four kinds of key equipment are connected through the above power flows or information flows to form a power network. Fig.2 shows typical mission chains of a typical HPV power system composed of key equipment, power flows and information flows.

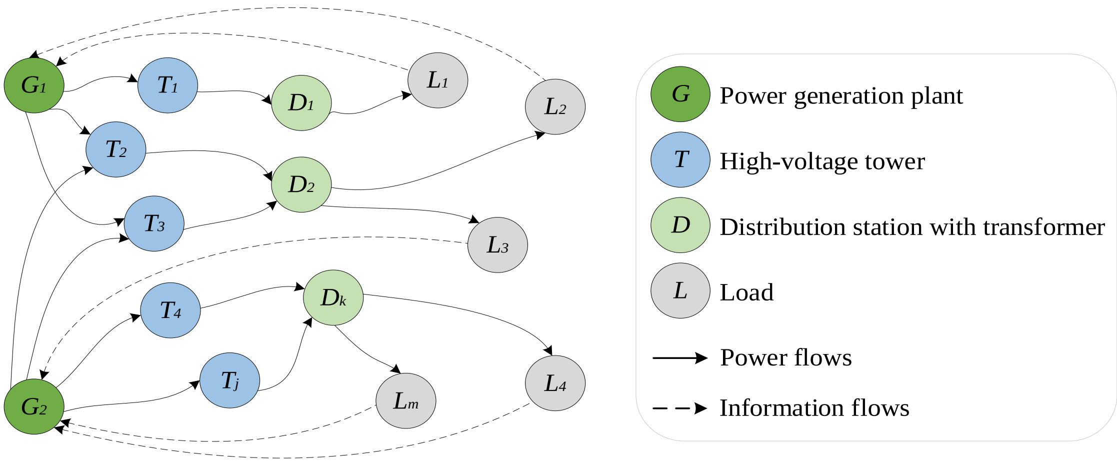

Fig.2. Schematic of typical mission chains.

In the power systems, various equipment performs different functions and are susceptible to failures due to various external and internal degradation. Considering the equipment reliability, the exponential distribution and the Exponential distribution can be used to describe the failure behaviour of equipment. The time to failure of equipment is modelled by the exponential distribution with parameter λ. The number of failures is modeled by the Exponential distribution with parameter μ. Equipment with different functions have different failure modes. Therefore, it is necessary to establish failure models of each kind of equipment.

Power plants include PV power plants and hydropower plants. Suppose that the PV power plants are not operating during bad weather, and the hydropower plants do not work during drought disasters. Moreover, the length of daylight is greatly influenced by seasons. So, the PV power generating capacity is affected by the seasonal factor. Since hydropower plants are more stable, and the hydropower generating capacity is less sensitive to seasonal changes. The restoration methods of power plants are affected by the natural environment. When the weather improves, the PV panels operate normally. When the transition from drought to non-drought occurs, the hydropower plant operates normally. If both cannot operate normally, the energy storage system is used to provide power. Let λ_1 denote the failure rate of the PV power plant due to adverse weather, λ_2 denote the failure rate of the hydropower plant due to drought, and μ_1 and μ_2 denote the restoration rate corresponding to the two failure modes, respectively.

HV towers are exposed to the external environment for a long time and are subject to various natural disasters. Internal degradation including aging, wear and tear and loose also can cause HV towers to fail. The power flows are redistributed according to the Kirchhoff's law, begetting power overloads on the remaining transmission nodes [48]. Let λ_3 and λ_4 denote the failure rate of power transmission nodes due to natural disasters and internal degradation, respectively. The actual current flowing through a HV tower is denoted by I_j. The rated current that the transmission node can withstand is denoted by I_{max}. If $I_j > I_{max}$, the HV tower is overloaded, which causes it to fail and to stop operating. After an overload occurs in a HV tower, the process of power redistribution may lead to cascading failures of other HV towers. For instance, in Fig.2, there were two original electric mission chains identified as $L_1 \to G_2 \to T_8 \to D_1 \to L_1$ and $L_2 \to G_3 \to T_5 \to D_3 \to L_5$. T_8 failed. T_5 is closest to T_8. Therefore, T_5 is used as a replacement for T_8. After installing new transmission lines between T_5 and G_2 and those between T_5 and D_1, the mission chain $L_1 \to G_2 \to T_5 \to D_1 \to L_1$ is formed. Then we can compare the relationship between the actual current and the rated current of T_5 to determine whether T_5 overloads. Due to the cascading failures in the power transmission subsystem, continuously replacing failed nodes until the restoration of the cascading failures is needed. This process may require long time and high O&M costs, but it is not the focus of this study. Natural disasters, internal degradation and overloads can also cause the system to fail, and all failed HV towers need to be restored. Let μ_3 denote the restoration rate.

A distribution station equipped with transformers can fail because of natural disasters and internal degradation. The rates of failures due to the two reasons are denoted by λ_5 and λ_6. Both failure modes can lead to the damage of distribution stations with transformer, and all failed nodes need to be restored. The restoration rate is denoted by μ_4.

3 Performance model of HPV power systems considering different nodes' electric power

For matrices A_{GT}, A_{TD} and A_{DL}, if nodes G_i, T_j, D_k and L_m are in a normal state and are connected physically, that is, $x_{ij} = x_{jk} = x_{km} = 1$, otherwise $x_{ij} = x_{jk} = x_{km} = 0$. It is assumed that each user's demand for power is registered in each power plant through the IoT. So $x_{mi} = 1$ holds for matrix A_{LG}. Other matrix elements x_{ij}, x_{jk} and x_{km} can be expressed as the multiplication of the indicator functions of nodes and edges.

$$\begin{cases} x_{ij} = \alpha(G_i) \times \alpha(T_j) \times \alpha(e_{ij}) \\ x_{jk} = \alpha(T_j) \times \alpha(D_k) \times \alpha(e_{jk}) \\ x_{km} = \alpha(D_k) \times \alpha(L_m) \times \alpha(e_{km}) \end{cases}, \quad (1)$$

where $\alpha(\cdot)$ denotes the existence of each node and edge. If a node or edge operates normally, $\alpha(\cdot) = 1$. Otherwise, $\alpha(\cdot) = 0$, indicating that a node or edge fails and is removed from the system symbolically.

The existence probability of each matrix element is the product of the existence probabilities of two nodes and edges, as shown in equation (2).

$$\begin{cases} p(x_{ij}) = p(G_i) \times p(T_j) \times p(e_{ij}) \\ p(x_{jk}) = p(T_j) \times p(D_k) \times p(e_{jk}) \\ p(x_{km}) = p(D_k) \times p(L_m) \times p(e_{km}) \end{cases}. \quad (2)$$

Because this paper does not consider the failure of the edges due to internal and external factors, $p(e_{ij}) = p(e_{jk}) = p(e_{km}) = 1$.

PV power generation nodes are affected by weather, and hydropower generation nodes are affected by drought disasters. Therefore, the probability of the existence of the i-th power generation node G_i, denoted by $p(G_i)$, is defined by

$$p(G_i) = r(t_i) \times \delta_1 + r(t_i) \times (1 - \delta_1), \quad (3)$$

where $r(\mathrm{t_i})$ denotes the probability of normal operation of node G_i in the system in a certain period. δ_1 is an indicator function. If G_i is a PV power generation node, $\delta_1 = 1$. Otherwise, $\delta_1 = 0$.

Power transmission nodes will fail due to natural disasters and component aging, wear, loosening, etc., and a cascade failure will also occur due to overload. The probability of the existence of the j-th power transmission node, denoted by $p(T_j)$, is defined as

$$p(T_j) = r(t_j) \times \delta_2 + r(t_j) \times (1 - \delta_2), \quad (4)$$

where $r(t_j)$ denotes the probability of normal operation of node T_j in the system in a certain period. δ_2 is an indicator function. If T_j fails due to natural disasters, $\delta_2 = 1$. If T_j fails due to internal degradation, $\delta_2 = 0$. $\alpha(T_j)$ is an indicator function of the existence of power transmission nodes, denoted as

$$\alpha(T_j) = \begin{cases} 1, & I_j \le I_{max} \\ 0, & I_j > I_{max} \end{cases}, \quad (5)$$

where I_j is the actual current. I_{max} is the rated current.

Power transformation and distribution nodes fail due to natural disasters and component aging, wear, loosening, etc. The probability of the existence of the k-th power transformation and distribution node, denoted by $p(D_k)$, is defined as

$$p(D_k) = r(t_k) \times \delta_3 + r(t_k) \times (1 - \delta_3), \quad (6)$$

where $r(t_k)$ denotes the probability of normal operation of node D_k in the system in a certain period. δ_3 is an indicator function. If D_k fails due to natural disasters, $\delta_3 = 1$. If D_k fails due to internal degradation, $\delta_3 = 0$.

Given that the load node's demand for power will not disappear before it is met, the probability of the existence of the m-th load node L_m is $p(L_m) = 1$.

3.1 The electric power of power generation nodes

The resistance of the HV circuit e_{ij}, denoted by R_{ij}, is calculated as

$$R_{ij} = \frac{\rho l_{ij}}{S}, \quad (7)$$

where ρ represents resistivity, S represents cross-sectional area, and l_{ij} represents the length of power transmission line e_{ij}.

The current of circuit e_{ij} is obtained by $I_{ij} = \frac{U_h}{R_{ij}}$, where U_h is HV power. The current of power generation node G_i is obtained by $I_i = \sum_j I_{ij} x_{ij}$.

The electric energy of the energy storage system is $Q_0 = \sum_i \omega Q_i$, where ω is the energy storage coefficient of power plants and Q_i is the total electric energy of node G_i. The actual output electric power of each power generation node, denoted by P_i, is obtained by

$$P_i = (1 - \omega) Q_i. \quad (8)$$

3.2 The current and electric power of power transmission nodes

The resistance of the HV circuit e_{jk} is $R_{jk} = \frac{\rho l_{jk}}{S}$, where l_{jk} is the length of power transmission line e_{jk}. The current of the circuit e_{jk} is $I_{jk} = \frac{U_h}{R_{jk}}$. The voltage of circuit e_{ij}, denoted by U_h, is constant. Thus, the electric power loss between the power generation node G_i and the power transmission node T_j, denoted by ΔP_{ij}, is $\Delta P_{ij} = \frac{U_h^2}{R_{ij}}$. Further, combined with equation (7), ΔP_{ij} can be expressed by equation (9).

$$\Delta P_{ij} = \frac{U_h^2 S}{\rho l_{ij}}. \tag{9}$$

Power generation nodes and power transmission nodes are many-to-many relations. When the power generation node G_i is connected to $\sum_j x_{ij}$ power transmission nodes, the electric power distributed to each circuit is the same. Namely, the electric power through circuit e_{ij}, transmitted from G_i to T_j, is $\frac{P_i}{\sum_j x_{ij}}$. Due to the power loss, the actual electric power of T_j, obtained by one circuit e_{ij}, is $\frac{P_i}{\sum_j x_{ij}} - \Delta P_{ij}$. The total actual electric power of the power transmission node T_j is $P_j = \sum_i \left(\frac{P_i}{\sum_j x_{ij}} - \Delta P_{ij} \right)$. Further, combined with equation (9), P_j is expressed by equation (10).

$$P_j = \sum_i \left(\frac{P_i}{\sum_j x_{ij}} - \frac{U_h^2 S}{\rho l_{ij}} \right). \tag{10}$$

3.3 The electric power of power transformation and distribution nodes

The electric power loss between the power transmission node T_j and the power transformation and distribution node D_k, denoted by ΔP_{jk}, is calculated by

$$\Delta P_{jk} = \frac{U_h^2 S}{\rho l_{jk}}. \tag{11}$$

Power transmission nodes and power transformation and distribution nodes are many-to-one relations. The electric power through the circuit e_{jk}, transmitted from T_j to D_k, is P_j. Due to power loss, the actual electric power of D_k, obtained by one circuit e_{jk}, is $(P_j - \Delta P_{jk})$. The total actual electric power of the power transformation and distribution node D_k is $P_k = \sum_j \left(P_j - \Delta P_{jk} \right)$. Further, combined with equation (11), P_k can be expressed as equation (12).

$$P_k = \sum_j \left(P_j - \frac{U_h^2 S}{\rho l_{jk}} \right). \tag{12}$$

3.4 The input electric power of load nodes

The voltage of the LV circuit e_{km}, denoted by U_l, is constant. Thus, the electric power loss between the power transformation and distribution node D_k and the load node L_m, denoted by

ΔP_{km}, is $\Delta P_{km} = \frac{U_l^2 S}{\rho l_{km}}$, where l_{km} is the length of power transmission line e_{km}. Ideal electric energy of the load node L_m, obtained by one circuit e_{km}, is Q_m, that is, L_m's demand for power. Power transformation and distribution nodes and load nodes are one-to-many relations. The electric energy through the circuit e_{km}, transmitted from D_k to L_m, is $\Delta P_{km} + Q_m$. If the total electric power of all power transformation and distribution nodes is large enough to supply m_0 users, m_0 users' demand for power will be met, which is expressed as

$$\sum_{m_0}(\Delta P_{km} + Q_m) \le \sum_k P_k < \sum_{m_0+1}(\Delta P_{km} + Q_m). \tag{13}$$

The actual input electric power of load node L_m, denoted by P_m, is defined as

$$P_m = \begin{cases} Q_m, & m \le m_0 \\ \sum_k P_k - \sum_{m_0}(\Delta P_{km} + Q_m), & m = m_0 + 1. \\ 0, & m > m_0 + 1 \end{cases} \tag{14}$$

Denote $\xi = \begin{cases} 1, & P_m = Q_m \\ 0, & P_m < Q_m \end{cases}$. The total number of users whose demand for power are met, denoted by m_0, is calculated as $m_0 = \sum \xi$.

3.5 Performance model of HPV power systems

For power systems, ensuring the normal O&M is the main goal. So, the evaluation of performance efficiency from the perspective of profit is unreasonable. Performance efficiency should be discussed from the perspective of the social service. First, for a single-user in an HPV power system, the performance efficiency of a single-user, denoted by PES_m, is defined as the ability of a power system to meet a single-user's demand for power under uncertain environment, that is, the ratio of the actual input electric power P_m of the load to its demand for power Q_m.

$$PES_m = \frac{P_m}{Q_m}. \tag{15}$$

Further, for all users in an HPV power system when performing a power supply mission, the performance efficiency of multiple users, denoted by PEM, is defined as the average value of the performance efficiency of many single-users in the power system.

$$PEM = \frac{1}{M}\sum_m^M PES_m. \tag{16}$$

Based on performance efficiency of users, the performance efficiency of HPV power systems is defined as the ability of a power system to meet the users' demand for power in a mission cycle under uncertain environment, that is, the mission success probability in the process of multiple power supply missions. The mission cycle mentioned above refers to the complete power supply process of $L_m \rightarrow G_i \rightarrow T_j \rightarrow D_k \rightarrow L_m$. "Satisfying the user's demand for power" mentioned above suggests that the actual input electric power P_m obtained by the user is equal to its demand for power Q_m, that is, $PES_m = 1$. The mission success criterion of HPV power systems is that the ratio of the total number of users m_0 to the number of satisfied users M in the mission cycle is greater than mission baseline τ, namely, $\beta(\text{mission success}) = \begin{cases} 1, & \frac{m_0}{M} \geq \tau \\ 0, & \frac{m_0}{M} < \tau \end{cases}$.

When an HPV power system performs a total of N power supply missions, N' power supply missions are successful. Thus, the performance efficiency of the HPV power system, denoted by PE, is expressed as

$$PE = \frac{N'}{N}, \tag{17}$$

where the number of successful missions is calculated as $N' = \sum \beta(\text{mission success})$.

4 Performance enhancement of HPV power systems based on restoration importance

4.1 Restoration importance

The number of edges connected by different nodes in a power system is different, so is the transmitted electric power. The improvement of system performance efficiency brought by restoring different failed nodes is also different. However, restoration resources are limited. Resources had better be allocated to more important nodes to achieve higher power system performance efficiency. The concept of restoration importance is introduced to measure the nodes' importance, represented by I^p. By prioritizing the restoration of failed nodes with high restoration importance, the restoration ability of HPV power systems is improved. Further, so does the performance efficiency of power systems. In this paper, the performance of node a is defined as the performance efficiency of multiple users brought from the work of the node a, denoted by P_a^{PEM}, expressed as

$$P_a^{PEM} = PEM(a). \tag{18}$$

The restoration importance of the failed node a, denoted by I_a^p, is defined as equation (19).

$$I_a^p = P_a^{PEM}(\text{after restoration}) - P_a^{PEM}(\text{before restoration}), \tag{19}$$

where $P_a^{PEM}(\text{after restoration})$ is the performance of node a after restored and $P_a^{PEM}(\text{before restoration})$ is the performance of node a when failing. Similarly, the restoration importance of node b can be obtained.

In an HPV power system, we assume that the failure of the power generation node G_i is non-destructive and does not require maintenance. Based on the natural weather conditions, each failed power generation node can automatically be restored to the normal state. However, the failure of the power transmission node T_j or the transformation & distribution node D_k is destructive and need to be maintained.

There are two different failed power transmission nodes: a and b. The restoration importance of node b is denoted by I_b^p. If $I_a^p > I_b^p$, $I_a^p - I_b^p > 0$. Since both nodes a and b fail, the power system is in the same state before the two nodes are restored. As a result, $P_a^{PEM}(\text{before restoration}) = P_b^{PEM}(\text{before restoration})$. Based on equation (19), $P_a^{PEM}(\text{after restoration}) - P_b^{PEM}(\text{after restoration}) > 0$. On this basis, according to equations (15), (16) and (18), inequality (20) can be obtained.

$$\sum_m \frac{P_m}{Q_m}(\text{after restoration of } a) - \sum_m \frac{P_m}{Q_m}(\text{after restoration of } b) > 0, \tag{20}$$

which is interpreted that the performance efficiency of multiple users after node a is restored is higher than that after node b is restored.

According to equation (14), the power distribution rule aims to meet the first m_0 users, namely $P_m = Q_m$. The $(m_0 + 1)$-th user gets power, but the demand for power is unsatisfying, which can be expressed as $P_m = \sum_k P_k - \sum_{m_0}(\Delta P_{km} + Q_m)$. Other uses may not have any power. Hence, the number of users whose demand for power are met after node a is restored is higher than that after node b is restored. So, compared to node b, the probability of satisfying the mission success criterion, that is $m_0/M \geq \tau$, will be greater after the node a is restored when performing a single power supply mission. Further, the number of successful missions, denoted by N', will also be greater in N power supply missions. Thus, if $I_a^p > I_b^p$, $N_a' > N_b'$. PE_a and PE_b represent the performance efficiency of a power system after the failed power transmission node a and b are restored, respectively. According to equation (17) about the definition of the performance efficiency of a power system, if $N_a' > N_b'$ and N is constant, $PE_a > PE_b$.

In summary, for the failed power transmission nodes a and b, if $I_a^p > I_b^p$, $PE_a > PE_b$. The node a should be restored earlier than node b. Similarly, for the failed power transformation and distribution nodes c and d, if $I_c^p > I_d^p$, $PE_c > PE_d$. Node c should be given priority to restore than node d.

4.2 Performance enhancement

The performance efficiency enhancement within the HPV power systems highlights the challenge of managing the limited resources. It becomes crucial to allocate limited resources in a reasonable manner, aiming to enhance the performance efficiency of the power system. Assuming that after the risk disturbances occur, many failed nodes in the power system need to be restored. But the failed nodes may not all be selected for restoration. Hence, importance measure-based restoration strategies can be used to improve the performance efficiency of HPV power systems. In this way, failed nodes with high restoration importance will be restored with priority. In this paper, a performance efficiency model for HPV power systems is proposed. The solution steps are as follows.

Step 1. Generate matrices $A_{LG} = [x_{mi}]_{M\times I}$, $A_{GT} = \left[x_{ij}\right]_{I\times J}$, $A_{TD} = \left[x_{jk}\right]_{J\times K}$, and $A_{DL} = [x_{km}]_{K\times M}$, and establish an initial HPV power system topology $W = (A, V, E)$.

Step 2. Natural disasters and internal degradation are simulated randomly by the Monte Carlo method, resulting in the failure of nodes in the HPV power system.

Step 3. Choose different restoration modes according to corresponding failure modes. Random restoration strategy and restoration importance measure-based restoration strategy are used to restore failed nodes.

Step 4. Calculate the performance efficiency of the m-th single user PES_m. If one of electric mission chains makes $PES_m = 1$ true, the number of satisfied users pluses 1, expressed as $m_0 \leftarrow m_0 + 1$.

Step 5. According to the criteria for the mission success of the HPV power system, that is $\frac{m_0}{M} \geq \tau$, determine whether the mission is completed successfully in a single power supply mission. If a mission is successful, the number of successful mission pluses 1, expressed as $N' \leftarrow N' + 1$.

Step 6. Calculate the performance efficiency PE of the HPV power system.

5 Case study

In Qinghai Province, China, the Longyangxia hydropower plant and the Talatan PV plant on the upper reaches of the Yellow River uses complementary hydro energy and solar energy to generate power. The hydropower plant makes full use of the quick adjustment ability of the turbine generator set and the storage function of the reservoir. According to the active power output of the PV plant, the original intermittent, fluctuating, unstable zigzag PV power energy is adjusted to a balanced, high-quality, safe, smooth and stable power energy. The fast complementarity of hydropower and PV power is perfectly realised. The Talatan PV plant and the Longyangxia hydropower plant are located at $(102.7288°E,\ 33.5807°N)$ and $(104.9924°\mathrm{E},\ 35.9569°\mathrm{N})$, respectively. The service scope in a certain period of the HPV power system is located in western China between $82°\mathrm{E}$-$105°\mathrm{E}$ and $31°\mathrm{N}$-$42°\mathrm{N}$. Based on the actual situation of the region, the number of power plants is $I = 2$. The number of HV towers is $J = 30$. The number of distribution stations with transformer is $K = 4$. To facilitate simulation, we set the number of user groups in the region $M = 100$. It is worth noting that 100 user groups do not refer to 100 small households, but include 70 residential communities, 10 hospitals, 10 factories, and 10 businesses.

According to the complementary HPV operation, the power system stores 0.1% of its power generating capacity to the energy storage system every day for emergency needs. The transmission lines' cross-sectional area is $S = 500mm^2$. The transmission lines' resistivity is $\rho = 2.82 \times 10^{-8}\ \Omega \cdot m$. The equipment is easy to be damaged and lose the normal working ability in uncertain environment. The number of equipment failures per day is exponentially distributed. The failure rate of HV towers under natural disasters is $\lambda_3 = 9.52 \times 10^{-4}$. The failure rate due to internal degradation is $\lambda_4 = 1.91 \times 10^{-4}$. The rated current of HV towers is $I_{max} = 500A$. The failure rate of distribution stations with transformer under natural disasters is $\lambda_5 = 9.52 \times 10^{-4}$ and the failure rate due to internal degradation is $\lambda_6 = 1.91 \times 10^{-4}$. The voltage of HV lines in the power system is $U_h = 220kV$ and the voltage of LV lines is $U_l = 220V$. The equipment needs to be restored upon failures. The number of failed systems that need repair per day follows the Exponential distribution. The restoration rate of HV plants, hydropower plants, HV towers, and distribution stations with transformer are $\mu_1 = 9.21 \times 10^{-3}$, $\mu_2 = 9.21 \times 10^{-3}$, $\mu_3 = 8.37 \times 10^{-3}$ and $\mu_4 = 7.96 \times 10^{-3}$, respectively.

Temperature in western China is lower in winters than that in summers. The length of daylight is relatively short, and the generating capacity of PV panels is decreasing. Increase in snowfall can also have an impact on the power generation efficiency of PV panels. In addition, there is more precipitation in winters than in summers, and hydropower generating capacity has increased. Therefore, the total electric energy is more from the hydropower plant and less from the PV plant in winters. The failure rate of the PV power plant due to adverse weather is $\lambda_1 = 8.99 \times 10^{-4}$. The failure rate of the hydropower plant due to drought disasters is $\lambda_2 = 2.34 \times 10^{-4}$. The Monte Carlo method is used to simulate the daily demand for power of 100 user groups and the O&M of the HPV power system in western China in winters. Fig.3 shows that the complementary electric energy of the HPV plant within 90 days.

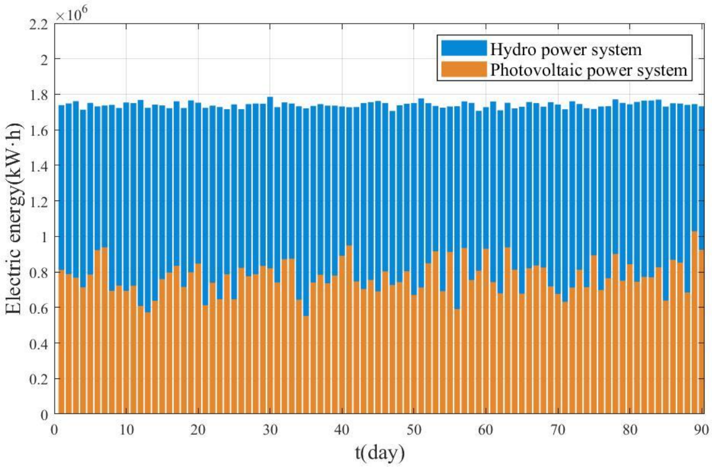

Fig.3. The complementary electric energy of the complementary HPV plant in winters.

In Fig.3, the daily electric energy in the region in winters is around $1.75 \times 10^6 kW \cdot h$. The power generation of the PV power system is smaller than that of the hydropower system on the whole.

In summers, the temperature in the western of China is higher than that in winters. The length of daylight is long, so the generating capacity of PV panels is large. Rainfall is insufficient in most areas and river levels may be low. So, hydropower generating capacity is limited. Therefore, the total electric energy is more from the PV plant and less from the hydropower plant in summers. The failure rate of the PV power plant due to adverse weather is $\lambda_1 = 2.81 \times 10^{-4}$. The failure rate of the hydropower plant due to drought disaster is $\lambda_2 = 8.34 \times 10^{-4}$. Affected by the high temperature in summers, the electric energy consumption of electrical appliances (e.g., air conditioners) will increase, putting higher requirements on the power supply. Monte Carlo method is used to simulate the O&M of the HPV power system in the western of China. The electric energy of the complementary HPV plant within 90 days is shown in Fig.4.

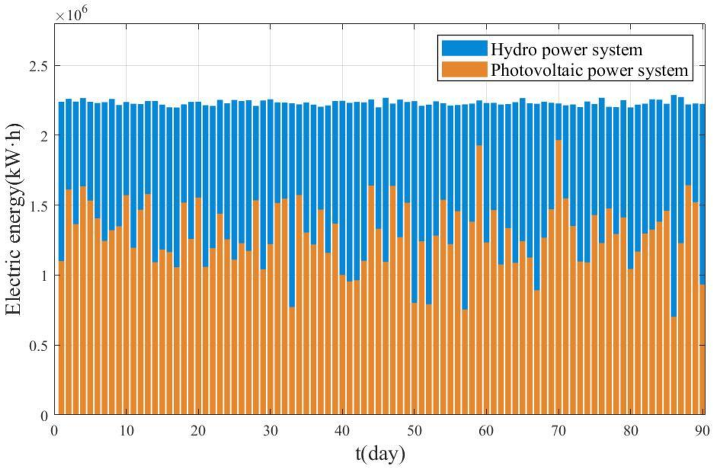

Fig.4. The complementary electric energy of the complementary HPV plant in summers.

In Fig.4, the daily electric energy in the western of China in winters is around $2.25 \times 10^6 kW \cdot h$. The power generation of the PV power system is bigger than that of the hydropower system on the whole. The fluctuation range of the PV power generation in summers (see Fig.4) is greater than that in winters (see Fig.3).

The operational processes of the HPV power system are analysed in both winters and summers. For the two seasons, the extent to which users' demand for power is met is quantified. Besides, the performance efficiency of the HPV power system with successive failures and restoration are calculated. The restoration importance of each equipment in case studies is sorted. The random-based restoration strategy and importance measure-based restoration strategy for the HPV power system are analysed and sensitivity analysis is performed. Finally, different power systems, including a single power system with solar energy, a single power system with hydro energy, and a complementary power system with solar energy and hydro energy, are compared considering novel restoration strategy in this section.

5.1 In winters

The number of users whose demand for power is met in the HPV power system in winters is compared in Fig.5.

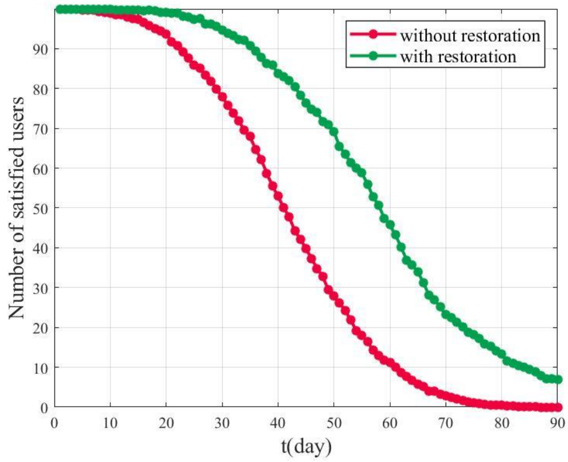

Fig.5. The number of satisfied users whose demand for power are met in the HPV power system in winters.

In Fig.5, without restoration after failure being considered, the number of satisfied users whose demand for power is met starts declining rapidly from about the 10-th day and the decline rate slows down from 60-th day in the HPV power system. The number of satisfied users approaches 0 until the 74-th day. After adding the restoration strategy, the number of satisfied users begins to decline from the 20-th day and remained non-zero until the 90-th day. It can be found that the restoration strategy is crucial to meet the users' demand for power.

The performance efficiency of the HPV power system under different mission baselines is calculated considering the restoration strategy. Due to the dominant role of the hydropower system in winters, sensitivity analysis for the failure rate of the hydropower plant is shown in the process of calculating performance efficiency. Fig.6 shows the performance efficiency of the HPV power system with different mission baselines under different failure rates in winters.

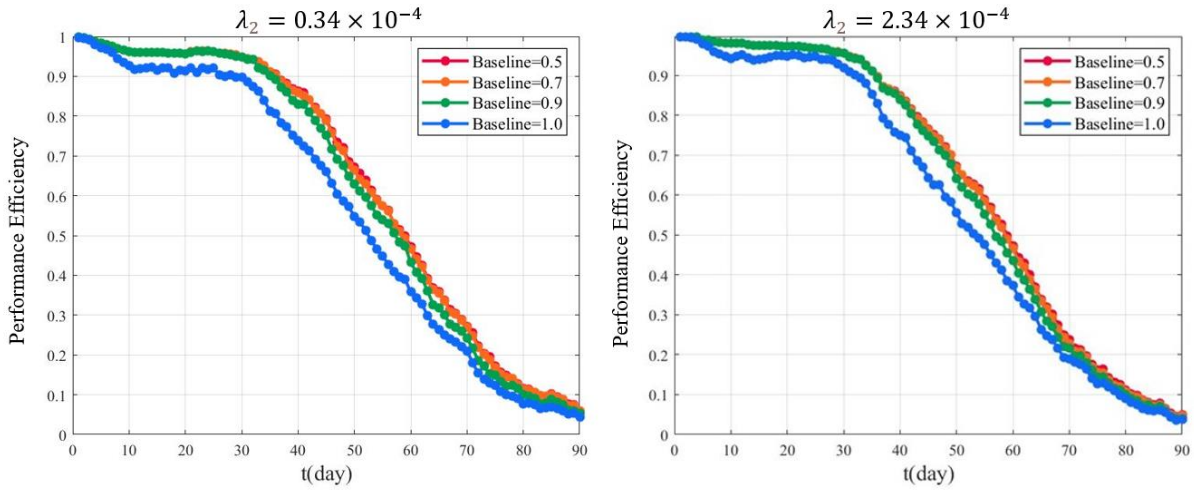

Fig.6. The performance efficiency of the HPV power system with different mission baselines under different failure rates in winters.

In Fig.6, under different mission baselines, the downward trend of performance efficiency is roughly the same. In the first 0-30 days, the performance efficiency decreases slowly. It decreases rapidly after 30 days.

According to section 4.1, the restoration importance of power transmission nodes is ranked as follows. T_{11}, T_{14}, T_{28}, T_{12}, T_{27}, T_{1}, T_{10}, T_{5}, T_{7}, T_{26}, T_{8}, T_{9}, T_{20}, T_{3}, T_{30}, T_{22}, T_{18}, T_{24}, T_{4}, T_{2}, T_{6}, T_{16}, T_{17}, T_{19}, T_{21}, T_{23}, T_{25}, T_{29}, T_{15}, and T_{13}. The restoration importance of power transformation and distribution nodes is ranked D_1, D_4, D_3, and D_2. The nodes at the front of the two sequences should be prioritized for restoration if they fail.

The performance efficiency under the two restoration strategies, including random-based restoration and importance measure-based restoration is compared in Fig.7. Besides, the sensitivity analysis is conducted on the failure rate.

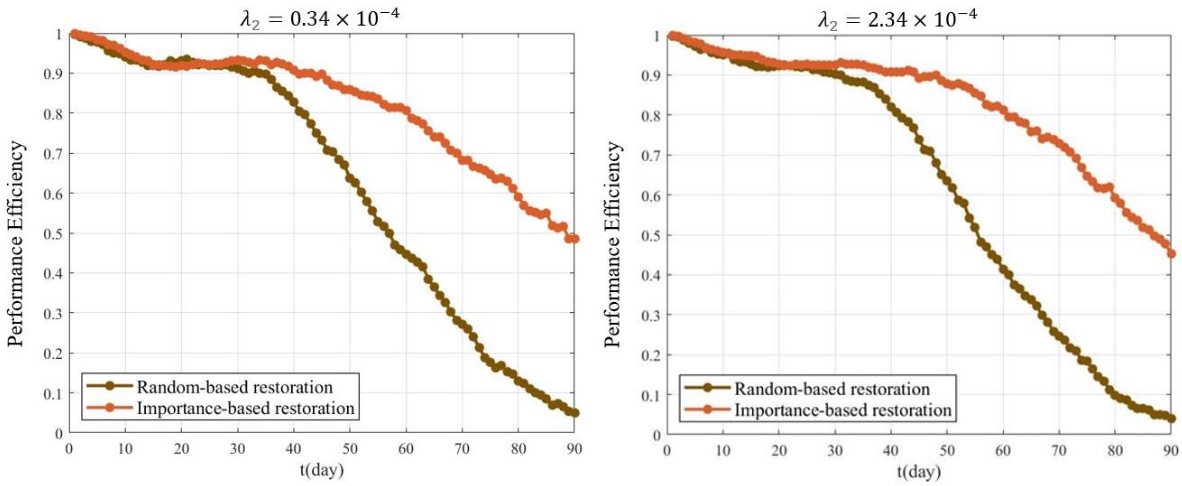

Fig.7. The performance efficiency of the HPV power system with different restoration strategies under different failure rates in winters.

As shown in Fig.7, in the first 30 days, the effects of the two restoration strategies are basically same. After the 30-th day, the importance measure-based restoration strategy was significantly better than the random-based restoration strategy. When the hydropower plant's failure rate is 0.34×10^{-4} and 2.34×10^{-4}, the application of the importance measure-based restoration strategy can increase the performance efficiency of the HPV power system by an average of 8.38 and 7.19 times in the last 10 days.

In the application of the importance measure-based restoration strategy, the O&M effect of the single PV power system, the single hydropower system and the HPV power system is compared.

Fig.8 shows the performance efficiency of different power systems in winters.

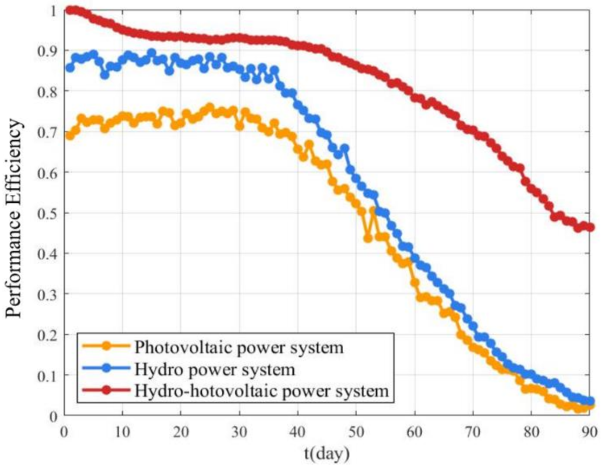

Fig.8. The performance efficiency of different power systems in winters.

In Fig.8, the performance efficiency of the HPV power system is higher than that of the two single-energy power systems. Specifically, during the last 10 days of O&M in the simulation, the performance efficiency of the HPV power system is 15.24 times and 10.36 times of that of the PV power system and the hydropower system, respectively. Due to the weak light intensity and short daylight hours in winters, the performance efficiency of the PV power system is lower than that of the hydropower system.

In summary, the effectiveness of the performance efficiency model and the importance measure-based restoration strategy of the HPV power system in winters is proved.

5.2 In summers

The number of users whose demand for power are met in the HPV power system in summers are compared, as shown in Fig.9.

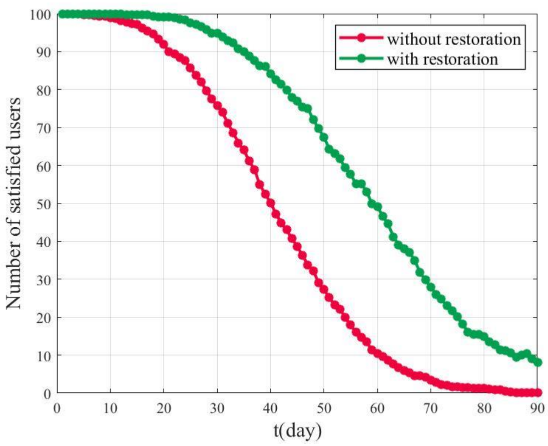

Fig.9. The number of satisfied users whose demand for power are met in the HPV power system in summers.

In Fig.9, with the complementary HPV operation, the number of satisfied users whose demand for power is met starts reducing from about the 10-th day without restoration after failure. The number of satisfied users approaches 0 until the 80-th day. After adding the restoration strategy, the number of satisfied users drops to around 10 from the 20-th day to the 90-th day. Therefore, a restoration strategy is essential to meet the users' demand for power.

In summers, the performance efficiency of the HPV power system under different mission baselines is calculated considering the restoration strategy. Due to the dominant role of the PV power system in summers, sensitivity analysis for the failure rate of PV plant is showed in the course of calculating performance efficiency. Fig.10 shows the performance efficiency of the HPV power system with different mission baselines under different failure rates in summers.

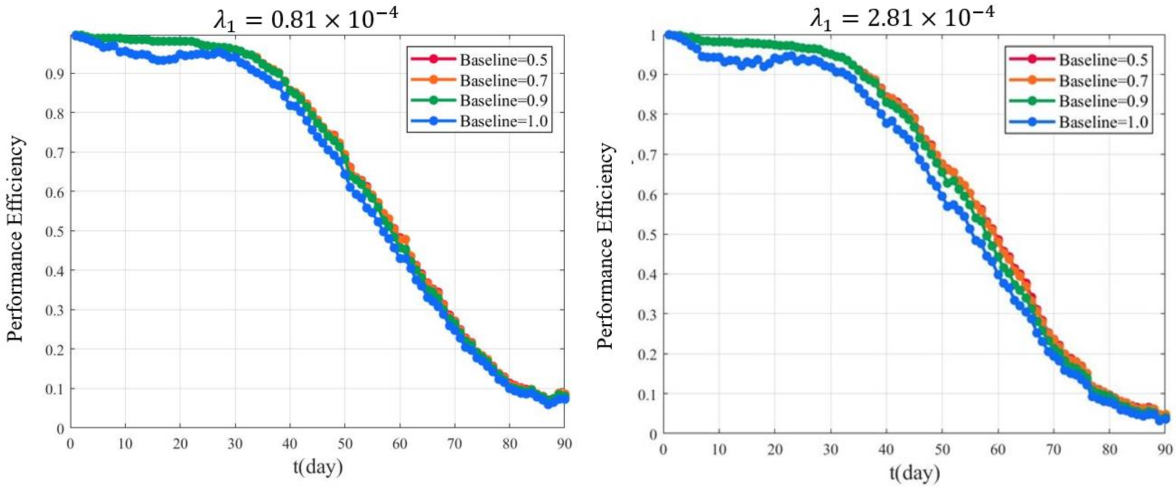

Fig.10. The performance efficiency of the HPV power system with different mission baselines under different failure rates in summers.

From Fig.10, under different mission baselines, the performance efficiency of the HPV power system shows a decreasing trend.

In different seasons, the restoration importance of nodes in the same HPV power system is the same. The performance efficiency of the two restoration strategies in summers, namely restoration in random order and in order of importance measures, are compared. Additionally, sensitivity analysis is performed. Fig.11 shows that the performance efficiency with different restoration strategies under different failure rates in summers.

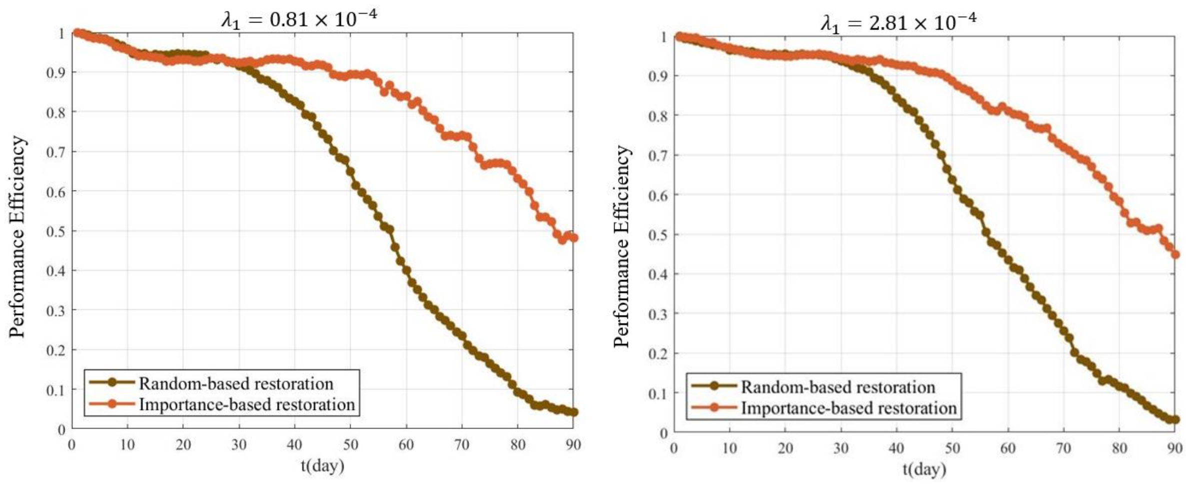

Fig.11. The performance efficiency of the HPV power system with different restoration strategies under different failure rates in summers.

Obviously, the importance measure-based restoration strategy is better than the random-based restoration strategy in Fig.11. Specifically, when PV plant's failure rate is 0.81×10^{-4} and 2.81×10^{-4}, the application of the importance measure-based restoration strategy can increase the performance efficiency by an average of 10.19 and 9.00 times in the last 10 days.

When the importance measure-based restoration strategy is applied, the O&M effect of the power system with a single RES and the HPV power system in summers are compared, as shown in Fig.12.

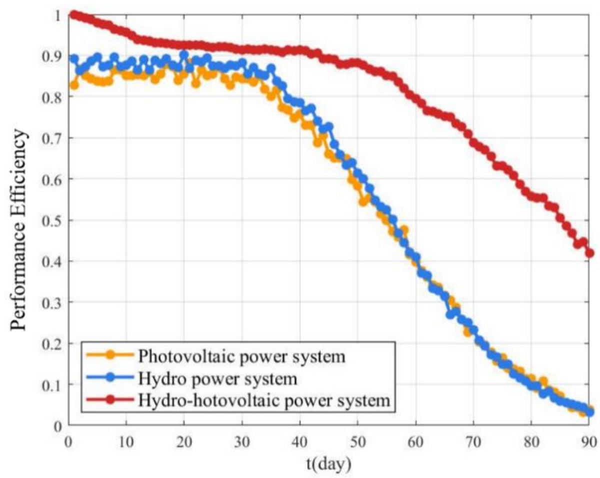

Fig.12. The performance efficiency of different power systems in summers.

In Fig.12, the performance efficiency of the complementary power system is higher than that of the two single power systems. In the last 10 days of the complementary HPV operation, the performance efficiency of the HPV power system is 12.00 times that of the PV power system and 11.96 times that of the hydropower system. Compared to winters, summers have more intense light and longer days. The performance efficiency of the PV power system is slightly lower than that of the hydropower system in summers, and the two are almost equal in the later period.

In summary, the above analysis proves that the performance efficiency model and the importance measure-based restoration strategy of the HPV power system in summers are effective.

6 Conclusions

This paper developed a method for synergistically and complementarily managing the HPV power system in winters and summers, and optimised the performance efficiency of the system. First, the actual O&M of the complementary HPV power system was analysed. The causes of failures include drought disasters, destructive natural disasters, extreme adverse weather, internal degradation, overloading, etc. The concept of mission chain was proposed with consideration of the power supply mission, based on which a network topology model is constructed using the core elements of the HPV power system. Second, a mission chain-based performance model considering different equipment's electric power for HPV power systems was developed. Third, in view of the limited resources, the restoration importance model was established to determine the restoration order of the failed equipment, so as to enhance the performance efficiency of the system. Last, the impacts of different restoration strategies on the performance of the complementary HPV power system and the effect of the importance measure-based restoration strategy on different power systems were discussed. The following conclusions can be drawn.

(1) The performance efficiency model of HPV power systems based on mission chains comprehensively considers the process of power generation, transmission, transformation, distribution and usage, which is a scientific and reasonable method to evaluate the performance of power systems facing the power supply mission to meet the users' demand for power.

(2) The restoration importance model can effectively evaluate the importance of nodes according to the changes of node performance before and after failure, which gives a reasonable restoration sequence of failed nodes, laying a foundation for improving the performance efficiency of HPV power systems as much as possible under limited resources.

(3) The restoration strategy based on restoration importance significantly enhances the performance efficiency of HPV power systems. Compared to random-based restoration strategy, the

importance measure-based restoration strategy improves the performance efficiency of an HPV power system by 7.19~8.38 times and 9.00~10.19 times in winters and summers, respectively. When applying the importance measure-based restoration strategy, nodes are prioritized according to their restoration importance. Node importance is defined as equation (19). Greater node importance indicates greater node performance after restoration. Then according to equation (18), the greater the performance efficiency of multiple users from the node restoration will be. When the user's demand for power of the power system is known and constant, the greater the actual electric power of multiple users. Then, the greater the number of users whose demand for power is satisfied. The mission of the power system is to complete the generation, transmission, transformation and distribution to meet the user's demand for power. According to the mission success criterion, the greater the likelihood that the power system accomplishes the mission. Therefore, according to equation (17), the greater the performance efficiency of the power system.

(4) Synergistically and complementarily managing the operation of HPV plants has good benefits. The performance efficiency of an HPV power system is higher than that of a power system with single RES. Compared to a single PV power system and a single hydropower system, the performance efficiency of an HPV power system in winters is 15.24 times and 10.36 times higher, respectively. The performance efficiency of an HPV power system in summers is increased by 12.00 times and 11.96 times, respectively. By combining the use of two energy sources, solar and hydro, the HPV power system balances the volatility of the energy sources and thus increases the overall power supply. In addition, the HPV power system can flexibly adjust the utilization ratio of different energy sources according to the actual demand for power, which makes the system more adaptable to different time periods and different load demands, and improves the flexibility and adjustability of power supply. Moreover, even if one energy source fails or fluctuates, other energy sources can still provide a certain amount of power generation to guarantee the stable operation of the HPV power system. Such a system is more stable than a single-energy system and reduces the risk of power outages and power instability. For example, a single PV power system generates less power when it is cloudy. As a result, the user receives less actual electric power. The number of users whose demand for power are met is low. According to the mission success criterion, the lower the likelihood that the

PV power system accomplishes the mission. According to equation (17), the lower the performance efficiency of the PV power system. However, applying the HPV power system on cloudy days will presents relatively good results. The HPV power system can compensate for the lack of power generation from the PV plant by raising the water level in the hydropower plant and increasing the water flow. Therefore, the generation capacity of the whole system will increase to achieve the effect of "valley filling". Further, compared to the PV power system, more actual electric power is received by the users in the HPV power system. The number of users whose demand for power is satisfied is higher. According to the mission success criterion, the greater the probability that the HPV power system accomplishes the mission. Therefore, according to equation (17), the greater the performance efficiency of the HPV power system.

Acknowledgments

The authors gratefully acknowledge the financial support for this research from the National Natural Science Foundation of China (No. 72071182).

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