Energy Conversion and Management 78 (2014) 105–113

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Plant management tools tested with a small-scale distributed generation laboratory

Mario L. Ferrari *, Alberto Traverso, Matteo Pascenti, Aristide F. Massardo

Thermochemical Power Group (TPG), DIME, University of Genoa, Italy

ARTICLE INFO

Article history:
Received 31 May 2013
Accepted 16 October 2013
Available online 16 November 2013

Keywords:
Distributed generation
Smart grids
Optimization software

ABSTRACT

Optimization of power generation with smart grids is an important issue for extensive sustainable development of distributed generation. Since an experimental approach is essential for implementing validated optimization software, the TPG research team of the University of Genoa has installed a laboratory facility for carrying out studies on polygeneration grids. The facility consists of two co-generation prime movers based on conventional technology: a 100 kWe gas turbine (mGT) and a 20 kWe internal combustion engine (ICE). The rig high flexibility allows the possibility of integration with renewable-source based devices, such as biomass-fed boilers and solar panels.

Special attention was devoted to thermal distribution grid design. To ensure the possibility of application in medium-large districts, composed of several buildings including energy users, generators or both, an innovative layout based on two ring pipes was examined. Thermal storage devices were also included in order to have a complete hardware platform suitable for assessing the performance of different management tools.

The test presented in this paper was carried out with both the mGT and the ICE connected to this innovative thermal grid, while users were emulated by means of fan coolers controlled by inverters. During this test the plant is controlled by a real-time model capable of calculating a machine performance ranking, which is necessary in order to split power demands between the prime movers (marginal cost decrease objective). A complete optimization tool devised by TPG (ECoMP program) was also used in order to obtain theoretical results considering the same machines and load values. The data obtained with ECoMP were compared with the experimental results to obtain a broad validation of the optimization tool.

1. Introduction

Distributed generation (DG) is expected to play an important role in future energy markets [1–3]. It is a new generation approach with high potential for energy cost saving [4,5] and pollutant emission reduction [6]. In detail, extensive development of this new paradigm is expected to significantly decrease energy losses due to electricity distribution and transformation [7] and for an easy expansion of cogeneration [8–12]. Moreover, distributed generation makes it possible to combine conventional and advanced energy technology [5]. While microturbine [13,14] and internal combustion engine [15] technology is also predicted to remain essential for DG because natural gas is a "clean" fuel, innovative generation systems (e.g. fuel cells [16], hybrid systems [17,18] and stirling engines [19]) are expected to increase their penetration of this new market because of the significant benefits due to their high conversion efficiency [20]. In addition, distributed generation allows easy integration with renewable energy sources [21–23], such as small hydroelectric plants, wind turbines [24], solar systems (both photovoltaic [25,26] and thermal), biomass plants [8] and small geothermal systems [27]. A further important aspect related to a wide development of polygeneration grids for DG is the easy application of storage technology for both electrical [28] and thermal [29–31] energy. In detail, storage systems are able to improve energy management because they make it possible to distribute demand avoiding generating energy in low efficiency or high cost conditions. Moreover, they are essential for reducing the oscillations associated with renewable sources [32] (e.g. sudden changes of power outputs from wind or solar systems).

Since the DG concept involves the development of new polygeneration grids equipped with several prime movers of different types and/or technologies, optimal generation management is associated with high complexity. For this reason, the distribution of load demand between several generators (with different efficiency, cost, reliability and availability characteristics) has to be

* Corresponding author.
E-mail addresses: mario.ferrari@unige.it (M.L. Ferrari), alberto.traverso@unige.it (A. Traverso), matteo.pascenti@unige.it (M. Pascenti), massardo@unige.it (A.F. Massardo).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.10.044

Nomenclature

Acronyms

DG	distributed generation
E-NERDD	energy and efficiency research demonstration district
ECoMP	economic co-generation modular program
ICE	internal combustion engine
mGT	micro gas turbine
PI	proportional integral
TPG	thermochemical power group
UDP	user datagram protocol

Variables

c	specific cost [€/J]
C	cost [€]
E	electrical energy [J]
F	fuel consumption [kg]
$\dot{F}$	fuel cost rate [€/J]
M	mass flow rate [kg/s]
N	number of machines
P	power [W]
Q	thermal energy [J]

Subscripts

acq	acquired
cons	consumed
dem	demand
el	electric
f	fuel
gen	generated
i	number of the machine
max	maximum
min	minimum
var	variable
th	thermal

performed using calculation software [33,34]. In detail, several optimization tools have been developed using different approaches [34], such as conventional analytical methods, evolutionary algorithms, hybrid intelligent optimization techniques and statistical models. However, an experimental approach is necessary for extensive development of these optimization algorithms for real system applications. Tests carried out using an experimental facility will be essential for software validation and for tuning control logics [17] (at both prime mover or grid levels) and optimization techniques [35].

At the University of Genoa, the TPG's experience with experimental rigs [18,36], real-time tools [37] and optimization software [22,35] was applied to study techniques for polygeneration grid management. Within the framework of a four year European Collaborative project called E-HUB ("Energy-HUB for residential and commercial districts and transport") [38] TPG has developed a new experimental facility [39], specially designed for tests on distributed generation systems. It is a flexible plant capable of emulating a an e-hub (a physical junction where energy and information streams are interconnected) where different forms of energy can be converted, consumed and/or stored. This test rig, named "Energy aNd Efficiency Research Demonstration District" (E-NERDD), is based on different prime movers (using fossil fuels or renewable sources) connected to the campus electrical grid and/or to an innovative thermal grid including storage vessels.

In this paper experimental results obtained with the E-NERDD rig are presented. The tests were carried out with natural gas-fed prime movers (a 100 kWe recuperated microturbine and a 20 kWe internal combustion engine) generating (in the laboratory) variable thermal demand values through fan coolers controlled by inverters. The objective was related to management improvement of power generation in a small industrial district: activities concentrated during the morning and in the early afternoon (significant base load demands due to overnight industrial activities). For this reason, the rig was managed by a real-time management tool developed in Matlab®-Simulink® environment, based on a cost decrease approach: load demand values split on the basis of machine cost ranking. These experimental results were compared with the data obtained with a second optimization model developed with a modular software by TPG, named ECoMP ("Economic Co-generation Modular Program") [40]. This is a complete optimization tool based on a hierarchical structure [41]: two different levels are present to couple the optimization of plant size and layout (not necessary in these tests because generators are fixed to the technology installed in the laboratory) with variable cost minimization considering all the constraints.

2. Thermal grid layouts for an energy hub

Since a thermal grid is critical for distributed generation to achieve significant market penetration, attention was focused on possible innovative layouts for obtaining a positive compromise between costs and energy saving. Thermal energy is not as easily managed as electricity, because in thermal grids water temperature is important to ensure proper heating quality; the energy required for pumping can reduce the positive effect in terms of fuel saving and losses can also be significant over short distances. For these reasons, it is essential to study a proper grid layout optimized for district size and building locations. A positive solution for a small district can be extremely ineffective for large energy hubs with hundreds of buildings characterized by different solutions (e.g. buildings equipped with generators of different technologies and dwellings operating just as energy users).

Fig. 1 shows the comparison of three possible thermal grids. Starting from the "state-of-the-art" layout (the most advanced conventional design), two new concepts designed for energy hubs are presented. For each solution two schemes are shown: while the "Ring scheme" aims to show the layout of the connection to the buildings, the "Flow scheme" is used to show the flow paths related to these plants.

The "State-of-the-art" layout is the typical scheme for cogeneration plants based on a single central plant [42,43]. It is used for traditional energy systems connected to a large heating grid, and for innovative plants based on biomass [44] or other renewable sources. The scheme is quite simple because all the buildings act as energy users (blue houses in Fig. 1). They receive hot water (red[1] arrows in Fig. 1) directly from the central plant [42] and deliver back the return water (blue arrows in Fig. 1). A storage vessel may be connected to the pipes to be charged or discharged depending on the generation/utilization mismatch. This layout, even if effective for central plant based systems, is not sufficiently flexible for complex energy hubs where buildings may act as generators or as users.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.