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A dynamic model of a 100 kW micro gas turbine fuelled with natural gas and hydrogen blends and its application in a hybrid energy grid

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ABSTRACT

The paper deals with the development of a dynamic model of a commercial 100 kW Micro Gas Turbine (MGT) fuelled with mixtures of standard (i.e. natural gas or methane) and alternative fuels (i.e. hydrogen). The model consists of a first-order differential equation (ODE) describing the dominant dynamics of the MGT imposed by its own control system during production electrical power. The differential equation is coupled to a set of nonlinear maps derived numerically from a detailed 0D thermodynamic matching model of the MGT evaluated over a wide range of operating conditions (i.e. mechanical power, fraction of hydrogen and ambient temperature). The efficiency of the electrical machine with power inverter and power absorbed by auxiliary devices is also taken into account. The resulting model is experimentally validated for a sequence of power step responses of the MGT at different ambient conditions and with different fuel mixtures.

The model is suited for simulation and control of hybrid energy grids (HEGs) which rely on advanced use of MGT and hydrogen as energy carrier. In this regard, the MGT model is used in the simulation of an HEG based on an appropriate mix of renewable (non-programmable) and non-renewable (programmable) energy sources with hydrogen storage and its reuse in the MGT. Here, the MGT is used as a programmable energy vector for compensating the deficits of renewable energies (such as *solar* and *wind*) with respect to user demand, while excess renewable energy is used to produce hydrogen via electrolysis of water. The simulated HEG comprises a solar PhotoVoltaic (PV) plant (300 kW), an MGT (100 kW) fuelled with natural gas and hydrogen blends, a water electrolyzer (WE) system (8 bar, 56 Nm^3/h), a hydrogen tank (54 m^3), and an Energy Management Control System (EMCS).

1. Introduction

The need to reduce greenhouse gas emissions coupled with limited fossil fuel stocks have made renewable resources attractive in world energy-based economies [1]. The target of conversion to 100% renewable energy can only become feasible by combining and integrating diversified energy sources [2]. In a medium-term time horizon, hybrid energy systems based on renewable and fossil sources will enable us to gradually approach this goal by reducing the non-renewable component. Hybridization of different energy sources is complicated by the non programmability [3,4] of renewable energy sources (such as *solar* and *wind*) which when used alone are not able to meet varying user demand for energy, either on a day-to-day or hour-to-hour basis [5], if they are used alone. Smart use of non-renewable resources (*fossil fuels*, *biomass derived fuels*, …) coupled with energy storage systems is therefore a necessary and viable way to compensate for energy supply and demand. Among other energy conversion systems, electrical generators based on internal/external combustion engines could accomplish this task [6–8]. Moreover, in the not-too-distant future, biomass and renewable derived fuels could become the primary energy sources, in replacing fossil fuels [2,9,10].

Interest in MGTs for combined electrical and thermal power generation has increased enormously for mini/micro smart grid applications thanks to their flexibility, versatility, low emissions and low noise, as confirmed by several papers in the recent literature. Ferrari et al. investigated experimentally tested a smart polygeneration grid based on different prime movers with the aim of improving distributed generation management [11,12]. The system was composed of a 100 kW MGT, a 20 kW internal combustion engine, a 450 kW SOFC-based hybrid system (emulated) and a

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100 kW absorption Basrawi et al. performed economic and environmental analysis on different configurations of a hybrid combined cooling heat and power (CCHP) system, which is based on a 30 kW or 65 kW MGT, PV panels, a heat storage system, batteries and an absorption chiller [13]. Comodi et al. proposed a power system consisting of a 100 kW MGT and a 40 kW PV system to reduce primary fuel usage, energy cost and problems related to the unpredictability of PV energy production, whereas the power produced by MGT is regulated to demand minus PV power output [8]. Carrero et al. presented the results of thermoeconomic analysis, based on hourly demand, of an MGT working as CHP unit and a micro humid air turbine (mHAT) [14]. It was shown that CHP and mHAT units are economically competitive for high electricity and low natural gas prices, while for all the price combinations considered, mHAT technology is more economical if investment in MGT technology is feasible.

Likewise, the interest in hydrogen as an energy carrier has increased in the last 10 years [15,16]. Hydrogen is usually produced by electrolysis of water, using a part or all of the electricity generated by PV and/or wind turbine (WT) systems, and then stored in pressurized tanks. The hydrogen is later converted back into electricity in fuel cells (see for example [17–23] and references therein) or sent to hydrogen stations for vehicle refueling [19].

Unlike in previous studies, where the MGT and hydrogen are used separately, here we propose a new energy strategy based on joint use of both. The excess of renewable energy (*solar*, *wind*, …) over demand is used to produce hydrogen by electrolysis of water. The hydrogen is stored in pressurized tanks and later used as a secondary fuel in the MGT [24–26], partially replacing fossil fuels (*natural gas*, *methane*, *syngas*, …) and reducing combustion emissions [25].

Most currently installed MGTs can be fuelled with low concentrations of hydrogen mixed with natural gas [27]. Concentrations under 1% by volume do not require any modifications of the MGT, whereas concentrations up to $5-10\%$ can be used with minor modifications to the MGT [28]. More radical modifications to the MGT are necessary if it is to work with concentrations up to 15% by volume. Recent studies show that the MGT can be fuelled with 100% hydrogen if the combustor is completely redesigned [24,25].

The purpose of the MGT is to compensate for any scarcity or unavailability of renewable energy. Energy stored in the form of hydrogen is partially fed back into the grid. Such HEGs could in principle be self-sustaining if the renewable energy vector is appropriately greater than the energy required in the course of a year. Large discrepancies between the electrical power produced by PV and/or WT systems and power supply loads can seriously destabilize the grid. In this regard, combined smart use of electrolysis and MGT can reduce negative effects that unpredictable behavior of non-programmable energy sources can have on the regulation of net electrical power produced. This strategy is original and has never been investigated before. Indeed, we found only one recent paper [29] reporting the results of thermoeconomic analysis of a 100 MW PV-hydrogen gas turbine hybrid power plant.

Table 1
Technical data of Turbec T100P provided by manufacturer [45] at ISO standard operating conditions.

ISO standard conditions	
Room temperature	288 K
Relative humidity	60%
MGT inlet losses	0 Pa
MGT outlet losses	0 Pa
Fuel	Natural gas
Fuel pressure	0.021.0 barg
Performance	
Electric Power	100±3 kW
Overall electric efficiency	30%±1
Thermal power	333 kW
Shaft speed	70000 rpm
Exhaust gas mass flow rate	0.8 kg/s
Exhaust gas temperature	543 K
Pressure in combustion chamber	4.5 bar
Turbine Inlet Temperature (TIT)	1223 K
Turbine Outlet Temperature(TOT)	918 K
$[NO_x]$ @ 15% O_2	<15 ppmv
$[CO]$ @ 15% O_2	<15 ppmv
Acoustic noise	70 dBA at 1 m

One of the main problems with HEGs is coordinating the tasks of the many subsystems involved in managing different energy fluxes, so that net electrical power tracks power demand [23,30–33]. The power control problem is even more arduous due to fluctuations in power fluxes arising from renewable energy plant. These vary with ambient conditions (e.g. *solar irradiance*, *air temperature*, *wind speed*), as well as with time-varying power demand. Thus numerical simulation becomes essential for designing increasingly complex HEGs especially with regard to aspects of virtual prototyping of their energy management systems.

Different modelling approaches to MGTs have been developed in the technical literature. Traverso et al. used a 1D code (TRANSEO) to describe the dynamics of a 45 kW MGT generator (Bowman TG-45) fuelled with natural gas [34]. Degobert et al. proposed a simple first order adaptive model to describe the dynamics of a 30 kW MGT generator (Capstone C330) fuelled with natural gas to numerically study the possibility of combining a photovoltaic system with a high speed micro-turbine [35]. The time constant of the model was expressed in table form in relation to variations in power. Roberts et al. investigated two modelling approaches for reproducing the dynamics of a modified 100 kW MGT (Turbec T100) coupled with an external vessel in order to emulate a fuel cell gas turbine hybrid system generator [36]. The first model was based on a simplified-physics time constant approach, and the second on first principles and a differential equation approach to capture the dynamic performance of the turbine. Reale et al. used a 3D CFD code (ANSYS CFX) to detail the behavior of a Turbec T100 in order to study the steady response of the MGT at part load with different fuels (methane-hydrogen blends) and at the same time to numerically predict the influence that higher hydrogen concentrations could have on the combustor [28,37,38]. Nikpey et al. used a commercial software tool (IPSEpro) to obtain a thermodynamic steady state model of Turbec T100 as base case for numerical investigation of innovative GT cycles such as the humid air turbine (HAT) cycle and the exhaust gas recirculation (EGR) cycle [39]. Henke et al. used a numerical simulation tool for steady-state thermodynamic analysis of MGT [40]. The MGT simulator was parameterized and validated experimentally on a Turbec T100 test rig which was appropriately modified to improve temperature measurement at positions with uneven spatial temperature distribution such as the turbine outlet. Caresana et al. developed a MGT simulation code which was tuned on steady-state data of a Turbec T100 fuelled with natural gas [41]. The simulator was then used to analyse the effects of ambient temperature on global performance of the MGT in cogeneration arrangement and the behavior of its components. The study was performed in the safe functioning interval of the MGT as declared by Turbec, i.e. from -25° C to $+40^{\circ}$ C where electrical power reduces from 120 to 80 kW.

The sensitivity of the MGT to ambient conditions, as also stated in Ref. [41], becomes more and more a key factor to take into account for sizing, simulation and control of energy grids in which uncontrollable and unpredictable power fluxes (e.g. produced by photovoltaic systems and/or wind turbines) need to be balanced by controllable power generation systems such as MGTs. Following