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A mathematical model for the dynamic simulation of low size cogeneration gas turbines within smart microgrids

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A B S T R A C T

Microturbines represent a suitable technology to be adopted in smart microgrids since they are characterized by affordable capital and maintenance costs, high reliability and flexibility, and low environmental impact; moreover, they can be fed by fossil fuels or biofuels. They can operate in cogeneration and trigeneration mode, thus permitting to attain high global efficiency values of the energy conversion system from primary energy to electrical and thermal energy; from the electrical point of view, microturbines can operate connected to the distribution grid but also in islanded mode, thus enabling their use in remote areas without electrification.

The paper describes the mathematical model that has been developed to simulate in off-design and transient conditions the operation of a 65 kW_{el} cogeneration microturbine installed within a smart microgrid. The dynamic simulation model is characterized by a flexible architecture that permits to simulate other different size single-shaft microturbines. The paper reports the main equations of the model, focusing on the architecture of the simulator and the microturbine control system; furthermore the most significant results derived from the validation phase are reported too, referring to the microturbine installed in the Smart Polygeneration Microgrid of the Savona Campus at the University of Genoa in Italy.

1. Introduction

In the last years the energy scenario in Europe and other developed countries has been considerably changed. This is mainly due to different factors such as the liberalization of electricity markets, the increase of energy production from renewable sources and the diffusion of distributed generation technologies. Moreover, the smart grid and microgrid concepts have become a real opportunity to locally provide energy to end users by exploiting environment-friendly technologies optimally managed from the economic point of view [1–4].

Among distributed generation technologies, CHP (Combined Heat and Power) units, and in particular cogeneration gas turbines, have acquired an important role since they are characterized by high efficiency and reliability, and not so high capital and maintenance costs [5–10]. There are a lot of ongoing projects that are focused on the installation of micro-CHP units to provide thermal and electrical energy to small urban and industrial districts and, generally, to end users in different sectors (residential, public health, commercial and industrial) [7,11–13]; it is profitable to install the aforementioned technologies mostly when the energy user load demand is characterized by a simultaneous request of both thermal and electrical energy, otherwise storage systems need to be considered, thus increasing installation costs of the whole infrastructure. Ummerhofer et al. in Ref. [14] highlight that micro-CHP units hold advantages over conventional power generation due to their efficient and decentralised nature. Argiento et al. in Ref. [15] assess that the combination of distributed interruptible load shedding and dispatched microgenerators provides to distribution network operators an interesting opportunity for power network emergency management; in Ref. [15] the authors report some test results derived from the application of probabilistic methods to a small low-voltage network with interruptible loads and micro-CHP generators.

Natural gas is the fuel used for cogeneration microturbines in most cases, even if nowadays biofuels are becoming more and more a new suitable alternative. As assessed by Gabbar et al. in Ref. [16], there is a real need to increase the penetration of gas technologies in the power grid and, to this end, in Ref. [16] the authors explore

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the integration of gas and renewable energy generation technologies within various electricity generation scenarios with the goal of developing resilient micro energy grids. As assessed in Ref. [17], the main applications of micro-CHP systems are not only connected to cogeneration but also to peak shaving and backup power services.

In literature CHP technologies are analyzed from different point of views. Several works are focused on the role of CHP in distributed generation energy systems in terms of operating costs and environmental impact. In Ref. [18] the economics of standard application of micro-CHP are analyzed, while in Ref. [19] the authors study a regional cogeneration-based smart energy network. Casanova et al. in Ref. [8] propose an emission characterization and evaluation of natural gas-fueled cogeneration microturbines and internal combustion engines, whereas in Refs. [6,20,21] accurate descriptions of the technology are reported highlighting the technical performance and the flexibility of gas turbines.

Meybodi et al. [17] put in evidence the flexibility of microturbines in distributed generation applications and their capability to be stacked in parallel in order to reliably supply large demands; in particular, the authors in Ref. [17] propose a technical-economic approach to select the optimum arrangement of microturbines and plan their operational strategy in small CHP systems.

Many literature works are focused on the design of the electrical and mechanical components of microturbines, with special care to machinery (centrifugal compressors and centripetal turbines), permanent magnet generators and combustion chambers built with materials enduring high temperatures. Several studies aim at designing more and more efficient recuperators [22–24] in order to increase the global efficiency of the plant. Utrainen et al. in Ref. [22] report that design engineers have to face a challenge to manufacture low-cost heat exchangers characterized by high thermal efficiency and low pressure losses, while Shah et al. in Ref. [23] discuss on the impact of a well-designed recuperator on the global efficiency of the gas turbine system.

About the mathematical modeling of microturbines, different approaches can be adopted. In literature simple models can be found to represent microturbines within optimization tools [12,19,25], whereas more complicated and accurate models are used when it is necessary to develop dynamic simulation tools able to represent the behavior of microturbines in transient operating conditions [26–29].

Optimization tools are used in the framework of Energy Management Systems (EMS) for the optimal operation of distributed generation facilities and microgrids with different power generation units (from renewable or fossil sources, often in cogeneration/trigeneration asset). In Ref. [25] the authors propose an EMS, to schedule the operation of three gas microturbines of a microgrid, based on the prediction of the energy production from the photovoltaic plant, the storage availability and the load; the proposed optimization procedure aims at minimizing a multi objective function representing the CO_2, CO and NO_x emissions of the microturbines. Chai et al. in Ref. [19] describe an IEMS (Intelligent Energy Management System) for the optimal operation of a CHP-based microgrid over a 24-h time interval; the goal of the aforementioned IEMS is that of finding the optimal set points of distributed energy resources and thermal/electric storage systems, in such a way that the total operation costs and the net emissions are minimized.

Simulation tools are developed to analyze the behavior of microturbines both in steady-state off-design conditions and during transient periods [9,29–32]. In Ref. [31] the authors propose a mathematical model, validated by operational data, to analyze the performance of a microturbine operating at partial loads. An approximate expression for the heat transfer rate of a heat recovery unit fed by the exhaust gas exiting a microturbine, operating at part-load, is developed in Ref. [33], while the autonomous operation of a microturbine with a voltage-frequency control strategy is described in Ref. [26], where a dynamic model developed in Matlab/Simulink is reported. The Modelica language is used in Ref. [28] to model a T100 Turbec microturbine, focusing on the functionality and the accuracy of the adopted approach. Different aspects are analyzed in Ref. [27], where the authors propose a microturbine simulator that takes into account the deterioration of each component (due to fouling, erosion, corrosion, etc.) by properly varying the characteristic parameters that describe the component efficiency. In Ref. [29], the performance of a Capstone C30 microturbine connected to a low voltage grid, during different transient events, is evaluated using a simulator developed in Matlab/Simulink; the machine speed and temperature control are implemented in the simulator. A detailed simulation model of a microturbine can be found in Ref. [34], where the dynamic or semi-dynamic submodels of the plant main components (compressor, recuperator, combustion chamber, turbine, generator and output static converter) are reported. Analogously, Skolnik et al. in Ref. [35] propose a set of models (for turbines, generators and heat exchangers) that can be connected to simulate different cogeneration units. Another interesting Simulink model is reported in Ref. [36], where the authors also discuss on different research issues related to microturbine size, location and operation.

Other literature works deal with the role of microturbines within larger distributed generation systems. For example, in Ref. [9] the authors examine the operating characteristics of a district heating system composed of a gas turbine engine (single or double shaft) coupled with a heat recovery boiler, with a separate oil boiler to cover peak load, back-up and summer operation. In Ref. [32] the performance of a CHP process, in terms of electricity generation, thermal power output and water output temperature, is studied with respect to the variation of the syngas flow input.

The present paper derives from an ongoing research activity at the University of Genoa, in Italy, focused on the development of mathematical models for the dynamic simulation of power systems operating within smart microgrids; in particular, CHP units, absorption chillers and Concentrating Solar Power (CSP) systems are modeled with reference to the plants installed in the Smart Polygeration Microgrid (SPM) in operation at the Savona Campus [1,12,13]. In this paper, the attention is pointed on the dynamic simulation of a cogeneration gas microturbine in the Matlab/Simulink environment. The proposed mathematical model has a general validity and it can be used to model any other CHP unit of the same configuration, that is a single shaft microturbine having a compact recuperator and a heat recovery boiler at its exit for the production of hot water. The simulator has been successfully validated by applying the mathematical model to study the behavior, both at partial loads and in transient conditions, of one of the two Capstone C65 microtubines installed within the SPM; the validation has been done by comparing the simulation results with experimental data coming from the SCADA system that supervises the SPM and also using data made available by the manufacturer [37].

The simulator has been developed mainly for the following reasons: to model in detail the behavior of a microturbine installed within a real smart polygeneration microgrid; to simulate different operating conditions and severe transient phenomena before experiment on field, thus preventing faults and bad operation modes; to use simulation results in order to build the performance curves which describe the behavior of the microturbine in off-design and transient conditions. Indeed, not so many data regarding the part load performance of the microturbine have been supplied by the manufacturer, but it is necessary to know them in order to improve the Energy Management System of the Savona Campus Smart Polygeneration Microgrid.