Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Reliability evaluation of integrated energy systems based on smart agent communication ☆

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HIGHLIGHTS

- Established reliability evaluation models for Integrated Energy Systems (IESs).
- Presented a two-hierarchy smart agent model to describe Smart Agent Communication (SAC).
- Presented an IES reliability evaluation approach based on SAC.
- Validated models and approaches on a multi-paradigm modeling and simulation platform.

ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form 13 November 2015
Accepted 26 November 2015
Available online xxxx

Keywords:
Reliability evaluation
Integrated energy system
Smart agent communication
$K-1$ algorithm

ABSTRACT

Reliability evaluation of Integrated Energy Systems (IESs) based on Smart Agent Communication (SAC) is studied in this paper. The typical structure and reliability evaluation modeling for IESs is firstly introduced. A new reliability evaluation approach is then presented, in which SAC based system reconfiguration is innovatively integrated into the reliability evaluation process. Based on this combination, state evaluation (key procedure of the reliability evaluation) along with system reconfiguration can be conducted autonomously in reliability evaluation. Algorithm and procedures of the system reconfiguration based on a decentralized agent communication algorithm ($K-1$ algorithm) is described. The system reconfiguration does not depend on global information of whole system, which can effectively improve reliability evaluation and modeling efficiency. The presented models and approaches are conducted on the multi-paradigm modeling and simulation platform-AnyLogic, and validated by extensive cases studies.

1. Introduction

In pressures of fossil energy shortage and global environmental deterioration, the concept of Integrated Energy System (IES) was presented [1–3]. IES is a new type of regional energy system including multiple sub-systems such as electricity, gas, cooling/heating, and other energy supply systems. IES breaks up the existing mode of individually planning, designing and operating for these sub-systems. In the processes of planning, design, and operation for IESs, the production, transmission, distribution, conversion, storage, and consumption of various types of energy are coordinated and optimized properly. These coordination and optimization will effectively improve energy efficiency, reduce polluting emissions, and lower the dependence of economic and social development on fossil fuels [4].

Generally, various energy supply terminals of electricity, cooling, heating, and natural gas are included in IESs, thus, IESs are directly and physically connected to corresponding energy consumers. Therefore, IESs become the most important part of energy supply, and their reliability performances have significant impacts on people's daily life and industrial production. Along with rapid economic development, people's requirements on the reliability of energy supply are increasing; therefore, ensuring the reliability of IESs has become a crucial task, and related research is in urgent need [5–7].

Actually, the structure, operation mode and operation optimization of IESs have previously been studied. Refs. [8,9] explore the structure and operation mode of IESs, where an IES structure based on compact transformer was proposed. Ref. [10] presented an idea

☆ This work was supported by the National Natural Science Foundation of China under Grant (51577147), the Doctoral Program of Higher Education for the Priority Development Areas, The Ministry of Education, China (20130201130001), the Fundamental Research Funds for the Central Universities, China (2014GJHZ05, XJJ2015034), the Independence research project of State Key Laboratory of Electrical Insulation and Power Equipment in Xi'an Jiaotong University (EIPE14106), and the China Postdoctoral Science Foundation (2014M562410).

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http://dx.doi.org/10.1016/j.apenergy.2015.11.033
0306-2619/

to integrate communication systems into IESs, and basic steps for the combination were introduced as a preliminary study. Ref. [11] proposed a robust operation optimization model for IESs. In the model, wind power uncertainty, operating constraints of natural gas system, coal supply and electricity infrastructure were considered. In Ref. [12], a general and optimal energy conversion path was presented by considering hydrogen as a part of IESs. Besides, researches on energy utilization efficiency of IESs have also drawn widespread attentions. Ref. [13] studied cascade utilization of chemical energy in Combined Cooling Heating and Power (CCHP) systems, and explored how to improve IES energy utilization efficiency. Ref. [14] established an IES multi-objective optimization model based on linear programming methods, where the economic operation of IESs was analyzed. In Ref. [15], the energy utilization efficiency of urban integrated energy systems was evaluated using an incremental evaluation method according to cost-benefit analysis theory. Ref. [16] proposed a new type of community-level IESs, and an operation control approach based on economic analysis was introduced.

Although quite a few works have been published, researches on reliability evaluation of IESs are still in early stages. In Ref. [17], a gas system was combined with an electric distribution system, reliability evaluation models for the combined system were established, and the largest electricity output of the system was quantitatively evaluated. Ref. [18] analyzed the positive effects of micro-turbine based CCHP systems on the reliability performance of power systems. In Ref. [19], the Markov model was used to quantitative analyze reliability performance of small CCHP system in buildings, the results indicate that combining the supply of heating, cooling and electricity can effectively improve the reliability of energy supply. It is worth noting that existing reliability researches aimed at CCHP systems, which focus on the aspect of energy generation and conversion. Reliability evaluation of IESs considering energy distribution network and interaction effects of electricity, gas, cooling and heating systems have not been reported.

Main contributions of this paper include: (1) Reliability evaluation models for IESs are established. The Two-state model for most repairable components is introduced, and the power output model for wind turbines is established, in which the uncertainty of wind energy is involved. Besides, a two-hierarchy smart agent model including component agent models and zone agent models is presented, which is the foundation of smart agent communication. (2) An original reliability evaluation approach for IESs is presented, in which Smart Agent Communication (SAC) [20] based system reconfiguration is innovatively integrated into reliability evaluation process. By the SAC, system state evaluation (key procedure of reliability evaluation) after failures can be conducted autonomously along with the reconfiguration process, which effectively improves the reliability evaluation efficiency for IESs. (3) The presented models and approaches are conducted on a multi-paradigm modeling and simulation platform-AnyLogic [21], and validated by extensive cases studies.

This paper is organized as follows: Section 2 introduces the structure and reliability evaluation modeling of IESs. Section 3 describes IES reliability evaluation algorithms. Extensive test results are presented in Section 4. Finally, Section 5 concludes the paper.

2. IES structure and reliability evaluation modeling

IESs contain multiple sub-systems and have significant multidisciplinary features. This section describes basic structure and reliability evaluation models of IESs. In these models, operating characteristics for different sub-systems and interaction effects between them are taken into account.

2.1. Basic structure of integrated energy systems

Generally, an IES includes electricity distribution network, distributed renewable energy system, gas system, cooling, and heating systems, and a typical structure of IESs is illustrated in Fig. 1.

As shown in Fig. 1, the electricity distribution network mainly consists of electric lines, transformers, and electrical loads. Meanwhile, the electricity network is interconnected with the heating system via steam turbine as well as distributed generation system via wind turbine and electricity storage devices. The gas system includes gas wells, gas pipelines and gas boilers. Through gas boiler, chemical energy in natural gas is transformed into heat energy in high-temperature steam, and thus, the gas system is interconnected with the heating system. The high-temperature steam in the heating system can supply heat loads, steam turbines, and heat-driven cooling equipment.

In conclusion, IESs consist of various sub-systems, which have different operating characteristics and interaction with each other. Thus, establishing reliability evaluation models to properly describe these features is of significance to IES reliability evaluation. In sub-sections below, IES reliability evaluation models will be introduced.

2.2. Integrated energy system reliability evaluation models

Aim at different operating characteristics of various subsystems in an IES, different reliability models are established in this paper.

A. Two-state model

The two-state model (see Fig. 2) is a widely used component model in reliability evaluation [22].

As shown in Fig. 2, based on the two-state model, components have two states: Normal state (N) and Repair state (R). In the two-state model, failure rate and repair time of components are assumed to be exponentially distributed. The time to failure (*TTF*) and time to repair (*TTR*) of components are generated by:

$$TTF = -\frac{1}{\lambda}\ln\beta_1 \tag{1}$$

$$TTR = -r\ln\beta_2, \tag{2}$$

where λ and μ are the average failure rate and repair rate of a component, respectively. $r = 1/\mu$ is the average repair time of a component. β_1 and β_2 are uniform random number between [0, 1].

Based on the two-state model, the state durations (Fig. 3) of a component can be determined, and thus, system state durations can be determined by combining those of all components in the system.

In this paper, most components in IESs are modeled using the two-state model. However, wind is a kind of energy resources that is highly intermittent and random, thus, distributed electricity generators (such as wind turbines) need some more specific models to describe the uncertain electricity output of them, which could have significant effects on reliability.

B. Distributed generation system model

In this section, the reliability evaluation model for wind turbines will be introduced. In this model, the uncertain power output is an essential factor. Power output of wind turbines depends on the wind speed, which is commonly modeled using Weibull distributions or Autoregressive-Moving Average models.

In this paper, historical wind speed data is fitted by a series of two parameter Weibull distributions, and in every six hours, wind