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THE MODEL RESEARCH ON BOUSTROPHEDON PATTERN OF RISK ELEMENTS TRANSMISSION BETWEEN THE SAME STRUCTURE MICRO-GRIDS

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Abstract. *In this article, the risk management of micro-grids with wind energy, solar energy, energy storage systems which are connected to large power grid is as the research object. Based on the risk elements transmission (RET) theory, a novel model on boustrophedon pattern of RET is proposed, and meanwhile the computing methods of risk value and impact factor are presented; the two micro-grids in the same area are as the study case, and the influences of power shortage risk on micro-grid itself and interactions to each other are detailedly analyzed. Finally, the recommendations on structure optimization and risk control of micro-grids are given. This study will help understand interactional mechanism of risk transmission between micro-grids and provide the basis for optimization decision-making of micro-grids configuration and control risk of power supply.*
Keywords: Risk management, Risk elements, Micro-grid, Power supply

1. **Introduction.** With the constantly emergence of the energy crisis and environmental problems, distributed generation, especially wind and solar power generation is becoming a hot spot of research within the scope of the world [1]. In recent years, the optimization research of energy storage capacity of micro-grid mainly focuses on four aspects [2], and they are: (1) configuration of energy storage of independent micro-grid from ensuring continuous power supply angle [3,4]; (2) configuration of energy storage from dampening the active power fluctuations of the distributed power angle [5,6]; (3) integrated configuration of energy storage that energy mode couples power mode [7,8]; (4) configuration of energy storage for other purposes such as keeping system stability [9], reducing peak and filling valley, keeping power invariability of tie-line, seamless transfer between the isolated network and grid-tied.

Affected by the natural factors, wind speed, light intensity, etc., distributed generation of micro-grid [10,11] has a high degree of uncertainty; thereout, it causes the imbalance problem of supply and demand, which affects power quality at best and at worst lowers the power supply reliability to the important user [12]. In view of this background, risk research of micro-grid has been paid more and more attention. Fazio and Russo [13] investigated a novel approach to model and conduct reliability assessment for wind farm, which is based on the universal generating functions. Such an approach combines the use of the z-transform and composition operators and that allows it to account for all the factors affecting the wind farm performance. Literature [14,15] presented new risk assessment indices about wind farm access power system, which considered the failure rate and the capacity constraints of transmission network. Ding and Xu [16] proposed a method to forecast short-term output power of photovoltaic plant based on the Markov chain. Wang et al. [17] developed a six-state reliability model with the energy constraints and the characteristics of system structure of the distributed PV power system are taken into account. Gao et al. [18] proposed a time series model of simple energy storage, which only considered maximum and minimum capacity constraints of the energy storage, and an analytical procedure is presented to analyze the impacts of energy storage on reliability of power systems with wind turbine generators. Literature [19,20] proposed a pseudo-sequential Monte Carlo simulation method for reliability evaluation of distribution system, the failure modes and effects analysis procedure of distribution system is discussed and the reliability evaluation flow is illustrated.

Although distributed power systems in the different micro-grids have certain complementarities to each other, as a result of similar energy source and smaller regional differences, power fluctuation of clean energy has higher consistent degree [21], which result in RET between the same structure micro-grids when the risk occurs in one of them. For the above reasons, in this article, the risk management of micro-grids with wind energy, solar energy, energy storage systems which are connected to large power grid is as the research object. This article is structured as follows: in Section 2, based on the RET theory, a novel model on boustrophedon pattern of RET is proposed; in Section 3, power supply analysis without risk within micro-grid is demonstrated; in Section 4, boustrophedon risk analysis between micro-grids is conducted, in which related definitions and the computing methods of risk value as well as impact factor are described; finally, in Section 5, the conclusions are given.

2. RET Theory and Boustrophedon Risk Elements Transmission.

Definition 2.1. *In a general way, the domain $U = \{x_1, x_2, \cdots, x_n\}$, where x_i represents the subject of the risk research. For the target object y of the risk research, if there is a mapping function f, which makes x_i meet the constraint $y = f(x_i)$, then x_i is referred to as the risk element of affecting target object y, and the correspondence f is called the function of risk element transmission [22].*

Definition 2.2. *For the two subjects of risk research X_i and X_j $(i, j \in R;\ i \neq j)$, if there are occurrences of risks at time t simultaneously, in which the risk status is respectively r_i^t and r_j^t, and that the change of risk state at the time $t+1$ meets the constraints $r_i^{t+1} = f\left(r_i^{t+1}\right) + \alpha f\left(r_j^{t+1}\right)$ and $r_j^{t+1} = f\left(r_j^{t+1}\right) + \beta f\left(r_i^{t+1}\right)$, then X_i and X_j are called respectively boustrophedon risk elements (BRE), and the interaction effect of risk state between the two subjects of risk research is called boustrophedon risk elements transmission (BRET). α, β represent respectively the coefficient of the RET.*

In BRET, the subjects of risk research are both the subjects of producing risk elements and the target objects affected by RET, and their transmission diagram is shown in Figure 1.

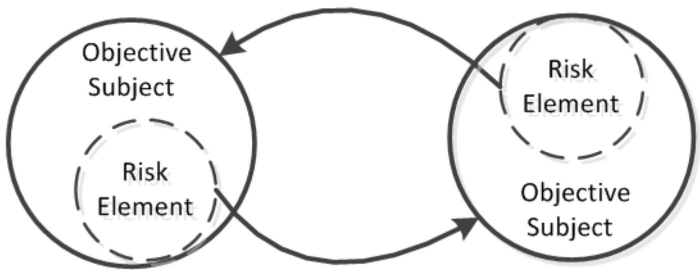

Figure 1. The transmission diagram of boustrophedon risk elements

3. Power Supply Analysis without Risk.

3.1. System model of micro-grid with wind/photovoltaic/storage energy. Usually, a micro-grid consists of wind turbine generator system, solar cells, storage batteries and load configuration [2]. And at any moment, output power of micro-grid with wind/photovoltaic/storages meets the following constraint:

$$P_W(t) + P_{PV}(t) + P_{SB}(t) \geq P_{LOAD}(t) \quad (1)$$

where $P_W(t)$ is the generated power of wind power generation at the time t, $P_{PV}(t)$ is the generated power of photovoltaic cells at the time t, $P_{SB}(t)$ is the charging and discharging power of storage battery at the time t, $P_{LOAD}(t)$ is the load power at the time t.

At the time t, when electric quantity of micro-grid generating cannot satisfy the self-supply, RCFS from large power grid will be utilized, and the constraint of electric quantity supplied by large power grid at time t to the micro-grid is shown as follows:

$$P_{RCFS}(t) = \sum_{i=1}^{n} P^i_{P,RCFS}(t) - \sum_{j=1}^{m} P^j_{M,LOAD}(t) \quad (2)$$

where $P_{RCFS}(t)$ is the remainder of RCFS from large power grid at time t; $P^i_{P,RCFS}(t)$ is the planning RCFS that large power networks have made for micro-grid i at time t; n is the number of micro-grids that have planning RCFS at time t; $P^j_{M,LOAD}(t)$ is the RCFS that has already been used by micro-grid j at time t; m is the number of micro-grids that already have started to use RCFS at time t.

3.2. Operational analysis of micro-grid. In this article, the power network system including two micro-grids in the same area is selected to make an analysis of risks. The two micro-grids have the following features: (1) similar power consumption and load curve; (2) wind power and light conditions are same; (3) all are connected to large power grid; (4) standby mode is RCFS.

Configuration of wind turbines, photovoltaic array and energy storage equipment in each micro-grid is as shown in Table 1.

Table 1. Configuration of each micro-grid

Micro-grid	Wind turbines power (kW)	PV power (kW)	Storage capacity (kWh)	RCFS (kW)
1	120	130	400	100
2	150	140	500	100

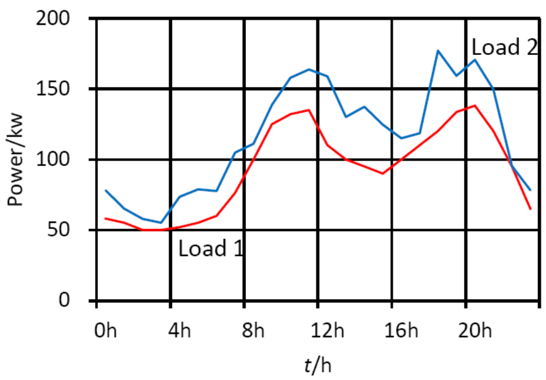

Figure 2. Typical daily load curves of each micro-grid

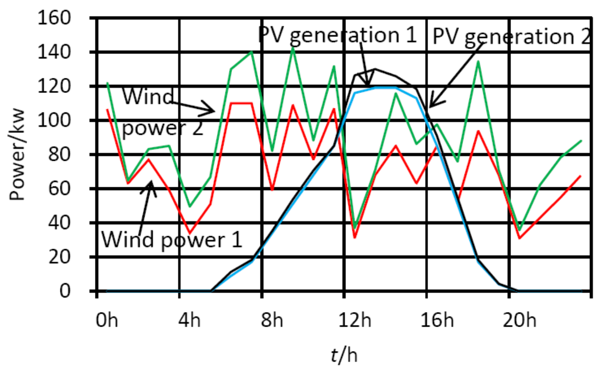

Figure 3. Typical daily power curves of each micro-grid's wind and PV generation

Daily load curves of each micro-grid are as shown in Figure 2. And the output power of wind power generation and photovoltaic power generation of the two micro-grids is as shown in Figure 3.

In order to prolong the operating life of the storage battery, the state of charge (SOC) needs to be controlled, which should meet the following constraint:

$$S_{\min} \leq S(t) \leq S_{\max} \tag{3}$$

where, $S_{\min}$ is the minimum value of the SOC of the storage battery; $S_{\max}$ is the maximum value of the SOC of the storage battery.

Power quantity curves of storage battery of two micro-grids are as shown in Figure 4.

Each micro-grid will plan its power supply capability according to the constraint shown in Formula (1) when the construction planning is implemented. $P_C^i(t)$ that is supply power capability of the micro-grid i at time t can be expressed as:

$$P_C^i(t) = P_W^i(t) + P_{PV}^i(t) + P_{SB}^i(t) \tag{4}$$

where, P_W is the output power of wind turbines; P_{PV} is the output power of the photovoltaic cells; $P_{SB}(t)$ is the charge and discharge power of the storage battery at time t.

The curves of power supply capability of each micro-grid (PSC) are shown in Figure 5. It can be seen from the diagram, planning target of the power supply capacity of each

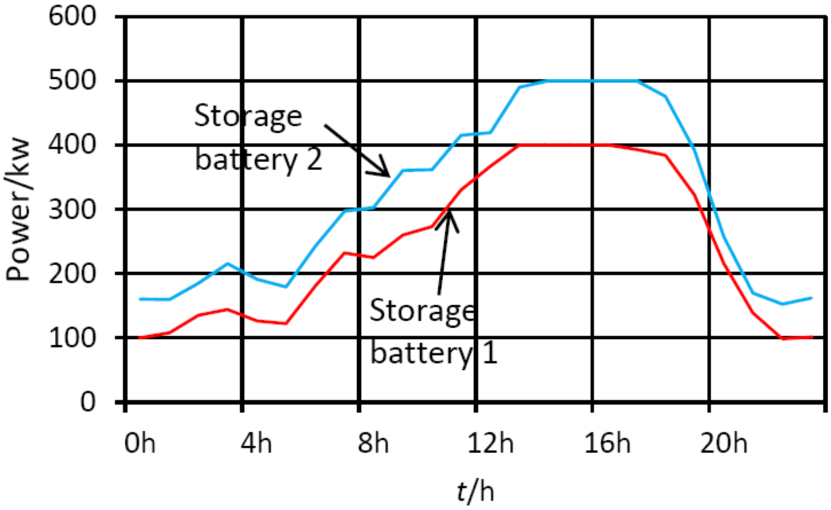

FIGURE 4. Typical daily storage curves of each micro-grid

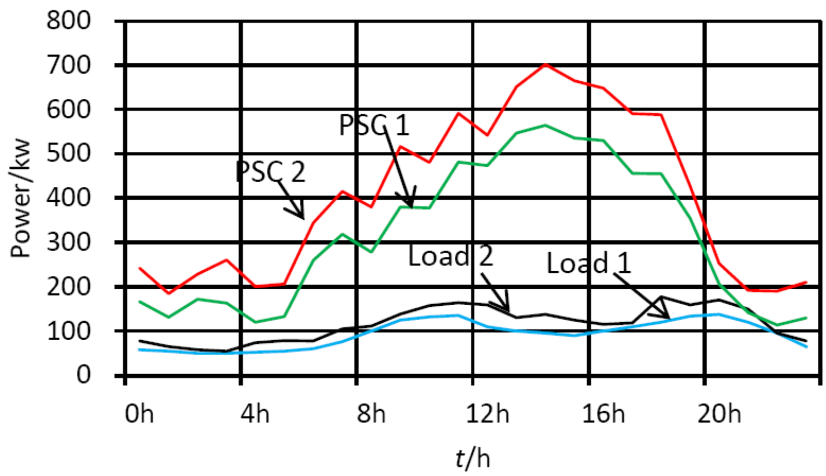

FIGURE 5. The curves of power supply capability of each micro-grid

micro-grid at any moment is greater than the load demand. At times of peak power, excess capacity will be stored in the storage battery; at times of troughs power, the balance power is provided by the storage battery; in ideal conditions, the risks of power supply do not exist in each micro-grid.

4. **Boustrophedon Risk Analysis.**

4.1. **BRET analysis between micro-grids.** When the lack of power supply capacity of the micro-grid exceeds the RCFS practically provided by large power network, it is considered that power supply risk happens in the micro-grid.

When the lack of power supply capacity appear in micro-grid i at time t, namely $P_{LOAD}^{i}(t) > P_{C}^{i}(t)$, the expected RCFS of micro-grid i at time t can be expressed as:

$$P_{E,RCFS}^{i}(t) = P_{LOAD}(t) - (P_{W}(t) + P_{PV}(t) + P_{SB}(t)), \quad (P_{SB}(t) \geq 0) \tag{5}$$

In general case, the maximum RCFS which micro-grid i actually obtained at time t can be expressed as:

$$P_{M,RCFS}^{i}(t) = \begin{cases} P_{E,RCFS}^{i}(t), & P_{E,RCFS}^{i}(t) < P_{RCFS}(t) \\ P_{RCFS}(t), & P_{E,RCFS}^{i}(t) > P_{RCFS}(t) \end{cases} \tag{6}$$

Definition 4.1. *After occurrence of the lack of power supply capacity in micro-grid, sometimes there will be a circumstance that using RCFS also cannot meet the load demand, and we define the situation as the risk of lack of electric power (RLEP).*

Definition 4.2. *The factors that cause the RLEP are called as the risk elements of lack of electric power (RELEP). There are external RELEP such as inadequate wind power and illumination as well as internal RELEP such as power generation equipment failure and power transmission fault.*

Definition 4.3. $R_{LACK}^{i}(t)$ *that the rate of RLEP of micro-grid i at time t can be expressed as:*

$$R_{LACK}^{i}(t) = 1 - \frac{P_{C}^{i}(t) + P_{M,RCFS}^{i}(t)}{P_{LOAD}^{i}(t)}, \quad R_{LACK}^{i}(t) \in [0, 1] \tag{7}$$

Combined with Formula (2), Formula (5) and Formula (6), $R_{LACK}^{i}(t)$ can also be denoted by:

$$R_{LACK}^{i}(t) = 1 - \frac{P_{C}^{i}(t) + \left(\sum_{i=1}^{n} P_{M,RCFS}^{i}(t) - \sum_{j=1}^{m} P_{LOAD}^{j}(t) \times R_{LACK}^{j}(t) \right)}{P_{LOAD}^{i}(t)}, \quad \left(P_{E,RCFS}^{i}(t) > P_{RCFS}(t),\ i \neq j\right) \tag{8}$$

It can get to know by Formula (8), RLEP of micro-grid i at time t is affected by that of the micro-grid j $(i \neq j)$ at time t; similarly, RLEP of micro-grid j at time t is affected by that of the micro-grid i at time t; that is, the risks between micro-grids affect and transmit each other at the same time t. It is known that there exists the BRET between micro-grids according to Definition 2.2.

Definition 4.4. $R_{I}^{i}(t)$ *that is risk impact factor of* $R_{LACK}^{i}(t)$ *in area network can be expressed as:*

$$R_{I}^{i}(t) = \frac{R_{LACK}^{i}(t)}{\sum_{j=1}^{m} R_{LACK}^{j}(t)}, \quad (j, i \in m) \tag{9}$$

where m is the number of micro-grids.

Risk impact factor $R_I^i(t)$ is the transfer coefficient that the RELEP of micro-grid i at the moment t can be transmitted to other micro-grids, which can be used to measure degree of influence and transmission of RELEP to other micro-grids; $R_I^i(t)$ can be also used to rank the degree that each micro-grid is at risk, which can provide basis of risk decisions for managers.

Based on the above discussions and analyses, it is obtained that BRET between two micro-grids has the following characters. (1) The main structures of two micro-grids are similar and vulnerable to the influence of same kind risk elements result in occurrence of risk, namely structural similarity and similarity of risk elements. (2) Two BRE subjects (also target objects) are both standalone system, and meanwhile they are also subsystems of certain large scale system, namely dual operating modes of subjects. (3) The interconnection of two BRE subjects is by means of certain shared resource such as RCFS. (4) The resource of large scale system including two BRE subjects is limited, namely limited shared standby resources. (5) The risks happen in two BRE subjects at the same time, namely simultaneity of risk occurrence.

4.2. **Power supply analysis of micro-grid invoking RCFS.** On the basis of example analysis described in Subsection 3.2, we will make further discussion on this example. Setting photovoltaic cells and wind turbines of two micro-grids cannot generate electricity at time 4h, 7h and 19h due to the reasons of illumination deficiency, inadequate wind power in the area. Because the load demand is smaller at 4h, reserve of electricity of the micro-grid can meet power utilization, namely, $P_{SB}(t) \geq P_{LOAD}(t)$, and at this moment storage batteries are in the state of discharging; micro-grids start producing electricity at 5h, 6h, $P_W(t) + P_{PV}(t) \geq P_{LOAD}(t)$, and at this moment storage batteries are in the state of charging; micro-grids again cannot generate electricity at time 7h and at this moment reserve of electricity of the micro-grid cannot meet load demand, namely, $P_{SB}(t) < P_{LOAD}(t)$, if storage batteries discharge to the minimum residual capacity at this moment, namely $S(t) \leq S_{\min}$, they will open the self-protection state and no longer supply power to micro-grid, so the micro-grid has to start using RCFS for power supply, because at this moment $P_{E,RCFS}^i(t) < P_{RCFS}(t)$, therefore, $P_{M,RCFS}^i(t) = P_{E,RCFS}^i(t)$. Figure 6 shows the RCFS curves of power supply of each micro-grid invoking. (Note: NRCFS represents necessary RCFS for micro-grid.)

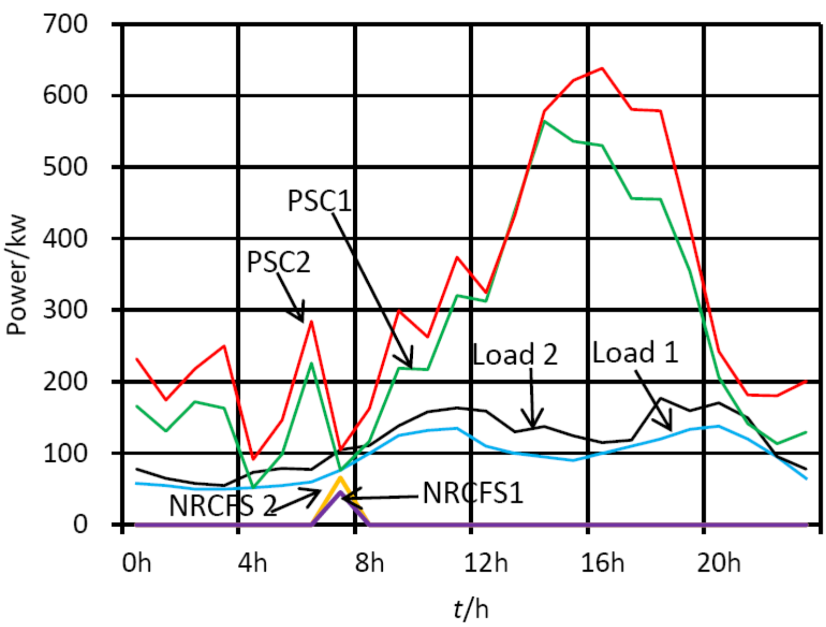

FIGURE 6. RCFS curves of power supply of micro-grid invoking

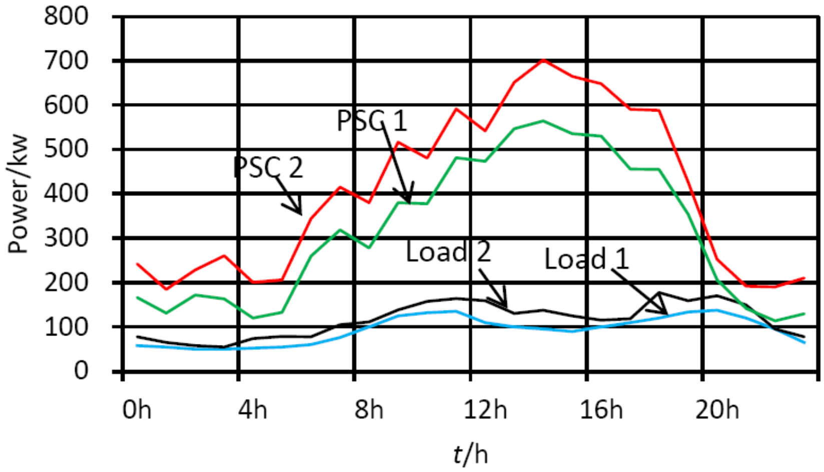

FIGURE 7. Risk curves of power supply capability

4.3. **RLEP analysis.** Going on discussing the example, two micro-grids still cannot generate electricity at time 8h, 9h result in $P^i_{E,RCFS}(t) > P_{RCFS}(t)$, consequently, $P^i_{M,RCFS}(t) \leq P^i_{RCFS}(t)$, that is, the RLEP happens in micro-grid i at time t. Figure 7 shows the risk curves of power supply capability of above two micro-grids.

The rate of RLEP of micro-grid 1 and micro-grid 2 at time 9h is worked out respectively according to Formula (7), and results are shown as follows:

$$R^1_{LACK}(9) = 0.2, \quad R^2_{LACK}(9) = 0.28$$

It can be seen from the analysis of RLEP of two micro-grids that $R^1_{LACK}(9) < R^2_{LACK}(9)$, and the RLEP of micro-grid 2 is greater than that of micro-grid 1.

The risk impact factor of lack of electric power of micro-grid 1 and micro-grid 2 at time 9h is figured out respectively according to Formula (9), and results are shown as follows:

$$R^1_I(9) = 0.417, \quad R^2_I(9) = 0.583$$

It can be seen from the risk impact factor of lack of electric power of two micro-grids that $R^1_I(9) < R^2_I(9)$, and the influence of the RELEP of micro-grid 2 to micro-grid 1 is greater than that of micro-grid 1 to micro-grid 2; the RLEP of micro-grid 1 is easier to be eliminated than that of micro-grid 2.

5. **Conclusions.** This article proposed the concept of BRET for the first time and constructed a model of RET between the same structure micro-grids, and this article conducted power supply analysis without risk and boustrophedon risk analysis of micro-grids in detail.

This article argues that, structural rationality of all the micro-grids in the same area should be considered when making construction planning of micro-grids; decision makers should stand in the height of the unified administration to organize and co-coordinate standby resources of micro-grids; the transitivity of risks between micro-grids in a same large scale system should be considered.

For the two micro-grids described in the example of this article, the biological energy generation and hydroelectric generation are added to them, which makes power generation structure of each micro-grid differentiated; as a result, the probability and point-in-time of risks occurrence of each micro-grid are different; in turn, scramble of standby resources cannot take place, so reserve capacity can be orderly allocated to more effectively lower the risks of power supply of micro-grids.

In the actual power supply, is there boustrophedon risk transmission phenomenon among different structure micro-grids? If there is, then how can we reveal and measure the transmission phenomena more scientifically? These will be our future research directions and objects.

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