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A small-scale CAES (compressed air energy storage) system for stand-alone renewable energy power plant for a radio base station: A sizing-design methodology

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A B S T R A C T

In this paper, a novel CAES system (compressed air energy storage) is proposed as a suitable technology for the energy storage in a small scale stand-alone renewable energy power plant (photovoltaic power plant) that is designed to satisfy the energy demand of a radio base station for mobile telecommunications.

The innovation introduced in this study concerns two aspects: the first one is the using of a small-scale CAES system integrated with a TES (thermal energy storage) unit with inter-cooling compression and inter-heating expansion; the second one is the cooling energy production, that is obtained by the cold air (3 °C) at the turbine outlet of the CAES system. For this reason, the storage system is defined a PSS-CAES (Polygeneration Small-Scale Compressed Air Energy Storage) system.

In this paper, a sizing-design methodology of the energy power plant has been illustrated and the overall performance has been calculated.

Results have highlighted that the storage system has an efficiency equal to 57%, that is an interesting value considering its small size. Moreover, the contribution of the PSS-CAES unit on the cooling energy requirements results equal to 17% with reference to the cooling energy required in the hours in which it works.

1. Introduction

Current energy policies and strategies are mainly addressed to sustain the diffusion of renewable energy source technologies, even if they are often recognized as less competitive than the energy conversion systems based on fossil fuels, due both to the intermittency of the energy sources (a mismatch between the electricity production and the corresponding occurrence of load demand), and to the high maintenance costs [1–4]. Thus, electricity storage systems are needed if the renewable power has to become a major source of base-load dispatchable power [5,6].

Existing storage technologies, based on various processes, include electrochemical batteries and fuel cells, supercapacitors, thermal-storage materials, flywheels, PH (pumped hydro), SMES (superconducting magnetic energy storage), chemical storage (hydrogen and synthetic natural gas) and CAES (compressed air energy storage) [7–9]. Each system is characterized by different storage capacity, storage efficiency and discharge time and thus, the choice of the best technology depends on its application [10–14].

Generally, for large scale applications, pumped hydro (PH) storage systems and compressed air energy storage (CAES) systems are the most viable technologies [6,15].

The PH storage system is the oldest large-scale storage technology (the first hydroelectric storage plant was built in 1892 in Zurich, Switzerland [16]) and is widely deployed, while the interest in CAES systems is more recent (the CAES system is in use only in two places in the world, Huntorf, Germany, and McIntosh, Alabama, USA) and an increasing number of studies are devoted to this technology for large-scale application, in which the compressed air is stored in underground caverns or rock formations [17].

In this paper, a novel CAES system is proposed as a suitable technology for the energy storage in a small scale stand-alone renewable energy power plant, that is designed to satisfy the energy demand of a radio base station for mobile telecommunications.

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Nomenclature

W	electric power [kW]
COP	coefficient of performance of the cooling system
E	electric energy [kJ]
t	time [s]
γ	number of PV base modules
M	air mass [kg]
T	temperature [°C]
$\dot{m}$	flow rate [kg/s]
c_p	specific heat for a constant pressure [kJ/kg K]
β	compression/expansion ratio
p	pressure [bar]
k	isentropic expansion factor
η_{pol}	turbo-machinery polytropic efficiency
ψ	mass increasing ratio
Q	thermal/cooling energy [kJ]
$\dot{Q}$	thermal/cooling power [kW]
ε	efficiency of the heat exchanger
u	global heat transfer coefficient [W/m^2 K]
A	heat exchange surface [m^2]
C	heat capacity rate [kW/K]

Subscripts and superscripts

d	demand
el	electric
cool	cooling
eq	equipment
PV	photovoltaic plant
i	day
*	single photovoltaic module
e	expansion
c	compression
a	air
atm	atmospheric conditions
av	availability
o	diathermic oil
HE	heat exchanger

At present, diesel generators satisfy the power requirements of radio base stations with high costs for maintenance and fuel supply. Thus, to reduce these operating costs, renewable energy power plants, integrated with efficient energy storage systems, can be the optimal solution [18].

Furthermore, the innovation introduced by the proposed storage system is based on the cooling effect that is obtained by the cold air at the outlet of the turbine (during the energy production).

For this reason, the storage system can be defined a PSS-CAES (Polygeneration Small-Scale Compressed Air Energy Storage) system [19,20].

The interest in this technology and in its performance is due to the growing attention to the power supply, by means of renewable sources, for telecommunications equipment in remote places where the storage of energy has a strategic role.

The purpose of this study is to evaluate the performance of the PSS-CAES system integrated with a PV power plant (photovoltaic), by applying a design methodology based on mathematical models.

2. Plant configuration and description

The small-scale CAES system, proposed in this study, has been sized to provide the storage of the energy from a stand-alone renewable power plant that has been designed to satisfy the energy demand of a radio base station for mobile telecommunications.

Fig. 1 shows the power plant configuration in which the main sub-sections are highlighted: i) a renewable photovoltaic (PV) power unit; ii) a compressed air energy storage (CAES) unit that consists of air compressors and turbines and an air storage tank; iii) a TES (thermal energy storage) unit that consists of heat exchangers and diathermic oil tanks.

Furthermore, backup power systems, such as electric generators and battery packages, are considered too. These systems provide power when the renewable energy power system or/and the storage system are out of service or in case it is necessary to reduce the size of the PV power plant with respect to the optimal size calculated by the methodology.

The proposed CAES unit is an advanced adiabatic storage system [10,11,21–24] in which inter-cooling compressions (3 volumetric compressors) and inter-heated expansions (2 dynamic turbines) are realized. Thus, a dedicated thermal energy storage system (TES) is used in order to increase the efficiency of the system by recovering the available thermal energy. The thermal fluid used in the TES unit is a diathermic oil that is stored into two tanks (cold and hot tanks).

The power plant system is designed and sized not only to satisfy the electric energy demand of the utility, without using fossil fuels (electric generator) or batteries, but also to cool the telecommunications equipment. Thus, a constraint on the CAES unit, regarding the temperature of the exhaust air from the last turbine has been assigned: this temperature has to be equal to 3 °C (a value higher than 0 °C to prevent freezing).

3. Design methodology

The design of the power plant (Fig. 1) is based on an analytical procedure whose assumptions, constraints and iterative procedures are devoted to the optimization of the operating conditions and performance. The study has been conducted by using a steady-state approach.

3.1. Assumptions and constraints

The power system is designed both to satisfy the electric power demand and to produce cold air useful for the refrigeration of the telecommunications equipment. Thus, the main constraint that has been assigned regards the temperature of the air coming out from the last turbine of the CAES unit. This temperature has to be equal to 3 °C.

Further design assumptions and constraints are summarized as follows:

- The maximum and minimum pressures of the air tank have to be fixed.
- The pressure in the air tank increases or decreases according to a linear trend [25–27].
- The gases are considered as ideal gases.
- The polytropic efficiencies of compressors and the turbines have to be assigned.
- The efficiencies of the heat exchangers have to be assigned.
- The same temperature is assumed for the air at outlet of each compressor.
- The same temperature is assumed for the air at inlet of each turbine.

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