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Identification of microturbine model for long-term dynamic analysis of distribution networks

Xiandong Xu [a,*], Kang Li [a], Fengyu Qi [b], Hongjie Jia [b], Jing Deng [a]

[a] School of Electronics, Electrical Engineering and Computer Science, Queens University Belfast, Belfast BT9 5AH, UK
[b] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- The feasibility of building a simplified microturbine model is discussed.
- A three-stage modeling method is developed to predict the microturbine output with saturation.
- A fast simulation method is proposed to analyze a distribution network with microturbines.
- A microturbine is used to evaluate the performance of the modeling and simulation method.

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ABSTRACT

As one of the most successfully commercialized distributed energy resources, the long-term effects of microturbines (MTs) on the distribution network has not been fully investigated due to the complex thermo-fluid-mechanical energy conversion processes. This is further complicated by the fact that the parameter and internal data of MTs are not always available to the electric utility, due to different ownerships and confidentiality concerns. To address this issue, a general modeling approach for MTs is proposed in this paper, which allows for the long-term simulation of the distribution network with multiple MTs. First, the feasibility of deriving a simplified MT model for long-term dynamic analysis of the distribution network is discussed, based on the physical understanding of dynamic processes that occurred within MTs. Then a three-stage identification method is developed in order to obtain a piecewise MT model and predict electro-mechanical system behaviors with saturation. Next, assisted with the electric power flow calculation tool, a fast simulation methodology is proposed to evaluate the long-term impact of multiple MTs on the distribution network. Finally, the model is verified by using Capstone C30 microturbine experiments, and further applied to the dynamic simulation of a modified IEEE 37-node test feeder with promising results.

1. Introduction

The integration of distributed energy resources (DERs) has significantly changed traditional design, operation, control and online management of electric power systems [1,2]. Microturbines (MTs), which can provide both electrical and thermal energy, have been widely used as DERs in the electricity distribution network (hereafter referred to as distribution network) [3,4]. Due to the advantages of high reliability, low emission, and high efficiency, an increasing number of MTs have been installed in the distribution network worldwide, and this has greatly enhanced interdependencies between the distribution network and natural gas network. Also, it has been observed that the gas network can significantly affect the operation of power systems through gas-fired generators [5]. Therefore, it is important to model the behaviors of various MTs, as well as to evaluate the impacts of large integration of MTs on the distribution network, in order to ensure a secure and reliable system operation.

In the study of energy systems, it is usually not possible to conduct large-scale physical experiments due to economic and security reasons. This promotes the popularization of using simulation as a tool to analyze the energy system behavior under various scenarios [6–8]. In order to describe behaviors of the whole system, both network and coupling unit models are required for simulating the system. As one of the main energy networks in urban areas, distribution networks have been investigated by way of modeling [9], simulation [10], planning [11], scheduling

* Corresponding author.
E-mail addresses: x.xu@qub.ac.uk, xuxiandong87@gmail.com (X. Xu).

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[12], etc. Several packages have been developed to study their dynamic behaviors [13–15]. Dynamic load models, such as heat pumps [16] and air conditioners [7], are embedded in the packages. Considering the interactions between the electricity network and the gas network, a suitable dynamic MT model is required, so as to analyze its coupling function. However, the existing literature, with a few exceptions [17,18], has mainly focused on the network analysis in steady states [6,19,20]. The dynamics of gas-fired generator and how they affect the interactions between the two networks are not well explored. In addition, in practice, the gas network information is usually not accessible to distribution network operators, which makes it difficult to analyze the impacts of natural gas pressure and other ambient conditions on distribution networks through MTs.

Due to the complex thermo-fluid-mechanical energy conversion processes [21], building MT models has become a significant but challenging work when analyzing dynamic impacts of natural gas networks and MTs on the distribution network. One important direction of the MT modeling is to conduct mechanism analysis, using available packages in commercial software, such as DIgSILENT, PSCAD and MATLAB/Simulink [18,22–26] For example, Rowen proposes a gas turbine mechanical model in [22], which describes the thermo-mechanical process of the MT prime mover. In [23], the correlation between the electro-mechanical and thermo-mechanical subsystems is modeled. The impact of MTs on the distribution network is analyzed under a range of load conditions [24]. Further, dynamic behaviors of hybrid MT and other distributed generation system are investigated by using simulation studies and small-scale physical experiments [25]. As a prime energy source, natural gas is also critical for MTs' operation. Hence, natural gas flow is incorporated into the thermo-mechanical model of gas turbines in [26]. An improved MT model is developed to reflect the interactions between power and natural gas systems [18]. However, in practice, MTs may have different brands and capacities. The parameters and models are not the same for each MT. Moreover, some of the design parameters for MTs are confidential, and therefore are hardly accessible.

In order to handle the unknown parameters and the strong nonlinearity, another direction of the MT dynamic analysis is based on black-box approaches, where system identification techniques are commonly employed. By correlating input and output data, these techniques can help to build a simplified model of the complex process and to predict its behaviors without requiring much prior knowledge [27]. A variety of techniques have been proposed to describe the dynamics of gas turbines. These include polynomial models, such as nonlinear autoregressive moving average with exogenous inputs models and nonlinear autoregressive exogenous [28,29], neural network models [30–32], and adaptive network-based fuzzy inference system [33]. These models are effective in correlating the fuel and mechanical power output for a specific MT, and are used in analyzing the transient stability of distribution networks [9]. However, it is difficult for the electric utility to obtain the operation data of MTs owned by different third parties in distribution networks. Thus, system operators can hardly build identification models or estimate the internal states of the MTs, which play a key role in the security analysis of distribution networks.

In this paper, a simplified compact MT model is developed for the long-term dynamic analysis of distribution networks, considering different requirements and data availability for utilities and customers. The main contributions can be summarized as follows: (1) Dynamic characteristics of the MT are analyzed in order to identify the model with the state space form and the piecewise method; (2) An electro-mechanical system model of the MT is derived using a three-stage subspace identification method to predict the MT power output under different operating conditions; (3) Based on the obtained model, a fast simulation method is proposed to the evaluate dynamic impact of MTs on the distribution network. Numerical examples show that the proposed model can capture MT power and heat output behaviors well over a wide operation range, and reflect the impact of multiple MTs on the distribution network.

The rest of this paper is organized as follows. Section 2 describes the feasibility of the model simplification and the three-stage model identification method. Section 3 presents a fast simulation method based on the proposed MT model. In Section 4, physical and numerical tests are performed to illustrate the accuracy and effectiveness of the proposed method. Finally, the conclusion is given in Section 5.

2. Identification of the MT model

In this study, the MT model is developed for the long-term dynamic analysis of distribution networks with multiple MTs. To achieve this goal, the model should be able to capture dominant characteristics of the eletro-mechanical subsystem of the MT, while simple enough for large-scale applications. To trade-off model complexity versus accuracy, a novel modeling method for the MT will be proposed in this section, based on mechanism analysis of the MT and black-box approaches.

2.1. Dynamic characteristic analysis

This paper investigates a single-shaft MT which is widely used to supply both heat and power in local areas [34]. As illustrated in Fig. 1, the MT is composed of thermo-mechanical and electro-mechanical subsystems. The dynamic model of the MT can be expressed as

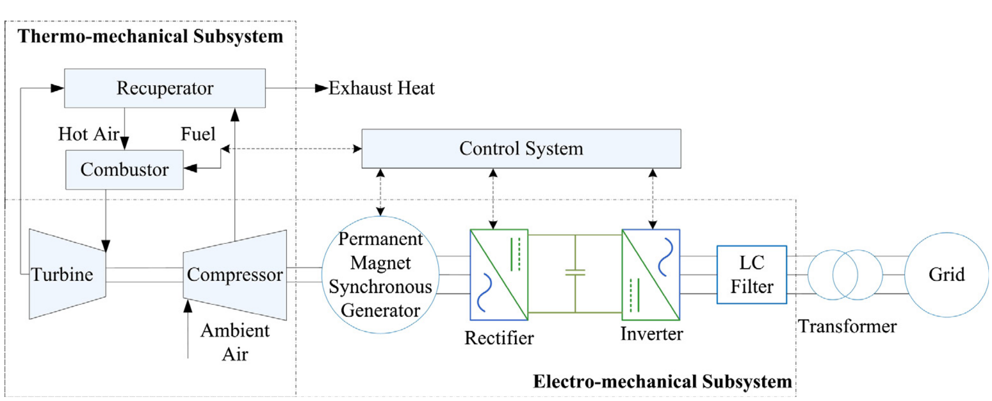

Fig. 1. An overview of the MT configuration.

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