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Smart polygeneration grids: experimental performance curves of different prime movers

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HIGHLIGHTS

- Measured performance curves for different prime movers.
- Microturbine, internal combustion engine, SOFC hybrid system, absorption chiller.
- Emulation rig for the hybrid system.
- Ambient temperature impact on the microturbine.

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ABSTRACT

This paper shows the performance curves obtained with an experimental campaign on the following different prime movers: a 100 kW microturbine, a 20 kW internal combustion engine, a 450 kW SOFC-based hybrid system and a 100 kW absorption chiller. While the size related to the microturbine and the engine are actual electrical power values, the hybrid system size is an electrical virtual power (an emulator rig was used for this plant) and the chiller value is a cooling thermal power. These experimental results were obtained with a smart polygeneration facility installed in the Innovative Energy Systems Laboratory by the Thermochemical Power Group of the University of Genoa. This facility was designed to perform tests on smart grids equipped with different generation technologies to develop and improve innovative control and optimization tools. The performance curves were obtained with two different approaches: tests on real prime movers (for the microturbine, the engine and the chiller) or measurements on an emulator rig (for the hybrid system). In this second case, the tests were carried out using an experimental facility based on the coupling of a second microturbine with a modular vessel. A real-time simulation software was used for components not physically present in the experimental plant. These results are a significant improvement in comparison with the available data, because experimental results are presented for different prime movers in different operative conditions (both design and part-load operations). Moreover, since both manufacturers and users are not usually able to control air inlet temperature, special attention was devoted to the ambient temperature impact on the 100 kW microturbine because this property has a strong influence on the performance of this machine. For this reason, empirical correlations on the ambient temperature effect were obtained from the experiments with the objective to perform an easy implementation of the optimization tools. Experimental performance curves (including several off-design conditions) are essential for smart grid management because (if they are implemented in optimization tools) they allow to find real optimal solutions (while tools based on linear or calculated correlations can obtain results affected by significant errors).

1. Introduction

Distributed generation (DG) based on smart polygeneration grids [1–3] is a promising energy production paradigm [3] with significant potential aspects related to decrease of pollutant emissions and cost savings [4]. The installation of small size generators close to users (both in residential and industrial buildings) is expected to decrease energy losses [5] and to improve fuel energy exploitation through cogeneration [6] and trigeneration [7] plants. Even if most small-size power systems can be installed for distributed generation paradigm (low emissions are mandatory),

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Nomenclature

Acronyms

Abs.	Absorption
DG	Distributed Generation
E. Grid	Electrical Grid
el.	electrical
Ex	heat Exchanger
GT	Gas Turbine
HS	Hybrid System
ICE	Internal Combustion Engine
mGT	micro Gas Turbine
PI	Proportional–Integral controller
PID	Proportional–Integral–Derivative controller
REC	RECuperator
S. Alone	Stand-Alone
sol.	solution
SOFC	Solid Oxide Fuel Cell
TPG	Thermochemical Power Group
UDP	User Datagram Protocol
WHEx	Water Heat Exchanger

Variables

Coeff	Coefficient (–)
COP	Coefficient Of Performance (–)
F	Faraday's constant (C/mol)
LHV	Low Heating Value (J/kg)
I	electrical current (A)
M	mass flow rate (kg/s)
P	power (W)
T	temperature (K)
TC1	compressor inlet temperature (K)
TOT	Turbine Outlet Temperature (K)
U_f	fuel utilization factor (–)
X	$P_{el}/(P_{el})_0$ (–)

Greek symbols

η	electrical efficiency (–)

Subscripts

0	nominal
b	blower
c	cooling
C	Calculated
cons	consumed
el	electrical
f	fuel
fc	fuel compressor
h	hot
in	inlet
M	Measured
max	maximum
mGT	micro Gas Turbine
SOFC	Solid Oxide Fuel Cell
th	thermal

the following devices are usually considered optimal solutions, in terms of cost performance, maintenance, future perspectives and environmental issues. Microturbines [8,9] and internal combustion engines [10] are predicted to be essential because of their features in terms of costs (especially internal combustion engines), maintenance (especially microturbines), emissions (using natural gas) and total efficiency (with cogeneration). Fuel cells [11–13] and hybrid systems [14–17] are expected to be a near term solution to generate at very high electrical efficiency conditions, even though some technical and cost issues must still be solved (e.g. cost and reliability aspects [18,19], component integration [20,21] and control system problems [22–24]). Moreover, the distributed generation paradigm is also an interesting approach to allow easy application of power plants based on renewable sources [25,26]. Since energy efficient generation has to be carried out with a thermal energy demand during the entire year [27], applying absorption chillers [28,29] seems to be mandatory for providing building refrigeration during the summer. Thus, the thermal grid layout must include cooling water pipes to implement trigeneration operations.

The coupling of different generation technologies, operating with different performance at both design and off-design conditions, requires proper software tools [30–32] to manage the systems, optimizing efficiency and/or marginal costs. The issue is the dispatching of grid load demands (both electrical and thermal) to the different generators. An obvious approach is based on utilizing renewable generation plants (when available) and dispatching the remaining loads to fossil fuel plants, favouring the highest efficiency (or lower marginal cost) devices. While for traditional technology (e.g. microturbines and internal combustion engines), it is important to take into account that plant performance significantly decreases at low load conditions, fuel cell based plants can show an increasing trend in the 50–100% load range [16,24]. Moreover, if the grids (both electrical and thermal) are equipped with energy storage devices [2,33,34], further complexity is involved for optimization.

Optimization activities usually require performance data from the generators to be implemented in the software tools. Even if experimental data are the best solution to produce reliable results, several works were based on performance values obtained with numerical models, especially when involving innovative plants. For this reason, several authors [35–37] presented performance curves of power plants for analyses related to distributed generation. Special attention was devoted to the effect of ambient temperature on microturbines [36], because of the remarkable impact that this parameter has on overall performance.

In this paper, experimental performance curves are presented and discussed for a 100 kW (electrical power) microturbine, a 20 kW (electrical power) internal combustion engine, a 450 kW (virtual electrical power) hybrid system based on Solid Oxide Fuel Cell (SOFC) technology and a 100 kW (thermal power) absorption chiller. These data were obtained from an experimental facility [2,32] designed and installed at the University of Genoa for experimental tests on smart polygeneration grids (including the development of prime mover management models). Special attention was devoted to the effect of ambient temperature on the microturbine (by developing empirical correlations) and to the performance of the hybrid system obtained by considering the coupling of an emulator test rig with a real-time transient model for components not installed in the facility [37,38].

In comparison with data related to these machines usually available at design conditions, this work shows experimental results in both design and part-load operations. Even if several previous works were focused on off-design conditions, usually the available data were obtained with calculation models considering