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Power management of a hybrid renewable system for artificial islands: A case study

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ABSTRACT

In this paper, a hybrid wind/solar/fuel cell power plant is designed and a possible power management strategy is proposed. In particular, wind and solar energy sources are used as primary power suppliers, while a pure-hydrogen-fueled fuel cell – with hydrogen produced by means of an electrolyzer recovering excess power – and a battery pack are employed to fulfill the power demand, when the power supplied by the renewable sources is not sufficient. The analysis is applied to a particular case study, i.e. the TUNeIT [TUNisia and ITaly] Project, that involves the realization of four artificial islands to connect Bon (Tunisia) and Pizzolato (Sicily), provided with electrical-power-demanding facilities for tourists. Components sizing has been performed with HOMER, where a load profile has been assumed in order to reproduce the possible power demand of one of these artificial islands, while Matlab/Simulink® is used for simulations and power management strategy design. The obtained results demonstrate the possibility of realizing an almost self-sustaining renewable power plant, able to realize a good integration of different energy sources and power converters, with no negative effects on end-user satisfaction. The system would consist of a wind turbine of 1 MW and a photovoltaic array of 1.1 MW, acting as primary power sources and several backup systems, such as a 72-kWh battery, a 300-kW fuel cell and a 300-kW diesel engine to cope with power demand unmatches and/or failures. In order to verify the system performance under different situations, simulation studies have been carried out using practical load demand profiles and real weather data. Typical winter and summer day loads have been kept for simulations of a four-season scenario and results are provided to show the effectiveness of the proposed system. The major drawback encountered during the analysis is the low value of the utilization factors of both wind turbine and photovoltaic array, which are 10.2% and 15.9%, respectively. This is obviously due to the low average wind speed and solar irradiation related to latitude and altitude of the islands and, because of these low utilization factors, despite the presence of two energy storage systems, the diesel engine must be sometimes turned on to satisfy the power demand. Nonetheless, the cost-of-energy of 0.522 €/kWh, which includes installing and operating costs during the entire lifespan of the power plant, seems very promising if justified by the benefit of very low pollutant emissions.

1. Introduction

Typically, small islands are served by isolated power systems often characterized by thermoelectric machines of high total nominal power, in order to face intensive seasonal power demand variations. This implies that they are run at very low loads for the great part of the year, causing very low utilization factors and relative high specific costs of energy production [1]. This, together with rising of energy demand, sudden fluctuations of fossil fuels price and increasing concerns for global warming and pollutant emissions, are favoring the penetration of green power generation systems in existing isolated power systems [2]. Renewable energy sources are in fact becoming the most promising solutions to cope with all the aforementioned issues, especially in the islands of the Mediterranean area, characterized by excellent wind and solar potentials [3]. In the last years, wind and solar power generation technologies have achieved high reliability and their market share

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Nomenclature

WT	wind turbine
PV	photovoltaic panel
FC	fuel cell
BAT	battery
EL	electrolyzer
ICE	internal combustion engine
COE	cost of energy [€/kWh]
DOD	battery's depth of discharge [%]
SOC	battery's state of charge [%]
NCV	net calorific value [TJ/tons]
EF	emission factor [kg CO_2/TJ fuel]
CF	consumed fuel [tons/year]
$C_{ann,tot}$	total annualized cost of power [€/yr]
$C_{NPC,tot}$	total net present cost [€]
E_{served}	annual total electrical load served [kWh/yr]
N	project lifespan [yr]
i	annual interest rate [%]
I_S	incident radiation on standard conditions [kW/m^2]
I_T	incident global solar radiation [kW/m^2]
I_{NOCT}	PV nominal cell operating irradiance [kW/m^2]
f_{PV}	PV scaling dimensionless factor
A_{PV}	PV area [m^2]
η_{PV}	PV efficiency [−]
$\eta_{PV,ref}$	PV reference efficiency [−]
β	PV array efficiency temperature coefficient [1/°C]
T_C	PV cell temperature
T_{ref}	PV reference temperature [°C]
T_{amb}	ambient temperature [°C]
T_{NOCT}	PV nominal cell operating temperature [°C]
T_S	PV standard reference temperature [°C]
V	wind speed [m/s]
V_{rated}	rated wind speed [m/s]
$V_{cut,in}$	cut-in wind speed [m/s]
$V_{cut,off}$	cut-off wind speed [m/s]
P	air density [kg/m^3]
C_p	WT power coefficient [−]
A_T	WT swept area [m^2]
$V_{OC,BAT}$	BAT open circuit voltage [V]
R_{BAT}	BAT equivalent resistance [Ohm]
V_{BAT}	BAT load voltage [V]
T_{BAT}	BAT operating temperature [°C]
I_{BAT}	BAT current [A]
$\dot{SOC}$	BAT state of charge derivative [1/s]
η_C	BAT coulombic efficiency
Q_{nom}	BAT nominal capacity [Ah]
V_{EL}	EL input voltage [V]
R_{EL}	EL ohmic resistance [Ohm]
I_{EL}	EL input current [A]
$V_{OC,EL}$	EL open circuit voltage [V]
l_m	EL membrane thickness [cm]
A_m	EL cell active area [cm^2]
λ_m	EL membrane hydration parameter [−]
T_{cell}	EL cell temperature [°C]
$\dot{m}_{H_2}$	EL output hydrogen mass flow rate [kg/s]
n_s	EL cell number
F	Faraday constant [C/kmol]
η_F	Faraday efficiency [−]
M_{H_2}	hydrogen molecular weight [kg/kmol]
P_{BAT}	BAT output power [kW]
$P_{CONV,L}$	converter power losses [kW]
$P_{CONV,IN}$	converter input power [kW]
$P_{CONV,OUT}$	converter output power [kW]
P_{EL}	EL output power [kW]
P_{FC}	FC output power [kW]
P_{Load}	load power demand [kW]
P_{ICE}	ICE generator power [kW]
P_{PV}	PV output power [kW]
$P_{rated,PV}$	PV rated power [kW]
P_W	WT output power [kW]
P_{RNW}	renewable power production [kW]

has increased unexpectedly: wind annual market has grown by 44%, passing 50 GW for the first time in 2014 [4], while photovoltaic panels market has reached 40 GW in 2013, after a year of relative stagnation in 2012, compared to 2011, growing by around 35%, [5]. This has pushed researchers towards the feasibility analysis of a complete replacement of fossil-fuel-dependent machines with renewable energy systems, [6]. At this aim, it is important to consider the energy production fluctuation, typical of RES (renewable energy sources), which may often cause unmatches in the power demand. To face this issue, wind parks have been often successfully coupled to several ESS (energy storage systems). Although the majority of the proposed ESS refers to PHSS (pumped hydro storage systems) [7–12] and [13], also applications of CAES (compressed air storage systems) and BS (battery systems) have been proposed. The use of CAES has been investigated in Ref. [14] coupled with micro-hydro turbines and in Ref. [15] as a support to an isolated hybrid wind-diesel system. In Refs. [16] and [17], a combined heat power configuration has been investigated. CAES and PHSS are particularly suitable for storage of medium or large energy amounts, but their integration in small power plants has been also analyzed by Ref. [18]. On the other hand, battery systems are often employed for their commercial maturity and low maintenance, even though deep discharge cycles can provoke premature wear [19], increasing maintenance and installing costs. Also hydrogen can be seen as a promising ESS – especially for islands where there is a very high availability of water – thanks to its high energy density by weight and its high electrical-to-chemical and chemical-to-electrical conversion efficiencies. Moreover, whereas BS and CAES are suited for the short-term storage of electricity, hydrogen shows applicability to long-term storage and to a wide range of sizes and power outputs, with charge and discharge rates not dependent to storage tank capacity, [20]. During low power demand periods, excess power can be sent to an electrolyzer to produce hydrogen, which can be later used in a fuel cell for energy production purposes, in high energy demand periods or when solar and wind power are not sufficient or available. Different kind of fuel cells – PEMFC (polymer electrolyte membrane fuel cell), SOFC (solid oxide fuel cell) and MCFC (molten carbonate fuel cell) – have been coupled together and/or with wind turbines and photovoltaic arrays in Ref. [21]. SOFC and MCFC, being high temperature fuel cells, are often used to realize combined heat and power plants [22] and [23], but PEMFCs are particularly suited for applications requiring rapid start-ups and high electrical efficiencies, reliability and durability, [24].

In this paper, a hybrid wind/solar/fuel cell power plant is designed and a possible power management strategy is proposed. In particular, wind and solar energy sources are used as primary power suppliers, while a PEMFC, together with a battery pack, is