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A model for the optimal design and management of a cogeneration system with energy storage

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ABSTRACT

In the current energy scenario, system design and operation strategies are paramount especially for plants fed by renewable sources and/or whose production is strictly connected to the users demand. The systems optimization must consider the possibility of energy storage and of the conversion among different forms of energy. In this paper, a hybrid cogeneration system composed by a cogenerative internal combustion engine, a photovoltaic plant, a boiler and a pump as turbine is investigated. Different energy storage options are included: a pack of batteries, a water reservoir and a hot thermal storage.

By applying the Particle Swarm Optimization method, the devices size and hourly operation are simultaneously optimized. The minimization of the overall cost is the optimization goal, while the main constraint is the fulfilment of the user request (electricity, heat and water). Results show that the cogenerative internal combustion engine supplies the 87% of the electricity and the 19% of the heat during winter time while, during summer period, it supplies the 89% of the electricity and the all heat. The use of a pump as turbine allows to reduce the battery discharge rate and the Depth of Discharge with a consequent increase of the battery lifetime.

1. Introduction

In recent years, the electric system has been involved in a series of important changes.

The increasing concern about environmental impact of energy systems and the awareness about the importance of a responsible use of fossil reserves have resulted in many efforts to shift the energy system towards a different, more sustainable energetic model. This new energy strategy can also support the development and the improvement of the domestic industry related to the energy efficiency and decrease the dependency from abroad and the related costs for fossil energy supply.

Among others, many significant actions have been taken to promote the use of renewable energy and increase the efficiency of the whole energy chain from the electricity production to the end-users consumption. Most of them are emphasized in the Directive 2009/28 by European Union [1]. Even distributed generation can contribute to reduce the transmission losses and the grid congestion problems and allows the use of low density distributed renewable sources (biomass, wind, solar, mini-hydro). In this context, cogeneration is an opportunity, too, leading to a better exploitation of fossil and/or renewable resources where there is also a thermal energy requirement. A report of the International Energy Agency [2] demonstrates how, taken together, renewables and co-generation can be particularly effective as low carbon energy solution.

One of the most relevant problems when dealing with not predictable renewable sources is the matching of their variable and intermittent availability with the users demand curve. For this reason, they are often integrated by devices fed by fossil fuels, mainly boilers and diesel internal combustion engines, able to work also in remote areas. Khelif et al. [3] studied a hybrid Diesel–PV system in the arid area of Southern Algeria considering different configurations and made a sensitivity analysis of the fuel cost on system profitability. Rehman and Al-Hadhrami [4] presented an economic, energetic and green house gas emissions analysis of a similar system in the hot desert of Saudi Arabia performed by means of HOMER software. Recently, more efforts have been done to take advantage by the use of energy storage. In a comprehensive review paper Díaz-González et al. [5] described different storage options for stationary applications and presented their operation principles and main characteristics. For isolated systems the most used storage technology are the electrochemical batteries, as suggested by the study of Cloutier and Rowley [6] for irrigation plants in Central Nigeria

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Nomenclature

A	area (m^2)
DoD	Depth of Discharge (of a battery) (%)
E	energy (kW h)
P	power (kW)
PF	penalty function (–)
Q	thermal power (kW)
S	size (m^2, kW, kW h, m^3)
TH	thermal storage (kW h)
V	volume (m^3)
X	objective function (–)
a	constant parameter (–)
a_{tl}	tilt angle (°)
c	specific cost (€ m^{-2}, € kW^{-1}, € kW h^{-1}, € m^{-3})
lc	lifetime cycles (–)
m	mass flow rate (kg s^{-1})
n	number of optimization variables (–)
n_{years}	lifetime of the battery (years)
nc	number of constrains (–)
np	number of particles (–)
t	time (h)
yec	yearly equivalent cycles (–)
z	constrain (–)

Abbreviations

BAT	battery
BL	boiler
CAES	compressed air energy storage
FT	fuel tank
HS	hot thermal storage
ICE	cogenerative internal combustion engine
LR	lower reservoir
PAT	pump as turbine
PSO	Particle Swarm Optimization
PV	photovoltaic
SOC	state of charge (of a battery)
UR	upper reservoir
ZEB	zero energy buildings

Greek letters

η_{BL}	boiler efficiency (–)
η_{ICE}	cogenerative internal combustion engine efficiency (–)
η_{PAT}	pump as turbine efficiency (–)
λ_z	penalty multiplier (–)

Subscripts

el	electrical
f	fuel
h	hour
th	thermal
us	user

fed by solar photovoltaic (PV) or wind. Other options well studied are hydrogen storage with fuel cells, as proposed by González et al. [7] to exploit the surplus wind via electrolysis, and Compressed Air Energy Storage (CAES) systems, as described by Ibrahim et al. [8] for a hybrid system in northern Quebec in order to reduce fuel consumption and by Ferretto et al. [9] as a direct integration of a wind farm to increase its utilization factor.

For medium and large storages, pumped hydro power plants are a consolidated technology, but they are now called to new challenges in order to increase their operational field and their response rapidity. For this reason, new types of sustainable hybrid systems matched with hydro storage have been suggested for irrigation systems or clean water supply. Hamidat et al. [10] analyse the efficiency of a PV based pumping system as a function of solar radiation and water total head for different kinds of crops in Nigeria, while in [6] solar photovoltaic (PV) with storage batteries is suggested for irrigation systems. Kaldellis et al. [11] propose a stand-alone photovoltaic-based water pumping system, able to cover irrigation and potable water needs in remote areas where the connection to electricity local grid is not feasible. These plants can work continuously, using solar energy as primary energy source and water for energy storage as presented by Margeta and Glasnovic [12]. In the last years, the use of pump as turbine (PAT) is increasing in pumping applications and several studies were focused on determining the machine performance in turbine operating conditions for a proper implementation in micro-hydro power plants [13].

The complexity of both isolated and grid connected hybrid systems makes their proper design and operation very difficult. For this reason many different approaches have been proposed and applied to the optimization of these systems. Ranaboldo et al. [14] implement a heuristic model to design off-grid systems based on wind and solar energy. More generally, the concept of distributed multi-generation approach is applied to systems where different energy vectors (electricity, heat, cooling power, hydrogen, water and so on) are produced and distributed energy resources are used, as well described by Koeppel and Andersson [15].

If properly designed and managed, such systems permit to get:

- High reliability, since they give a certain independence from a single source or vector.
- High flexibility: the same thermal and electrical request can be satisfied by different vectors. The best actual combination of sources and vectors can be found as a function of their present cost, availability, and emissions.
- Synergy: the valuable characteristics of each vector and plant can be better exploited, for example matching the low environmental impact of renewable sources with the operational flexibility of combustion engines, or the distribution of electricity on long distances with the easy storage of water.

In [16] a comprehensive review of many different approaches for the characterization, planning, evaluation and optimization of such systems is reported. Aim of the optimization is often the overall cost minimization: the better optimal hourly, daily or annual operation strategy able to satisfy users' needs is evaluated. In other cases, the main goal is the independence from fossil fuels. Note that in these cases, a certain grade of lack of availability must be often accepted.

The paper is structured as follows: in Section 2 a brief overview of the optimization method and tools is presented while the opportunities exhibited by small cogenerative systems with energy storage are given in Section 3. The physical and mathematical models of the hybrid stand-alone energy system for a resort is presented in Section 4 while the optimization results are presented and discussed in Section 5. Finally, conclusion remarks are given in Section 6.

2. Optimization method and tools – Particle Swarm Optimization

The optimization method used in the research is based on the Particle Swarm Optimizer (PSO), which is a heuristic method, since it is iterative and works by getting closer and closer to the optimal solution as the iterations go on. The method is well documented by many authors in numerous books and papers [17–21].