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SECURITY ASSESSMENT FOR ELECTRICITY-HEAT INTEGRATED ENERGY SYSTEMS BASED ON SECURITY REGION

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ABSTRACT

The improvement of the automation level in electricity-heat integrated energy systems (IESs) has laid foundation for the load transfer after contingencies. As the energy coupling core and energy supply source, the energy hub (EH) plays an important role in IESs, where the load of EH's pipeline segment outlets is defined as operating points. First, the model of security region (SR) is proposed with the consideration of EH's equipment and pipeline segment N-1 contingencies and the system normal operation. Second, based on the security boundary of SR, the distance from an operating point to a boundary is presented for security assessment. Finally, the effectiveness of the proposed SR model and security assessment method is demonstrated on a test case, which can provide guidance for dispatchers.

Keywords: security region, electricity-heat integrated energy systems, energy hub, N-1 security, security assessment

1. INTRODUCTION

As the principal requirement of integrated energy systems (IESs), security is the foundation of researches in planning, operation, and trading. How to assess the IES security status after N-1 contingencies quickly has become the focus of academic and industrial fields.

Some methods have been proposed to analyze the security of IES. In [1], a robust scheduling model is constructed for IES with the consideration of N-1 faults occur at gas pipeline and power transmission. A hybrid control method of power and gas IESs is proposed based on the significant contingency screening, which can reduce the load shedding [2]. However, above researches mainly use the 'point-wise' method for security assessment of several points, which need longer calculation time and fail to give the global security information. To address these problems, the 'region' method could be adopted to provide security boundaries of IES including the whole security operating points. With the security region (SR), the security assessment could be conducted by the relative position of the operating point and SR.

The application of 'region' method in electric power distribution systems (EPSs) is mature [3], while it's still rough in IESs. The security region for electricity-gas IESs is first proposed in [4], where the operation limits under normal situations are focused. Furthermore, with the consideration of uncertainty of wind power generations, a robust security region for electricity-gas IESs is modeled in [5] without considering N-1 contingencies. It can be concluded that the SR considering N-1 contingencies has been scarcely applied in IESs and the SR for electricity-heat IESs is rarely studied.

Nowadays, the automation level of distribution system and district heating system is sufficient, which lays the foundation for SR technical feasibility of electricity-heat IESs based on the energy hub (EH). The load of EH pipeline segments defined as the operating point are observable and controllable. In this regard, this paper presents the concept and model of SR for electricity-heat IESs. What's more, the formulation of security boundaries and distance from an operating point to a boundary are proposed, with the security assessment analysis.

2. CONCEPT AND MODEL OF SECURITY REGION FOR ELECTRICITY-HEAT INTEGRATED ENERGY SYSTEMS

A typical electricity-heat IES applied in the city is utilized to describe the SR, whose energy supply sources are EHs. As shown in Fig.1, the EH can be divided into two parts including regional energy station (RES) and substation transformer (ST). Due to the fact that EH's equipment and pipeline segment contingencies are the most serious in IESs, therefore they are selected as the N-1 test objects in this paper.

The source of district heating system (DHS) is RES including gas boiler (GB), combined heat and power (CHP), and electric boiler (EB). The multi-heat sources supply mode could increase heating reliabilities. In this paper, the primary heat supply network is mainly considered. The EPS is supplied by ST with medium-voltage feeders, where different segments are connected through tie switches. When a contingency occurs at RES, the faulty thermal pipeline will be shut down by valve and the normal thermal pipeline will supply its load. When a contingency occurs at ST, the tie switch will be closed and the connected feeder will supply the faulted feeder.

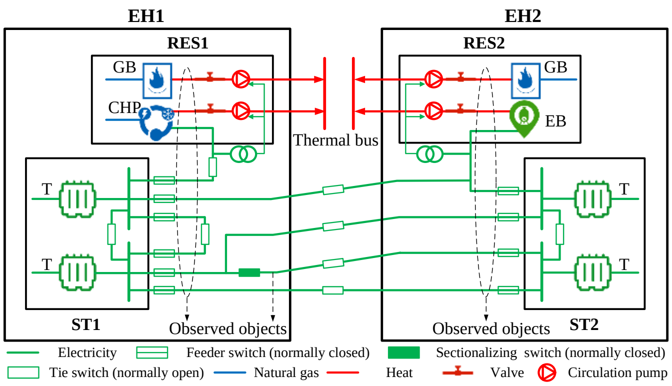

Fig.1 Schematic of electricity-heat IES based on EHs

2.1 Concept of security region for electricity-heat IES

In the electricity-heat IES, if a contingency occurs at EH's equipment or pipeline segment, the system will not lose the load except fault areas, then the IES could be called N-1 security. The security region is defined as the set of operating points satisfying N-1 security and normal operation. An operating point refers to the pipeline segment load of EH outlets, whose accumulation represents the load of EH's equipment.

2.2 Model of security region for electricity-heat IES

After the N-1 contingency at equipment or pipeline segment in EH, the load transfer should be carried out within the equipment and pipeline capacity limits. At the meanwhile, the system should guarantee the normal operation conditions. The model of SR for electricity-heat IES can be expressed as

$$\Omega_{\mathrm{SR}} = \left\{ \boldsymbol{L} \middle| f(\boldsymbol{L}) \ge 0, g(\boldsymbol{L}) \le 0 \right\} \tag{1}$$

where Ω_{SR} is the security region. $\boldsymbol{L}$ is the set of operating points, expressed as $\boldsymbol{L} = \{L_1, \cdots, L_w, \cdots, L_{\mathrm{W}}\}$; L_w is the wth load of EH's pipeline segment outlet; W is the total number of pipeline segments. $f(\boldsymbol{L}) \ge 0$ represents the energy supply requirements during normal operation. $g(\boldsymbol{L}) \le 0$ represents the capacity constraints of pipeline and equipment after load transfer.

When DHS is in operation, the circulation pump (CP) is powered to maintain the necessary pressure for water flow, and the thermoelectric couplings of extraction CHP will also make up the normal lower operation constraints $f(\boldsymbol{L}) \ge 0$. It should be noted that if the system satisfies the load transfer constraints $g(\boldsymbol{L}) \le 0$, it will meet the normal upper operation constraints due to stricter N-1 limits. The load transfer constraints are given by

$$\begin{cases} L_k^a = \begin{cases} \sum\limits_{k=1} L_k^{\mathrm{shift,e}}, a = \mathrm{e} \\ L_k^{\mathrm{shift,h}}, a = \mathrm{h} \end{cases} \\ H_j = \sum\limits_{k \in \Upsilon_j} L_k^a (\forall j) \\ L_{ij}^{\mathrm{shift},a} = \begin{cases} \sum\limits_{m \in \Upsilon_i, n \in \Upsilon_j} L_{mn}^{\mathrm{shift,e}}, a = \mathrm{e} \\ L_{mn}^{\mathrm{shift,h}}, m \in \Upsilon_i, n \in \Upsilon_j, a = \mathrm{h} \end{cases} \\ L_{mn}^{\mathrm{shift},a} + L_n^a \le C_{L_n}^{(m)} (\forall m, n) \\ L_{ij}^{\mathrm{shift},a} + H_j \le C_j (\forall i, j) \end{cases} \tag{2}$$

where a is the energy type of EH pipeline segment, including electricity e and heat h. When the pipeline is delivering electricity, there may be sectionalizing switches on the feeder m, where L_k^a represents the sum of the transfer load of feeder segments. When the pipeline is delivering heat, L_k^a represents the transfer load of the pipeline segment. $L_{mn}^{\mathrm{shift,e}}$, $L_{mn}^{\mathrm{shift,h}}$ represent the electric load, thermal load transferred to the pipeline n when a N-1 contingency occurs at the pipeline m. H_j is the load of equipment j. $L_{ij}^{\mathrm{shift},a}$ is the load transferred to equipment j after a N-1 contingency occurs at equipment i. $C_{L_n}^{(m)}$ is the rated capacity of the pipeline L_n, which also indicates an interconnected relation between the pipeline m and n. C_j is the rated capacity of the equipment j. Υ_i, Υ_j represent the set of pipeline segment outlet of equipment i, j, respectively.

Inequalities in (2) have shown the transfer path and capacity constraint of load transfer after pipeline segment or equipment contingency in EH. Due to the shorter pipeline of the city IES, the voltage and water pressure parameters can be maintained by the reactive power compensation device and CP, which can be generally satisfied. Therefore, the IES energy flow is simplified to focus on the overload problem in the load transfer after the N-1 contingency.

2.3 Boundary of security region for electricity-heat IES

In order to analyze the main problem, assuming that the transmission capacity of the pipeline is sufficient. The formulation of security region boundary can be simplified as

$$\Omega_{SR}=\begin{cases}BD_1\\ \cdots\\ BD_w\\ \cdots\\ BD_W\end{cases}=\begin{cases}0\le L_1\le C_j-\sum\limits_{k\in\Upsilon_j}L_k^a-\sum\limits_{m\in\Upsilon_m,n\in\Upsilon_j,L_{mn}^{\text{shift},a}\ne L_1}L_{mn}^{\text{shift},a}\\ \cdots\\ 0\le L_w\le C_j-\sum\limits_{k\in\Upsilon_j}L_k^a-\sum\limits_{m\in\Upsilon_w,n\in\Upsilon_j,L_{mn}^{\text{shift},a}\ne L_w}L_{mn}^{\text{shift},a}\\ \cdots\\ 0\le L_W\le C_j-\sum\limits_{k\in\Upsilon_j}L_k^a-\sum\limits_{m\in\Upsilon_W,n\in\Upsilon_j,L_{mn}^{\text{shift},a}\ne L_W}L_{mn}^{\text{shift},a}\end{cases}\tag{3}$$

where BD_w represents the security boundary of L_w. It should be noted that when the pipeline supplies power to key equipment in DHS, the lower limit is updated to the relevant upper limit of the electric load.

From (3), we can get the conclusion that the SR is surrounded by 2W hyper-planes. The SR is uniquely determined by the system topology and equipment capacity. The security boundary could reflect the system planning effect in energy supply capacity, in return, it can be applied to IES planning to balance security and efficiency.

2.4 Distance from an operating point to a boundary of security region

The distance from an operating point to SR boundaries is important for security assessment. If the distance is nonnegative, the operating point can be called N-1 security. Otherwise, the operating point is insecurity. What's more, the distance value means a margin for load increase or decrease, which contributes to the security assessment.

$$D_w=\frac{BD_w(\boldsymbol{L})}{\sqrt{a}}\tag{4}$$

where D_w is distance from the operating point $\boldsymbol{L}$ to SR boundary BD_w; a is the number of pipeline segment load on the boundary BD_w.

3. CASE STUDY

In this section, the electricity-heat IES in a demonstration area is selected as the test case. For the convenience of analysis, the number of STs, RESs and pipelines are reduced. The structure of the test case is shown in Fig.2. There are two EHs, including two STs, ten medium-voltage feeders, two RESs, and four main pipelines of DHS. The detailed parameters of EHs are listed in Table 1, where the total capacity of STs, RESs is 52MVA and 28MW, respectively. The transmission capacity of the pipeline is sufficient, and the power factor of the system is assumed to be the same.

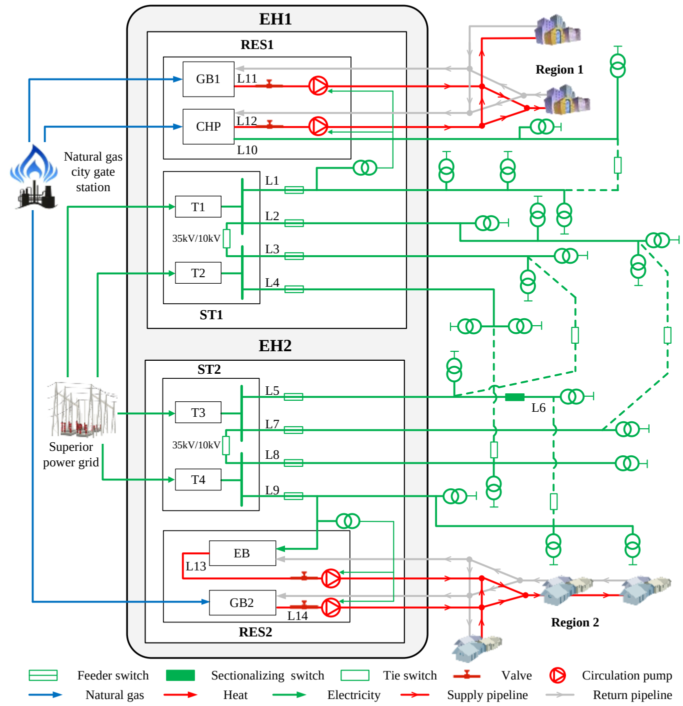

Fig.2 The test case of electricity-heat IES

Table 1. Equipment parameters of EHs

EH	Object	Equipment name	Capacity
EH1	RES1	GB1	8MW
		Extraction CHP	Heat: 4MW Electricity: 5MW
	ST1	T1	16MVA
		T2	16MVA
EH2	RES2	EB	6MW
		GB2	5MW
	ST2	T3	10MVA
		T4	10MVA

3.1 Security region of the test case

There are 14 pipeline segments in the test case. Feeders L_1 and L_9 supply CP and EB, respectively. As the output of extraction CHP, pipelines L_{10} and L_{12} possess thermoelectric couplings [6]. Besides, feeders L_5 and L_6 are multi-sectioned and multi-linked. Based on the topology of the test case, there are 28 security boundaries of SR, expressed as

$$\Omega_{\rm SR}=\left\{BD_1,BD_2,\cdots,BD_{14}\right\}$$

$$=\begin{cases}\dfrac{P_{\rm CP}}{\cos\varphi}\le L_1\le\dfrac{C^{\rm e}_{\rm CHP}-L_{10}\cdot\cos\varphi}{\cos\varphi}\\ 0\le L_2\le C_{\rm T3}-(L_5+L_6+L_7)\\ 0\le L_3\le C_{\rm T3}-(L_5+L_6+L_7)\\ 0\le L_4\le C_{\rm T4}-(L_8+L_9)\\ 0\le L_5\le C_{\rm T2}-(L_3+L_4)\\ 0\le L_6\le C_{\rm T4}-(L_8+L_9)\\ 0\le L_7\le C_{\rm T1}-(L_1+L_2)\\ 0\le L_8\le C_{\rm T2}-(L_3+L_4)\\ (\dfrac{L_{13}}{\eta_{\rm EB}}+P_{\rm CP})\cdot\dfrac{1}{\cos\varphi}\le L_9\le C_{\rm T3}-(L_5+L_6+L_7)\\ \dfrac{c_m\cdot L_{12}}{\cos\varphi}\le L_{10}\le\min(C_{\rm T1}-(L_1+L_2),\dfrac{C^{\rm e}_{\rm CHP}-c_v\cdot L_{12}}{\cos\varphi})\\ 0\le L_{11}\le C^{\rm h}_{\rm CHP}-L_{12}\\ 0\le L_{12}\le C_{\rm GB1}\cdot\eta_{\rm GB}-L_{11}\\ 0\le L_{13}\le C_{\rm GB2}\cdot\eta_{\rm GB}-L_{14}\\ 0\le L_{14}\le C_{\rm EB}\cdot\eta_{\rm EB}-L_{13}\end{cases}\quad(5)$$

where $C^{\rm e}_{\rm CHP}$, $C^{\rm h}_{\rm CHP}$ are the electricity and heat capacity of CHP. $C_{\rm T1}$, $C_{\rm T2}$, $C_{\rm T3}$, $C_{\rm T4}$, $C_{\rm GB1}$, $C_{\rm GB2}$, $C_{\rm EB}$ are the capacity of substations T1, T2, T3, T4, and GB1, GB2, EB, respectively. $P_{\rm CP}$ is the maximum consumed power of CP. $\eta_{\rm EB}$, $\eta_{\rm GB}$ are the energy conversion efficiency of EB and GB. $\cos\varphi$ is the power factor. c_m 、 c_v are the lower and upper limits of electric-heating ratio in CHP. Each inequality in (5) constitutes a hyper-plane, so the SR is surrounded by 28 hyper-planes.

3.2 Security assessment based on the SR of the test case

The light load operating point A and heavy load operating point B are selected to calculate the distance to security boundaries for security assessment. ***L*** can be expressed as ***L***=(L_1, L_2, …, L_{14}), whose dimension is 14. Assume that the operating point A is ***L***$_{\rm A}$=(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1), and the operating point B is ***L***$_{\rm B}$=(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3). When the inequalities in (5) are equal, the corresponding security boundaries can be defined as BD_1 to BD_{28}. The calculation results of distance from the operating point A, B to security boundaries are shown in Table 2 and Table 3, respectively.

Table 2. Distance from the operating point A to security boundaries

Boundary *BD_w*	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8	BD_9	BD_{10}
Distance D_w/MW	1.40	1.60	1.70	1.70	1.70	1.70	1.70	3.40	1.70	8.5
Boundary BD_w	BD_{11}	BD_{12}	BD_{13}	BD_{14}	BD_{15}	BD_{16}	BD_{17}	BD_{18}	BD_{19}	BD_{20}
Distance D_w /MW	1.70	3.40	1.70	**8.50**	1.70	8.50	**0.15**	1.70	0.90	3.20
Boundary BD_w	BD_{21}	BD_{22}	BD_{23}	BD_{24}	BD_{25}	BD_{26}	BD_{27}	BD_{28}		
Distance D_w /MW	1	2	1	5.2	1	2.5	1	2.8		

Table 3. Distance from the operating point B to security boundaries

Boundary BD_w	BD_1	BD_2	BD_3	BD_4	BD_5	BD_6	BD_7	BD_8	BD_9	BD_{10}
Distance D_w /MW	2.25	**-0.10**	2.55	**-1.70**	2.55	**-1.70**	2.55	0.85	2.55	5.95
Boundary BD_w	BD_{11}	BD_{12}	BD_{13}	BD_{14}	BD_{15}	BD_{16}	BD_{17}	BD_{18}	BD_{19}	BD_{20}
Distance D_w /MW	2.55	0.85	2.55	5.95	2.55	5.95	**-1.50**	**-1.70**	0.71	2.15
Boundary BD_w	BD_{21}	BD_{22}	BD_{23}	BD_{24}	BD_{25}	BD_{26}	BD_{27}	BD_{28}		
Distance D_w /MW	3	**-2**	3	3.20	3	0.50	3	0.80		

From Table 2, the distance from operating point A to all security boundaries is positive which indicates the operating point A is secure. The distance to boundary BD_{17} is the smallest, which means that if the EB load increases, L_9 may not guarantee it's operation. Therefore, the security margin of increaseable EB load is low. The distance to boundary BD_{14} is the biggest. When the N-1 contingency occurs at L_7, the security margin of transformer T2 after load transfer is sufficient.

It can be seen from Table 3 that there are negative values in the set of ***D***, so the operating point B is insecure. The bold distance from B to boundary BD_2 、 BD_4 、 BD_6 、 BD_{17} 、 BD_{18} 、 BD_{22} is negative, indicating that B is outside six boundaries. The *D* of B to boundary BD_2 is -0.10MW, which is close to 0, so the L_1 is slightly overload. When N-1 contingency occurs at one of the above pipelines, the transfer equipment will be overloaded and cannot satisfy the N-1 security guideline. At this time, the system will lose load. In order to ensure the system's N-1 security, a feasible method is to reduce those pipeline load whose security distance is negative.

4. CONCLUSIONS

This paper proposes a new security assessment method for electricity-heat IES based on security region (SR). The concept and model of SR is defined and constructed. Furthermore, the boundary and the distance from an operating point to a boundary are expressed mathematically, which lay foundations for security assessment. If the distance from an operation point to boundaries is non-negative, then the point can be called N-1 security, otherwise it is insecurity. Above researches provide security analysis methods for the IES planning and design. In the next step, further work will be carried out about more accurate SR model, optimization control method for operating points of different security status.

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