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Evaluating the reliability of multi-energy source buildings: A new analytical method for considering the dynamic behavior of thermal loads

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ABSTRACT

Developments in energy conversion technology and multi-carrier energy systems have led to higher flexibility of energy systems, thus improving the reliability of supply and decreasing the energy costs. Usually in previous studies on reliability evaluation of Multi-Energy Source Building (MESB), the required energy for supplying the loads is considered to be fixed during each time interval and the ability of the system to supply the loads is evaluated on the basis of this assumption. In this paper, due to the high amount of the thermal loads in a building's energy portfolio, the flexibility of these loads is addressed and an analytical method is presented to model the dynamic behavior of thermal loads in reliability analyses of MCEBs. The proposed method is based on Markov chain concepts integrating thermodynamic equations. In addition, in order to evaluate the validity of the proposed method, a Monte-Carlo simulation method is employed. The methods are simulated on test systems and the results are presented and discussed.

1. Introduction

The most demanded energy by consumers is in one of the forms of electricity, gas or heat. Traditionally, the required infrastructures to supply each type of energy were built and utilized separately [1]. Environmental constraints, the power market restructuring, the need to improve the system efficiency and the demand for high reliability supply have increased the utilization of distributed generation sources [2]. Developing new technologies such as fuel cell, combined heat and power (CHP) and micro-turbines have increased the use of small-scale distributed generation sources and devices that can convert one form of energy into electricity [3,4]. Reference [5] deals with the effects of the heat dumping on the operation of four different residential micro-CHP systems. In [6] optimal sizing of distributed energy resources in medium voltage or low voltage micro-grids according to different criteria is carried out. In order to accommodate high penetration rate of non-dispatchable renewable energy sources, different type of energy storages are suggested for installing in energy system [7]. In Ref. [8] the results of a technical and of a cost analysis of two different types of thermal energy storage systems (hot water thermal energy storage systems and latent heat thermal energy storage) for residential micro-CHP plants are presented. In addition, developing technology for converting different forms of energy into others can increase the flexibility of an energy system if the interaction between different forms of energy in the studies is considered [9]. On this basis, the concept of multi-carrier energy systems and energy hubs has been introduced. The presented studies in this field have tried to model the interactions taking place "inside" the multi-carrier energy systems as well as the interactions with the "outside" world, at both the operational and the planning stage [10]. Reference [11] presented a model that avoids some limitations identified for the conventional energy hub model in which a mathematical model has been formulated with the use of graph and network theory.

A Multi-Energy Source Building (MESB) represents an energy system where energy carriers at the input are converted into different forms of energy by converters to supply loads at the output. The converters include combined heat and power resources, transformers, batteries, heaters and coolers and so on [12–15]. A MESB, due to the possibility of the substitution of the energy may increase the reliability and efficiency [16,17]. Previous researches on MESB mainly concentrated on the modeling and on the evaluation of the

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Nomenclature

Indices
α, β,ω, θ Indices for the input and output energy carrier, respectively
i, j, k Indices to show the order of system states
iter Index to show the order of iterations
n Index to show the order of the system elements (converters)
sys Index for system
D Index to show order of time

Water Heater Parameters
a Thermal resistance of tank walls (kW/°C)
c_e Specific heat constant of water (kWh/m^3 °C)
C_e Tank thermal capacity (kWh/°C)
q Hot water rate of extraction (m^3/h)
T_a Ambient temperature (°C)
$T_T(t)$ Water temperature at time t (°C)
T_d Desired temperature for outlet water (°C)
T_{in} Inlet water temperature (°C)
T_{out} Outlet water temperature (°C)
T_{min}/T_{max} Minimum/maximum limitation of water temperature (°C)
P_{WH} Power supply of the water heater (kW)
P_{WHreq} Required power to maintain water temperature at a determined temperature (kW)

Energy hub and Reliability Modeling Parameters
$\zeta\alpha\beta$ Capacity of the connection from α to β
λ_{ki} Transition rate from state k to i
λ_n Failure rate of connection n (failure per year- *f/y*)
μ_n Repair rate of connection n (failure per year- *r/y*)
$\rho_{n,i}$, $\bar{\rho}_{n,i}$ Status of connection n
m_i Mean time of staying in state i
p_i Probability of state i
ps Ratio of success
F_{ki} Frequency of entering into each state k from a state i

N number of the system elements (converters)
R_n, Q_n Availability and unavailability of connection n
C Coupling matrix
E Input power vector
L Output power vector

economic advantages of these systems [12–17]. In [18], the exergy principles in the context of supply systems are applied to achieve rational use of energy resources in a MESB by taking into account the different quality levels of energy resources as well as those of building demands. As the advantage related to their possibility to increase the reliability of energy systems has not been completely studied in previous researches it is discussed in the following.

In [1], a method for assessing the reliability of a multi-carrier energy hub has been provided. Moreover, in [19], the system efficiency and safety have been considered in the planning study of an energy hub. In these two references, the system loads have been assumed fixed during the time intervals and, based on that, the reliability indices have been calculated. This is while, the flexibility of loads is another parameter in energy systems which can improve the reliability and reduce the system costs. Many studies have considered the loads flexibility (especially thermal loads) and the supply costs have been minimized by scheduling and controlling these loads [20–22]. In [23], a new formulation of shiftable loads is employed to find the optimal power dispatch in smart grids with distributed energy resources. In [24], the authors have addressed the flexibility of thermal loads and, by employing Monte Carlo simulation method, the impact of the loads dynamic behavior on the system reliability indices has been shown.

On the basis of previous researches, in this paper, a novel approach for evaluating the reliability of a MESB due to the flexibility of the thermodynamic loads is presented and discussed. The novel contributions of the proposed method are presenting a new analytical method based on Markov chain is presented in order to model the system reliability considering a high portion of thermal and cooling loads in a building energy demand. The proposed method is based on basic theoretical equations and can be developed for modeling the reliability of other energy systems.

In order to demonstrate the effectiveness of the proposed method, the presented method is simulated on two test systems and the results are compared to the results of Monte Carlo method.

The rest of the paper is organized as follows: in Section 2, the dynamic behavior of loads is presented and the necessity of carrying out the proposed research is discussed. In Section 3, the modeling approach of different parts of the problem is presented and the proposed method is detailed by combining thermodynamic equations with the Markov chain concepts. In Section 4, Monte Carlo simulation method is briefly presented as a method to evaluate the proposed method. Simulation results on some test systems are shown in the Section 5, and finally in Section 6 some conclusions are presented.

2. Problem description

2.1. Investigating the inflexible and flexible loads

For several loads in a building the energy demand should be supplied by various carriers, such as electricity, gas and heat. Therefore, a desirable performance is defined for each of these loads considering their characteristics. The loads can be divided into two categories: inflexible loads and flexible loads. Inflexible loads refer to the loads in which, along with energy connection (or disconnection), their performance changes instantaneously from a desirable to an undesirable status (or vice versa) [24]. Lighting loads are an example of inflexible loads (Fig. 1). In computing the reliability indices, for any period of time a fixed amount of energy is considered that if it is supplied, the status of the system is supposed as success and if it does not, the status is supposed as failure.

In contrast, flexible loads refer to the loads in which, along with energy disconnection (or connection), their performance does not change simultaneously from a desirable to an undesirable condition (or vice versa). Thermal loads are the most important example of this kind of loads which may act such an energy storage due to its thermodynamic equations. For example, in the case of a water heater, the water temperature is defined within a specified range

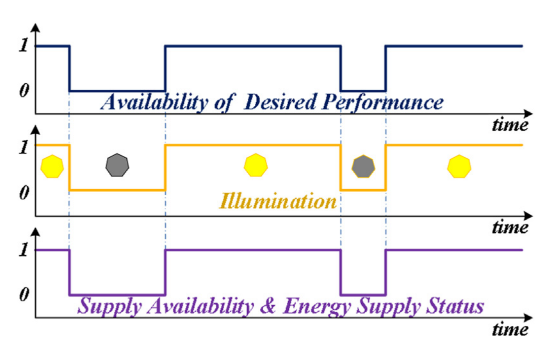

Fig. 1. The performance response of inflexible loads to energy supply varying.