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Reliability Evaluation of Integrated Energy System with Energy Synthetic Utilization

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ABSTRACT

Integrated energy system (IES) takes advantage of flexibility based on energy synthetic utilization, thereby considered as the future energy carrier with great potential. The energy hub (EH) is essential for multi-level energy exploitation and flexible conversion between electricity and other energy sources. It is hoped that this research will contribute to a deeper understanding of the impact of energy coupling on system reliability and help to map out future organizations. This paper presents a method for measuring reliability in IES based on the thought of impact increment and hierarchical decoupling optimization. It follows a case-study design to verify the efficiency of the hybrid methodology given before. Supported by the numerical results, the effects of energy synthetic utilization in terms of system reliability are evaluated and also analyzed at a power flow level.

Keywords: energy synthetic utilization; impact-increment; reliability evaluation; integrated energy system

1. INTRODUCTION

When the shift of energy is coming at the horizon, the traditional energy industry should work out an innovative way to upgrade energy structure. The development of integrated energy system gas has revolutionized the European energy industry[1] to overtake the traditional energy system as the future power supplier. IES enables multiple energy to work together, breaking through the blockades under the past independent operation. The integrated system embodies its flexibility in the collaborative management of the various energy carriers.

Some problems have accompanied the flexibility. A natural gas spill accident led to the meltdown of the local power plant in California, causing an electricity supply crisis for residents which lasts the whole summer in 2016. This supply crunch has exposed potential risks to the hybrid energy system. Therefore, it is necessary to evaluate the reliability of a system to prevent a small spill from becoming a wide blackout.

To assess the likelihood of an accident and the impact is the main task of reliability evaluation[2]. It provides information about system safety and adequacy on energy suppling, that is the ability to resist disturbance dynamically and balance the demand and energy supply statistically. Reliability evaluation for an integrated energy system can be divided into three stages, including state simulating, state analysis, and indices calculation. Among these procedures, multi-energy flow calculation is under consideration when analyzing each system state.

However, the interaction between heterogeneous energy forms is by no means easy, which calls for an efficient and accurate method to tackle the complexity. Multi-energy flow modeling and solving problem play an essential role for state analysis, reflecting energy transmission within the system. As the basic analytical tools in the study of IES, multi-energy flow analysis has experienced years of exploration and achieved some results on both synthetic and separate methodologies. The iterative method between thermal network and hot-water network is the traditional way for heat system calculation. Liu[3] integrates the Newton-Raphson method with it in electricity-heat-combined systems. It enlightens the analyzing method for the combination of distributed generation and thermal storage. Ref.[4] proposed a co-modeling method for energy flow in the gas system and the power system. Moreover, a variety of solving techniques has been developed to analyze the energy flow, including the iterative method[5] and decoupled strategy[6]. Liu[7] pursues way for daily operation scheduling problems based on security-constrained unit commitment (SCUC) and gas network constraints. More recently, the modeling and simulation of IES are fixed with further consideration of fluctuations in renewable power[8] and time lag[9] between various energy carriers. The researches mentioned above contributed a lot to energy flow analysis, but the risk of the interactions of various energy carriers is still yet to be evaluated.

Optimal multi-energy flow serves as an efficient way to determine the minimum load curtailment and reliability indices. Geidl[10] considered the multi-energy flow based on the energy-hub model, providing a universal framework for optimal flow analysis in a hybrid energy system. A real-time optimal flow model based on the CCHP model in Ref.[11] is oriented toward annual economic operation with the concern of thermal storage. The aim of the multi-objective optimization model in Ref.[12] is co-realization of operation economy, environment friendliness, and security. The above researches are designed for optimal operation under a certain circumstance, while the reliability evaluation requires an efficient way of quick calculation to deal with plenty of uncertain scenarios.

To assess the reliability and flexibility of the power system coupled with various energy, this paper integrated the Impact-increment based state Enumerate method[13] and the energy-decoupled method to analyze the interaction of different energy carriers.

In section 2, a two-layered decoupled energy analysis is proposed to solve interactive and complimentary relationships of various energy carriers. In section 3, a composite reliability evaluation process for a power system with complementary energy carriers is concluded. A case study is carried out with the proposed method in section 4. The numeral results compare the system with and without energy coupling and then study the influence of the multi-energy complementarity.

2. SYNTHETIC OPTIMIZATION OF MULTI-ENERGY

Because of the complementary roles of multiple energy carriers, the two-layer model is adopted to decouple the calculation of optimal energy flow. The two layers represent the two calculating stages in the process. The first layer is carried in the energy hub, focused on the energy conversion and allocation between each energy sub-system. The other can make a flexible response to this allocation strategy in power system, heat system, and gas system according to its optimal flow. In turn, the upper considers the feedbacks from the lower layer and makes the next round of decisions about the distribution of the energy supplies. The lower layer follows this new instruction and calculates the optimal flow in each sub-system to accomplish with the whole system supplying fulfillment. The recursive optimization and feedback emendation comes to an end with the coordinative optimization of the multi-energy flow.

The calculation of optimal power flow is executed in each subsystem so that the power flow convergence difficulty can be avoided, which is caused by the great value difference between various systems. Based on the model of the sub-system modeling method, the two-level algorithm reduces complexity and speeds up the calculating process.

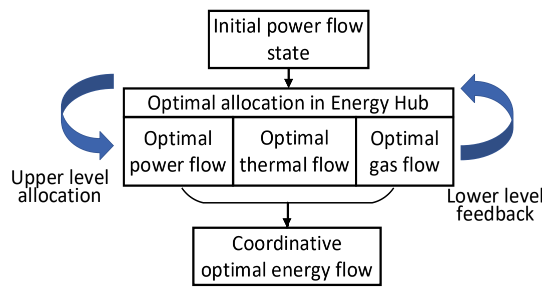

Fig 1 Optimization framework.

2.1 *Upper layer optimization*

It is the energy hub that has strong ties with the upper layer optimization in the proposed algorithm. The energy hub can be divided into several types according to their component[10]. Relationships between energy input $\boldsymbol{P}$ and output $\boldsymbol{L}$ can be express as,

$$\begin{pmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{pmatrix} = \begin{pmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{pmatrix} \begin{pmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{pmatrix} \tag{1}$$

where the coupling matrix is composed with conversion efficiency; the coupling factor $c_{\alpha\beta}$ represents the macroscopic efficiency of transformation from pattern α to pattern β, which is equal numerically to the product of distribution rate $\boldsymbol{\eta}$ and conversion efficiency $\boldsymbol{\nu}$.

$$\eta = \begin{pmatrix} \eta_{T,e} & \eta_{AC,e} & \eta_{CHP,e} & \eta_{HE,e} & \eta_{F,e} \\ \eta_{T,g} & \eta_{AC,g} & \eta_{CHP,g} & \eta_{HE,g} & \eta_{F,g} \\ \eta_{T,h} & \eta_{AC,h} & \eta_{CHP,h} & \eta_{HE,h} & \eta_{F,h} \end{pmatrix} \tag{2}$$

$$\nu = \begin{pmatrix} \nu_{e,T} & \nu_{g,T} & \nu_{h,T} \\ \nu_{e,AC} & \nu_{g,AC} & \nu_{h,AC} \\ \nu_{e,CHP} & \nu_{g,CHP} & \nu_{h,CHP} \\ \nu_{e,HE} & \nu_{g,HE} & \nu_{h,HE} \\ \nu_{e,F} & \nu_{g,F} & \nu_{h,F} \end{pmatrix} \quad (3)$$

To be more precise, the relationship between input and output is shown as follows.

$$\boldsymbol{L} = \boldsymbol{CP} = \boldsymbol{\eta} \cdot \boldsymbol{\nu} \cdot \boldsymbol{P} \quad (4)$$

More than the junction of energy conversion, the energy hub also acts as an essential part in the decision of optimal allocation of the composite system. The optimization concerns the coordinative optimization of the whole system rather than the detailed operating conditions in the subsystem. Therefore, the optimization framework of the upper layer is followed.

$$\begin{gathered} \min \sum_{e,g,h} \sum_{i=1}^{N_{EH}} \left(c_i P_i + \alpha_i \Delta L_i \right) \\ \boldsymbol{L} = \boldsymbol{CP} \\ \boldsymbol{\Delta L} = \boldsymbol{L}_o - \boldsymbol{L} \\ \boldsymbol{P}_{min} \le \boldsymbol{P} \le \boldsymbol{P}_{max} \\ 0 \le \boldsymbol{L} \le \boldsymbol{L}_o \end{gathered} \quad (5)$$

where e,g,h refer to the power network, heat network, and gas network, respectively; c is the energy cost on the input side; α is the penalty factor to assess the economic loss of load; $\boldsymbol{P}_{max}$ and $\boldsymbol{P}_{min}$ are the upper and lower limits of the energy flow; $\boldsymbol{L}_o$ represents the load demand of the node where the energy hub is.

2.2 Lower layer optimization

Targeting minimal load curtailment($\boldsymbol{LC}$) in each sub-system is the goal. The energy flow equations serve as equality constraints in the lower layer optimization(not described in this article). The inequality constraints are associated with fluid flow velocity($\boldsymbol{m}$) as well as supply and return water temperature($\boldsymbol{T}_s$ $\boldsymbol{T}_r$). Take the optimal heat distribution model as an example.

$$\begin{gathered} f(x) = \min \sum_{i \in \mathrm{N_D}} LC_{\mathrm{h,i}} \\ f_h(\boldsymbol{m}, \boldsymbol{T}_s, \boldsymbol{T}_r) = 0 \\ \boldsymbol{LC}_h = \boldsymbol{L}_{load,h} - \boldsymbol{\Phi}_h \\ 0 \le \boldsymbol{\Phi}_h \le \boldsymbol{L}_{load,h} \\ 0 \le |\boldsymbol{m}| \le \boldsymbol{m}_{max} \\ \boldsymbol{T}_{s,min} \le \boldsymbol{T}_s \le \boldsymbol{T}_{s,max} \\ \boldsymbol{T}_{r,min} \le \boldsymbol{T}_r \le \boldsymbol{T}_{r,max} \end{gathered} \quad (6)$$

3. RELIABILITY EVALUATION OF MULTI-ENERGY SYSTEM

Section 2 mainly handles the complexity in the calculation of different energy distribution in the state analysis stage. The proposed algorithm shows practicability and high efficiency. To further improve the efficiency of the reliability calculation, IISE is adopted to collect proper states before applying energy flow optimization[14]. The core idea is that part of the influence of higher-order faults can be included in those lower-ordered counterparts. Since the number of possible states arrangement with fewer fault elements is relatively smaller, the size of the state set required to be analyzed can be greatly reduced, and more precise results can be obtained at the very early stage.

To quantify the composite system reliability with consideration of complementary interactions, it requires unified reliability indices for different energy forms. The electricity can travel at the speed of light and electricity outage comes at once, while the consumers are desensitized to the cut of heat and gas supply over a short time. Therefore, it allows for a bigger weighting of electricity load cut(w_e) in the index. Take expected energy not supplied (EENS) during a year as the index to evaluate the system reliability.

$$\begin{aligned} R &= w_e R_e + w_g R_g + w_h R_h \\ &= \sum_{e,g,h} \sum_{s \in \Omega_s^k} w \Delta P_s \Delta I_s \end{aligned} \quad (7)$$

After settling down the detailed method for state simulation, state analysis, and reliability indices, the procedure of the integrated energy system reliability evaluation can be concluded as follows:

1.Input the energy prices and operating parameters of the hybrid energy system and energy hub. The stop criteria, maximum iterations, and order of fault elements are clarified here.

2.Enumerate the system states with k fault elements to form the k order scenario set Ω_s^k.

3. Initialize the iteration counter.

4.If the number of iteration does not meet the upper limit, optimize the energy allocation between three subsystems. Otherwise, a failure message is displayed.

5.Under the instruction of the upper layer calculation results, the optimal energy flow in each sub-system is determined analytically to coincide with their conditions.

6.Repeat the procedures above and execute the next round of energy optimization until the solution reaches the convergence criterion, then move on to the next system states.

7.When completing the assessment of states in Ω_s^k, obtain the expectation for the load curtailment of all states.

8.If the current order is lower than the maximum order, increase the order k with 1, and go back to stage2. Otherwise, the composite system reliability can be quantified by collecting and summing up the expectation value of each state space.

4. CASE STUDIES

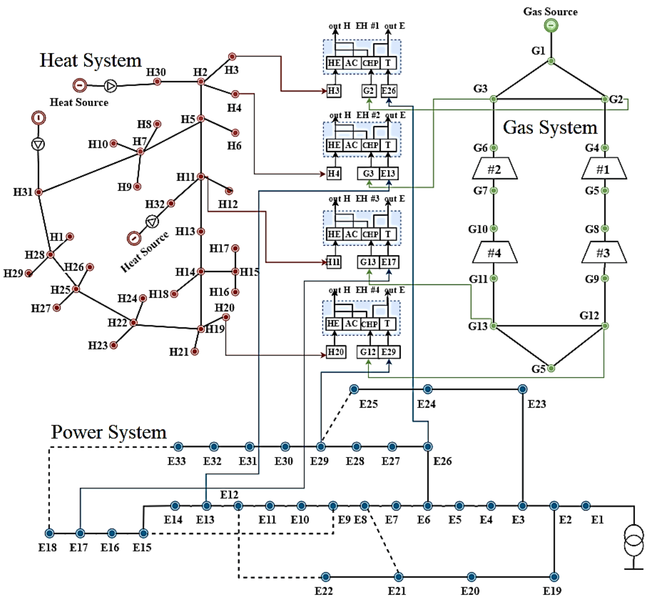

Fig 2 Integrated energy system.

Taking IEEE33 system integrated with gas system in [15] and heat network in [3] as an example to analyze the influence of the energy complementation to system reliability. The sub-systems are combined via four energy hubs, as shown in Fig 1. Only the failures of key equipment, i.e. transmission lines, transformer, and compressor, are taken into account.

4.1 Reliability evaluation

Table 1 Results of different methods.

	EENS of the integrated energy system			Computing time (s)	Number of states
	R_e(MWh/yr)	R_h(MWh/yr)	R_g(MWh/yr)		
SE1	97.41183	10.3492	278.1008	416.57	81
SE2	114.5292	11.4940	281.5612	26012.6	3240
IISE1	112.7751	12.0077	321.8448	416.87	81
IISE2	116.0466	12.1303	312.8930	26429.32	3321
MCS	118.0758	12.0513	312.2707	105717.28	2395631

Compared with the different maximum order and various state simulating methods, including state enumeration, impact increment state enumeration, and Monte-Carlo simulation, the listed results prove the efficiency and accuracy of the IISE-based reliability evaluation method with maximum order as 2. Thus, it is used in the subsequent calculation.

4.2 Weakness of Integrated energy system

With the guidance of the system reliability calculation, detecting the key elements and vulnerable spots is essential for reliability enhancement. The key elements are those elements whose failure can result in a threat to the energy supply. Vulnerable spots refer to the load buses are prone to suffer.

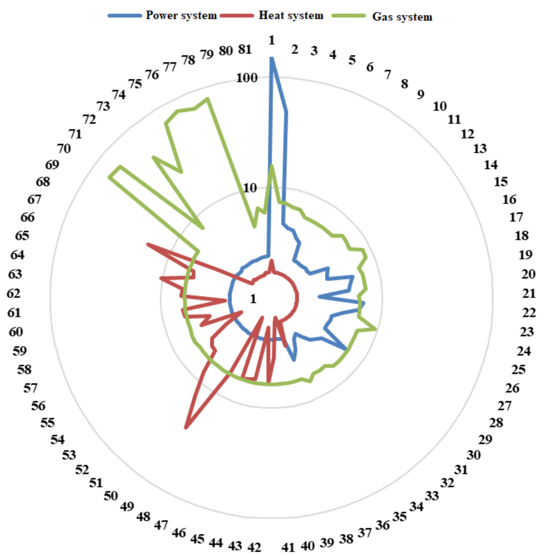

Fig 3 Adverse influence of each branch failure.

From Fig.3, the characteristics of the weak spots can be concluded. Typically, the weak spots usually spare insufficient alternate transmission lines and carry a considerable amount of energy.

It is self-evident that branch 1(transmission line 1) is the gateway for power transmission. Branch 2 also takes an important task for power transfer because of its location. Both of them are weaknesses. As for the heat network, the failure of branch 49 and branch 67 profoundly endanger energy supply, since they are arterial pipes in the heat network. The vulnerable points in the gas system share the same features. The status of branches 70 and 71 have a huge impact on the gas system. The symmetric distribution of gas comes with the symmetric network. Failure of branches 75 to 78 can break the balance, therefore the pipes on the opposite side are forced to undertake extra gas delivery work. Therefore, the elements with the two features mentioned above should be reinforced by adding an alternative transmission path.

From Fig.3, Bus 24,25,30 are the most vulnerable nodes in the power system and there exist two reasons. Firstly, the load bus with high and unreasonable demand of power supply can only result in load curtailment and insufficient energy support. Because of their long-distance to the source nodes, they are more likely to suffer from a power deficit. Among the bus 32,7,8,30 with the same load, more branches must be ensured of power flow carried out effectively to fulfill the need of bus 30, which has a modestly lower likelihood.

4.3 Influence of synthetic utilization of multi-energy

Compared with the reliability of the system under separate operation, the effect of synthetic usage of multi-energy lies not only in the interactions between systems but also in the single sub-system.

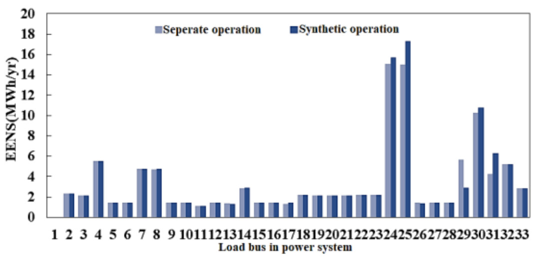

Fig 4 Power system EENS under two operating conditions.

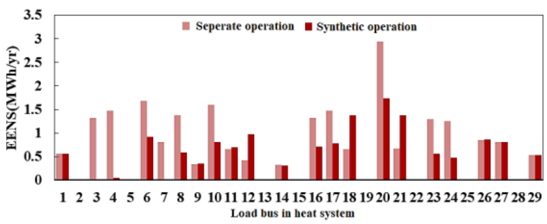

Fig 5 Heat network EENS under two operating conditions.

The type of energy hub decides the convert direction. With the Air conditioner (AC) and Combined heat and power (CHP) equipment, the energy flow is extracted from the gas and power system and transferred into the heat network. Therefore, the energy shortage is shifted to the heat network. The AC is deeply involved in energy conversion due to its high efficiency. CHP acts as backup equipment to transform electricity to heat when severe power outages arise and ACs fail to work. Though there exists conversion from gas to electricity to support the electric needs, the effect is limited by the participation of CHP and little redundancy of gas.

Load loss in the gas system is increased after integration with the other two sub-systems since natural gas is at the bottom of the entire energy supplying chain. The nodes equipped with EH in the power system and heat system are under the support of spared gas. The enhanced reliability for these coupling nodes, on the other hand, poses threat to the supply of their counterparts. That is a reliability shift within a single system. Adjustment of the bus reliability is derived from the direct effect on the local load bus and the indirect impact of altered energy distribution. Take the nodes E29, E25, E30 in the power system as an instance.

From Table 2, the failure of branch 2 is decisive to the reliability shift, so this state is analyzed in detail.

Table 2 Energy supply reliability in power system when the failure of line1 or line2 occurs.

System operating states	Fault branch	EENS of the bus (MWh/yr)				
		E31	E30	E29	E25	E24
Separate	1	3.5304	4.7072	2.8243	9.8850	9.8850
	2	0.5573	4.7072	2.7854	5.0865	4.8033
Synthetic	1	3.5304	4.7072	2.8243	9.8850	9.8850
	2	2.7769	4.7072	0.0000	7.3906	5.4924

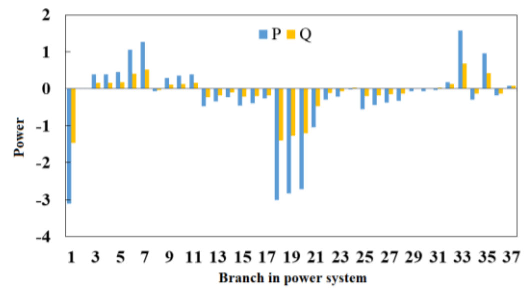

Fig 6 Active power and enactive power of branches.

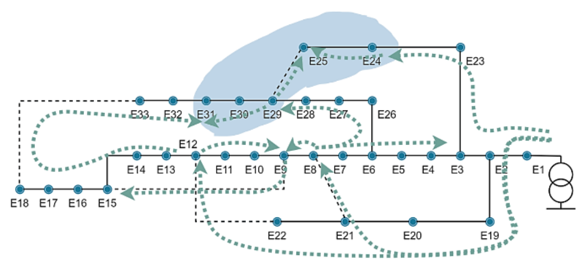

Fig 7 Active power and enactive power distribution.

Fig.6 illustrates the homogeneous sign of active power and reactive power in the critical branch, indicating their similar flow direction and distribution as fig.7. Their same locations of demand and sources account for the phenomenon: From a macro perspective, the system appears as an inductive network because of branch reactance. There is merely one bus equipped with a reactive power source and the only active power resource is settled at the same place. The active and reactive power loads are all positive.

E29 is located in the largest concentrations of the load buses and the power flow flushes towards it. The additional electric needs from AC bring about higher load curtailment, especially for the downstream buses of the power flow. The first reason is that their voltage (E24, E25, E31) stands on the stable threshold. The voltage difference limits the energy carried to these buses. In the reactive system, the reduction of current is used to control the voltage and leads to power shortage. If load curtailment is taken on the buses far from source nodes, the reduction of current is greatest, because almost all branches in the system are influenced. For another, operating patterns of EH allow for the energy boost for their own energy needs rather than the common nodes in the system. Based on the above-mentioned factors, the energy supply reliability of the nodes equipped with energy hub is enhanced and vice versa.

5. CONCLUSION

The proposed method for quick reliability calculation serves as a potent tool to evaluate the influence of the synthetic utilization of multi-energy, thereby supplying the designing and decision basis for the integrated energy system. The effectiveness and accuracy of the combination of two-layer optimization and the IISE method are verified. It is noted that the impact is explained at a microscopic level. There exists some work yet to solve in the future. The proposed method can efficiently calculate the system reliability, but the number of states is still in the curse of dimensionality. For another, the details of the micro-cutting process of the energy flow are still untapped.

ACKNOWLEDGEMENT

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