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A dynamic optimization-based architecture for polygeneration microgrids with tri-generation, renewables, storage systems and electrical vehicles

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ABSTRACT

An overall architecture, or Energy Management System (EMS), based on a dynamic optimization model to minimize operating costs and CO_2 emissions is formalized and applied to the University of Genova Savona Campus test-bed facilities consisting of a Smart Polygeneration Microgrid (SPM) and a Sustainable Energy Building (SEB) connected to such microgrid. The electric grid is a three phase low voltage distribution system, connecting many different technologies: three cogeneration micro gas turbines fed by natural gas, a photovoltaic field, three cogeneration Concentrating Solar Powered (CSP) systems (equipped with Stirling engines), an absorption chiller equipped with a storage tank, two types of electrical storage based on batteries technology (long term Na–Ni and short term Li-Ion ion), two electric vehicles charging stations, other electrical devices (inverters and smart metering systems), etc. The EMS can be used both for microgrids approximated as single bus bar (or one node) and for microgrids in which all buses are taken into account. The optimal operation of the microgrid is based on a central controller that receives forecasts and data from a SCADA system and that can schedule all dispatchable plants in the day ahead or in real time through an approach based on Model Predictive Control (MPC). The architecture is tested and applied to the case study of the Savona Campus.

1. Introduction

The development of the renewable energy sector, the concept of sustainable energy, and the use of technologies for distributed generation have focused attention on smart grids. Microgrid research fits very well with ongoing smart grid activities throughout the world and several challenges need to be investigated [1]. Microgrids are able to integrate different distributed and heterogeneous sources, either programmable or stochastic (these latter, typically, are the renewables like wind and solar), and require intelligent management methods and efficient design in order to meet the needs of the area they are located in ([2–4]). Generally, microgrids are low voltage distribution networks installed in small areas (like University Campus sites or districts), but also buildings or industrial plants can themselves be seen as microgrids. Energy Management Systems (EMSs) are vital tools used to optimally operate and schedule microgrids [5]. Experimental tests and demonstration projects are fundamental to derive new methods and tools for the optimal planning and management and for simulation purposes, as described in [6–8].

In the recent literature, different papers can be found about the development of models for the simulation and optimization of microgrids with storage and renewable energies both at planning and at operational level. Chen et al. [9] present a methodology for the optimal allocation and economic analysis of an energy storage system in microgrids. Mohammadi et al. [10] present an optimized design of a microgrid in distribution systems with large penetration of dispersed generation units (among which PV, wind turbines and batteries). Marnay et al. [11] propose an optimization approach to incorporate electrical and thermal storage options in the Berkeley Lab's Distributed Energy Resources Customer Adoption Model (DER-CAM). Different recent works are also related to operational management problems ([12,13]) and are usually aimed at the best management of intermittent renewable

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Nomenclature

Symbol	
B	benefit (€)
C	cost (€)
CAP	battery capacity (kW h)
D	electrical/thermal load (kW)
E	emissions (t_{CO2})
E_f	emission factor (t_{CO2}/m^3 or t_{CO2}/kW h)
Ev	vehicle stored energy (kW h)
e_f	electricity fee (€/kW h)
G	solar radiation (kW/m^2)
I	current (A)
LHV	lower heating value (kW h/m^3)
N	number (–)
NG	fuel price (€/m^3)
P	power (kW)
PL	power loss (kW)
p_f	packing factor (–)
Q	fuel quantity (m^3)
R	electrical resistance (Ω)
S	area (m^2)
SOC	battery state of charge (-)
S_b	base power (kW)
t, T, Δ	time (h)
TES	thermal energy price (€/kW h)
V_b	base voltage (V)
v	velocity (m/s)
x	electrical reactance (Ω)
Z_b	base impedance (Ω)
δ	phase angle (rad)
η	efficiency (-)

Subscript	
B	boiler
CHI	chiller
CR	control room
CSP	concentrating solar power
c	cool
el	electrical
HP	heat pump
h	heat
in	inlet
OUT, out	outlet
PE	primary energy
PV	photovoltaic
pc	power conditioning
pp	purchasing price
$ppwf$	purchasing price without fee
RES	renewable sources
S	battery storage
SEB	smart energy building
SPM	Smart Polygeneration Microgrid
Sv	vehicle storage
t	time
th	thermal
tx	taxed
utx	untaxed
W	wind

sources. Marzband et al. [5] compare two algorithms to implement an energy management system based on local energy market in microgrids in islanding mode, based on mixed-integer nonlinear programming. Mohamed and Koivo [14] present a genetic algorithm approach to solve the problem of electric power dispatch optimization of microgrids for a system that includes a fuel cell, a diesel engine, a microturbine, and minimizes total operating costs. Zhang et al. [15] analyze the case of a smart building composed of multiple smart homes (that share a microgrid) and propose a mixed integer linear programming model to minimize total 1-day-ahead expense related to smart building's energy consumptions, including operation and energy costs. Bracco et al. [7] present a static mixed integer non linear optimization model for the Smart Polygeneration Microgrid (SPM), neglecting the electrical network, the storage systems, and the electrical vehicles. As regards software tools, Homer energy software [16] simplifies the task of evaluating design options for both off grid and grid connected renewable power systems for remote, stand alone, and distributed generation applications. At the industrial side, few software algorithms are available for the optimization of microgrids. One example is the Siemens DEMS (Decentralized Energy Management System) [17] that includes a very good user friendly and flexible interface, in order to monitor data and to obtain necessary forecasts, minimizes overall costs, uses simplified models for technologies and storage systems, and neglects thermal and electrical distribution networks.

A major issue for the optimal operation of microgrids is how to deal with the uncertainties due to the intermittent renewable sources and the variable loads, while minimizing economic and environmental impact objectives. Model Predictive Control (MPC) is a viable approach, as demonstrated by many application areas. MPC is a mature methodology, but there is still a significant investigation to carry out concerning with its practical implementation in the day-by-day management of energy infrastructures [18]. In the field of power systems management, Xia et al. [19] focus attention on the optimal control dynamic dispatch and the dynamic economic dispatch formulations, and propose an MPC approach that gives better performances and overcomes technical limits related to ramp rate. Dagdougui et al. [12] present an optimal controller based on MPC and applied to a general building system.

With respect to the current literature, the optimization model presented in this paper is dynamic and provides details on the electrical grid, the power losses, the electrical vehicles, the economic assessment of the different plants, the carbon footprint over the whole power flows. Moreover, it allows the inclusion of on/off status of all plants, internal and external grid connections, and thus the possibility to define/customize in situ intervention and the switching between grid connected and islanded modes.

Then, in this work, attention is focused on microgrid optimal control and on the formalization and application of a dynamic decision model to a real case study/test bed facility: the University of Genoa Smart Polygeneration Microgrid (SPM) linked to the Sustainable Energy Building (SEB), which is an intelligent building directly connected to the SPM ([7,8]). The SPM is a three phase low voltage distribution system, connecting three cogeneration micro gas turbines fed by natural gas, a photovoltaic field, three cogeneration Concentrating Solar Powered (CSP) systems (equipped with Stirling engines), an absorption chiller equipped with a storage tank, two types of electrical storage based on batteries technology (long term Na–Ni and short term Li-Ion), two electrical vehicles charging stations, and other electrical devices. The grid is integrated with the other generation systems already in operation inside the Savona Campus, such as one cogeneration gas turbine and two traditional boilers, fed by natural gas. The SEB, which is presently under construction, will be supplied with