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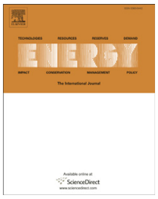

Components design and daily operation optimization of a hybrid system with energy storages

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A B S T R A C T

The study and the optimization of single devices, plants and integrated systems among producers and users, must be performed considering the possibility of energy storage and conversion among different forms of energy in order to reach the best overall energetic and environmental performance. Small CHP distributed plants are particularly interested in these challenges, both in stand-alone and grid-connected configurations. In this paper, the optimal design and management strategy of a trigeneration system composed by a PV plant, a diesel CHP engine, a reversible heat pump and a boiler is studied. The possibility of hybrid storage by means of a hot and a cold reservoirs, a pack of batteries, and a pumped hydro energy storage is investigated. By applying a model based on the Particle Swarm Optimization, the devices size and the operation strategy are simultaneously optimized. The most suitable devices' hourly-based operation profile and the best management strategy of the energy storages are predicted. The minimization of the overall costs is the problem's optimization target, while the main constrain is the fulfillment of the users' request of electricity, heat, cooling and drinking water.

1. Introduction

The world energy demand is growing day by day due to the rapid growth in population, urbanization and industrialization [1]. Furthermore, the total primary energy consumption is mainly based on non-renewable energy sources, such as coal, natural gas and oil, resources which cover more than 85% of the overall demand. As pointed out by Ref. [2], the use of non-renewable energy sources creates environmental problems such as acid rain, ozone depletion, local pollution, global warming, but also induces economic and political crisis. In addition to the environmental concerns, the fossil fuels depletion will increase their costs. Therefore, researchers are motivated to seek environmentally clean alternative fuels and energy sources. These alternatives are required to fulfil criteria such as no or less release of emission, suitability for both mobile and stationary applications and being within an affordable price range [3].

In this context, the utilization of renewable energy sources (RES) particularly in small plants and distributed generation, has become more important than previously.

These plants allow the employment of low density distributed sources as biomass, wind, solar, mini-hydro and also contribute to reduce the transmission losses and the grid congestion problems. Moreover these plants are an interesting solution for insulated communities or communities looking for energetic self-sufficiency [4,5].

The spread of these plants poses new challenges and opportunities. The integration into energy supply systems has to consider the RES availability, the needs of the overall electric system and the specific needs of the place where they will be installed. Therefore, the plant design and management strategy need to be optimized taking into account the above-mentioned parameters.

Obviously, the majority of RES plants produce energy with high variability and unpredictability; a fact that increases the uncertainty about their capability of meeting the instant demand.

Energy storage is the most suitable option to reduce RES uncertainty and guarantee the satisfaction of the user without reducing the request. In practice, energy storages have the fundamental role of increasing the system capacity, reducing distribution losses, unifying systems composed by conventional and renewable energy sources and adapting the production to the demand [6–9], key factors that justify the abundant research projects aimed at developing new energy storage technologies or improving the

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Nomenclature

A	area [m^2]
E	energy [kWh]
P	power [kW]
PF	penalty function
Q	thermal power [kW]
S	size
TH	thermal storage [kWh]
V	volume [m^3]
X	objective function
a	constant parameter [−]
c	specific cost
f,F	function
i,j,z	i-th, j-th, z-th
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]

Abbreviations

BAT	battery
BL	boiler
CHP	combined heat and power
COP	coefficient of performance
CS	cold thermal storage
DoD	depth of discharge (of a battery) [%]
FT	fuel tank
GA	genetic algorithm
HCS	hybrid cogenerative system
HS	hot thermal storage
ICE	internal combustion engine
LR	lower reservoir
PAT	pump as turbine
PHES	pumped hydro energy storage
PHS	pumped hydro storage
PRE	percentage of renewable energy
PSO	particle swarm optimization
PV	photovoltaic
RES	renewable energy sources
RHP	reversible heat pump
SOC	state of charge (of a battery)
TCS	traditional cooling system
UR	upper reservoir

Greek letters

Δ	difference
λ_z	penalty multiplier

Subscripts

c	cold
el	electrical
f	fuel
h	hot or hour [h]
th	thermal
us	user

available ones.

In many cases, renewable energy plants are also integrated by devices fed by fossil fuels, mainly diesel internal combustion engines [10–13]. In this context, if there is also a thermal energy requirement, cogeneration is a further opportunity, leading to a better exploitation of fossil and/or renewable resources [14].

The complexity of hybrid systems makes very difficult their proper design and operation. For this reason, many different approaches have been proposed and applied to the optimization of these systems [15–18]. 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.

An extensive review of the different approaches used for the characterization, evaluation and optimization of these systems, is given in Ref. [16]. The overall cost minimization is the most widespread optimization goal. The optimal hourly, daily or annual operation strategy is evaluated to satisfy users' requirement. However, the emissions minimization or the fossil fuels independence are becoming the optimization goals of several recent works. Note that fossil fuels independence is a risky target because a certain grade of lack of availability must be often accepted.

Multi objective optimization procedures are sometimes implemented in order to consider different aspects. The optimal operation strategy of a distributed energy system, composed by a PV, a fuel cell and a gas engine and able to produce electricity and heat is presented in Ref. [19]. The objectives of the optimization are the minimization of the total energy cost and of the annual CO2 emissions. A multiple objective optimization model was implemented based on the Pareto optimal set. It was found that, compared with pure economic optimization, an increased share of electricity from distributed energy sources and a different operation schedule are obtained. The optimum sizing of the devices of a hybrid power station based on wind turbines, hydro turbines, pumps and reservoirs operating in an island system is studied in Ref. [20]. Both the maximization of the return of the investment and that of the renewable energy sources penetration are investigated. The results show that in island systems with a high generating cost, the RES penetration increase is combined with a reduction of the cost of energy, while in systems with low generation cost, this is true only for relatively small hybrid power systems.

In this paper, an original optimization model based on the Particle Swarm Optimization (PSO) theory is proposed and applied to a Hybrid Cogenerative System (HCS). The HCS has to supply electricity, heat, cooling power and water to an isolated tourist resort. A diesel engine, a PV plant, a pack of batteries, a boiler, a reversible heat pump, a pumping device which can also be used as turbine (PAT), water reservoirs and hot and cold thermal storages are the plant installed components.

The model's peculiarity is the ability to simultaneously optimise both the sizes and the hourly loads of each plant device. The proposed approach allows, on the one hand, to easily manage several constraints on the users' demand, the devices size, the operation strategy and the operation load and, on the other hand, to solve the optimization problem with a personal computer in a couple of hours although the optimization variables are 79.

Note that, since 2013, the Authors are involved in this research field [18,21–26] but, only in the present work, they presented the optimization of both the device sizes and their hourly loads of a HCS that has to supply electricity, heat, cooling power and water. A comparison between a HCS where the cooling demand is supply

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