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Adequacy assessment of power systems incorporating building cooling, heating and power plants

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A B S T R A C T

Electric power systems have been changing from the conventional and traditional electric units to the efficient, economical, less-polluting and reliable ones. Building cooling, heating and power (BCHP) systems can yield these goals and save energy as well as improve the reliability of the system. However, for significant integration and the use of large amount of BCHP generation in electric power systems, some approaches should be followed in order to study the reliability of the BCHP systems. In this study, we focused on the reliability aspects of power systems incorporating BCHP systems in the local distribution systems. The Markov method based on the state-space analysis is used to investigate the impacts of implementation of BCHP systems on the power systems' reliability. The Markov method is well suited to analyze the reliability of systems based on a continuous stochastic process. The Roy Billinton test system and the IEEE reliability test system are used to illustrate the results. Case studies show the effects of BCHP systems on general adequacy of electric power systems. Various case results demonstrate the efficiency and effectiveness of the proposed method.

1. Introduction

Over the last few decades, some changes have been made in the field of distributed generation which overcame some major issues of power systems. With the advancement of energy technology, heating and cooling can be supplied simultaneously in the distributed generation systems [1]. Building cooling, heating and power (BCHP) systems are broadly identified as an alternative resource to solve dilemmas such as energy supply security, increasing energy demands and cost, as well as environmental issues [2–4]. Many applications of the BCHP systems have been investigated so far. Some major benefits of the BCHP systems consist of increasing resource energy efficiency, reducing air pollutant emissions, producing combined electricity, heating, and cooling. In recent studies, BCHP systems have been investigated from different aspects such as optimization, model, feasibility analysis, evaluation, and reliability. For instance, a method based on the mixed integer linear programming is used in [5,6] to study the optimization of operation and design of trigeneration systems for building applications. This method is also used in [7] to investigate the optimal design of trigeneration systems in a hospital complex. The performance of a small combined heat and power (CHP) plant for use in a conventional house in the Republic of Ireland is evaluated in [8]. The environmental sustainability of a micro-CHP unit fueled by solar energy is discussed in [9] which is useful for the long-term exploitation of the designed system. Ref. [10] investigated the performance of a CHP system installed at the Mississippi State University where both summer and winter conditions are considered. The most interesting approach to this issue has been proposed by [11] which provides the near real-time optimization making use of an aggregation of micro CHP devices in Belgium. Ref. [12] proposed a novel model of the CHP systems based on the three models which are cooling, heating, and power; heating and power; and cooling and power to demonstrate the improvement of the site energy. A new model of the CHP systems based on the two bed silica gel-water adsorption chiller is proposed in [13] in order to achieve an accurate prediction of the chiller performance considering both variable and stable heat source temperature. Ref. [14] proposed a comprehensive input–output matrix approach for modeling trigeneration systems for optimal operation of a composite scheme with electric chillers and absorption. Ref. [15] discussed a new model of the CHP systems to guarantee primary energy savings considering the quality and type of the energy being consumed. In [16], the energy demands for electricity and heat in the CHP systems for residential applications are analyzed to demonstrate that the condensing gas boilers are economically more interesting and also have a modest effect on primary energy consumption. In [17], it has been revealed that the increased flexibility in the structure of

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electricity markets will lead to both negative and positive effects for CHP systems in which these effects should be modeled properly. Ref. [18] developed a new concept of the CHP systems where the catalysts development, design of the stack and its components, design and testing of the natural gas reformer are modeled. The problem of economic feasibility analysis and energy efficiency evaluation of the micro trigeneration systems for CHP systems with an available Stirling engine is investigated in [19]. Ref. [20] studied various integrated configurations of different types of commercially available micro gas turbine cogeneration systems in absorption cooling chillers based on the biogas. Economic viability of several options in the trigeneration systems are analyzed based on the net present value and a simple payback time in [21]. An interesting approach in [22] investigated the optimal design of CHP systems considering fluctuating electricity prices in Denmark. The results obtained in [23] suggested an optimal design of the CHP systems based on several aspects such as economical, energy, and environmental considerations. The feasibility of landfill gas trigeneration in Hong Kong is studied in [24] based on the greenhouse gas emission reduction, primary energy-saving, and economic benefit. Ref. [25] proposed a unified general model to assess the energy performance of different types of poly-generation systems with natural gas as the energy input. Refs. [26,27] studied the reliability considerations of BCHP systems in terms of optimal design and operation. A method based on the Monte Carlo simulation is proposed in [28] to estimate the reliability of two suggested configuration of cogeneration plants. The methods were improved in [29,30] in terms of risk analysis of the BCHP systems in order to achieve the best optimization model of the systems. An analytical approach based on the Markov method is presented in [31] to evaluate the availability as well as the unavailability of the BCHP system based in the failure and repair rate of each BCHP system's component. Ref. [32] proposed a method based on the fault tree logic modeling in order to assess the reliability and critical failure predictability requirements for fuel cell stacks. The main contribution is investigating the effects of stack reliability and critical components on the system availability and reliability.

A power system for the purposes of operation, planning and analysis can be divided into three appropriate subsystems which are generation, transmission and distribution. For this aim, the hierarchical levels (HL) have been developed for adequacy assessment of power systems [33] in order to establish a consistent means of grouping and identifying these subsections. The hierarchical level I (HLI) refers to generation facilities and their abilities to satisfy the system demand. The HLI is also known as "generating capacity reliability evaluation" where distribution and transmission are not included. The hierarchical level II (HLII) refers to the composite generation and transmission (bulk power) system to deliver energy to the bulk supply points. In other words, composite system (HL-II or bulk system) reliability evaluation considers both the transmission and generation system in the analysis. The hierarchical level III (HLIII) refers to the complete assessment of the system including distribution and its ability to satisfy the customer demand. It is worth noting that the complete HLIII studies are mainly impractical because of the scale and complexity of the problem. Therefore, unlike the HLI and HLII studies which are regularly performed, analysis at the HLIII is performed separately using the HLII load point indices as input values. Adequacy assessment in power systems is the basic and most important step which should be involved in either the proposed or existing facilities to satisfy the operational constraints as well as the system load and demand. The methods used for conducting the probabilistic adequacy analysis on power systems fall into three categories, analytical [34], Monte Carlo simulation [35], and combinations [36] of the simulation and analytical techniques. The reliability parameters used in analytical techniques are usually assumed to be constant. The proposed way for the BCHP model to be used in this study is similar to the approach in [37] which is compatible with the system adequacy and can be used for other particular considerations like the system complexity (e.g. the system assessment incorporating transmission lines). Thus, the proposed method can be extended to different types of complex models. The BCHP model used is based on the multi-state capacity outage probability table (COPT) which also provides more accurate results. After review of the literature and to the best of the authors' knowledge, none of the previous works have investigated the effects of the BCHP systems on the probability distributions of power system reliability indices. Markov method is well suited to evaluate the reliability of systems based on a continuous stochastic process. This paper proposes a novel procedure and method based on the Markov method for estimating the reliability of the power systems at the HLI incorporating BCHP systems.

The rest of this paper is organized as follows. Section 2 introduces the structure of BCHP systems with the major focus on the electricity side. An analytical approach based on the Markov method for the reliability assessment of the BCHP systems is proposed in Section 3. Test results and case studies are summarized in Section 4. Section 5 concludes this paper.

2. System construction of the redundant BCHP systems

The structure of BCHP systems is given in Fig. 1. It can be seen that in order to produce electricity, the gas turbine powered by natural gas is used. Following this, the exhaust output of the gas turbine is entered to the heat recovery steam generator (HRSG). This process is conducted by dividing the recovered heat between the absorption chiller (i.e. for providing the cooling load) and the heat exchanger (i.e. for providing the heating load). However, if either the cooling or heating cannot completely satisfy the demand, an auxiliary gas-fired boiler would be served to mitigate the shortage. Furthermore, if the electricity generated is not enough for the energy demand, the electricity needed is taken from the outside electric power grid. Finally, in order to improve the thermal efficiency as well as store the extra exhausted heat, the heat storage tank can be added [38,39].

The BCHP system has capability of connecting to the outside power grid. If both the power supply from the BCHP system and the outside grid is not sufficient for the system's load, the BCHP is considered to be in failure mode. On the other hand, for being in success mode, both the BCHP system and the outside power grid should be in the success mode. If the islanding issue is occurred, the BCHP system is disconnected from the grid. In this case, the electricity demand of the system comes from either the outside grid or the BCHP system. In case of heat production, there is always possibility of some excess electric power generation which is difficult to be disposed, especially if there is no demand in consumer side. However, in case of electricity production, the extra heat can be recovered [31].

3. The reliability evaluation framework

In the reliability evaluation, a system is considered to be either in success mode or failure mode [40]. If a power system has sufficient energy to supply the load, the system is defined as a success mode. The power system is considered to be in failure mode if the system capacity is not enough for the load demand. Hence, each failure and success states have their own probabilities and duration which are also called the reliability indices. In the following subsections, an analytical approach based on the Markov method is proposed to investigate the reliability of the BCHP systems. The Markov method serves as a useful tool to model the BCHP system accurately. This model is invaluable for the operator, since the