Energy 93 (2015) 393–405

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Challenges in load balance due to renewable energy sources penetration: The possible role of energy storage technologies relative to the Italian case

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form
3 August 2015
Accepted 12 September 2015
Available online 22 October 2015

Keywords:
Plant flexibility
Plant cycling
Energy storage
Grid imbalance

ABSTRACT

With the rapid growth of the electricity produced by RES (renewable energy sources), especially those highly variable and unprogrammable (e.g. wind and solar power), the need of energy system flexibility increases significantly.

Since RES currently represent a significant fraction of the power supply, their variable nature poses challenges to power grid operation, such as RES curtail and loss in global efficiency of thermoelectric plants, since they are often operated at part-load as fluctuating back-up power.

In particular, thermoelectric plants recently moved their role from base-load power to fluctuating back-up power. Such a cycling operation represents a less obvious effect of grid flexibility requirement due to RES penetration. Main effect is the increment of both energetic costs, due to reduced efficiency operation, and wear-and-tear costs.

This aspect is deeply analysed in reference to the Italian electricity generation mix in the period 2008–2012. Moreover, the possible coupling of energy storage systems with thermoelectric plants is highlighted as an alternative solution respect to retrofitting of existing plants.

1. Introduction

In the next years, a rapid growth of renewable sources exploitation is foreseen in order to cover with renewable sources up to 20% of the final energy consumption in 2020 and an even larger share by 2050 [1]. In fact, RES (renewable energy sources) technologies are expected to take the leadership in the forthcoming energy generation portfolio in order to achieve a sustainable energy generation. Anyway, their utilization is slowed down by the characteristic intermittency and the fluctuating trend and, moreover, by the inadequacy of electricity networks. To ensure such a penetration, electricity systems need to be flexible in order to balance at every moment generation and consumption.

In some European countries (Denmark, Spain and Germany) the renewable energy share has already exceeded 20% [2], highlighting critical issues such as grid congestion and perturbation [3,4] due to the large number of highly unpredictable, intermittent and fluctuating power plants [5]. Moreover, in order to mitigate the serious concerns indicated above, RES are curtailed during low consumption periods limiting the exploitation of renewable power plants.

What above represents the critical issues, relative to the RES exploitation, usually analysed in literature [6–10] together with the possible solution identified in ESS (energy storage systems) integration, mainly contributing to:

- grid reliability improvements thanks to the reduction in both fluctuating energy delivered to the grid and energy absorption from the grid (leading to mitigation of grid overload);
- reduction in curtailment of unprogrammable renewable energy generation due to network constraints;
- deferring investments of grid improvement.

A further negative aspect to overcome is the RES impact on thermoelectric power generation. In literature, few articles deal with RES implications on conventional power generation; however, some specific studies on wind variability and its effect on traditional generators are available. A model to estimate emissions from fossil fuel generators used to compensate variable wind and solar power is presented in Ref. [11]. Specifically, a quantification of CO_2

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http://dx.doi.org/10.1016/j.energy.2015.09.057
0360-5442/

Nomenclature

E_{st}	energy stored (MWh)
H_{eq}	equivalent operating hours (h)
M_{dp}	mean delivered power (MW)
P_{CC}	electricity production (GWh)
P_{CC_2012}	electricity production of 2012 (GWh)
P_g	gross electricity production (GWh)
W_g	gross installed power (GW)

and NOx emission is provided considering natural gas turbine as power technology used to compensate variable renewables. An interesting model of wind/gas/energy storage generation systems, described in Ref. [12], demonstrates a method for integrating significant quantities of wind energy while reducing power fluctuations, showing the financial feasibility of the solution in relation to the produced wind energy.

In the present paper, the particular issue of RES impact on conventional power generation is analysed with particular attention to the Italian scenario. As detailed in the following, in order to overcome the grid balance problem due to the difference between energy generation and consumption, part of the Italian thermoelectric plants were managed in the last years as backup of RES. The consequent significant negative effects on thermoelectric generation performance are deeply investigated in this work. In fact thermoelectric plants, with particular reference to CC (combined cycles), are operated as part-loaded plants, which can be ordered to increase or decrease output as required, and generally subjected to hot and cold stand-by periods. This cycling operation causes a significant reduction in electric efficiency (CC plants exhibit the greatest efficiency degradation when operated in part-load conditions [13,14]) and thermal/pressure stresses resulting in a relevant wear-and-tear damage [15,16]. These aspects bring about an increasing of fuel costs and O&M costs due especially to more frequent repairs, reduced component life and more frequent forced outages [15–18].

Therefore the cycling aspect, or rather the power output variation due to starting up, shutting down, ramping up and down [17], is a central issue consequent to the increasing penetration of RES in the electricity generation system [19].

During power plant cycling, as anticipated, components suffer of large temperature and pressure stresses than lead to accelerated component failures and forced outages [18]. Consequently, costs associated with power plant cycling, widely studied in literature [17,20,21], are due to five significant components [20]: capital replacement costs and maintenance cost, cost of forced outages due to cycling, capital replacement costs and maintenance cost related to load following, cost for fuel, CO_2 emissions and auxiliary services during start-up, beyond that cost for decrease in rated efficiency.

For what above the research of solutions that can mitigate problems caused by cycling became crucial. To this regard, preclusions relate to any solution that requires the construction of new power plants, due to the already too large installed power and further curtailment of RES. Therefore, the most plausible solutions are identified to act directly on the existing power generation facilities. A potential approach is, in fact, the retrofitting of existing power plant [22]. Recent improvements [23] regard the operation flexibility enhancement (i.e. faster re-start and ramp faster within a wider load range) and, preliminarily, solutions to increase efficiency at part load and mitigate thermal and pressure modulation varying load condition [24].

Therefore, in this paper an alternative solution is proposed and preliminarily analysed. In particular, the ESS (energy storage systems) integration with large thermoelectric plants (specifically combined cycles) is proposed. This solution could allow operation in conditions closer to the nominal ones, obviously reducing cycling and consequent penalties indicated above. In other words, the energy surplus generated by CC plants, that can work close to nominal conditions, can be stored by ESS avoiding their continuous shutdown and restart.

At system level, no previous studies are available regarding the analysis and quantification of efficiency penalization on the thermoelectric sector due to RES penetration. In the research work herein presented, CC plants part-load operation, as RES backup, and related efficiency are evaluated by using quantitative parameters. In particular, the analysis is carried starting from the analysis of operation data of the whole Italian thermoelectric power generation sector with reference to the period 2008–2012 (Section 2), by analysing performance of single plant technologies (Section 3). Consequently, the impact of RES exploitation on the thermoelectric generation efficiency is evaluated, relative to the Italian case, in terms of primary energy penalty. Basing on these results, a reference management strategy of CC plants is identified (Section 4); moreover the impact of their possible coupling with ESS is quantified limited to the advantages related to fuel and wear-and-tear costs.

2. Material and data analysis

2.1. Analysis of production and fuel consumption of the whole thermoelectric power generation sector

In this section data relative to installed power and energy production of systems connected to the Italian grid are described and analysed. The source is the annual reporting of Terna, the Italian energy TSO (Transmission System Operator). Specifically, reports relative to the years from 2008 to 2012 were considered. In this period, the number of unprogrammable renewable power plants increased considerably.

To this purpose, Fig. 1 shows the trend of the installed power in the period from 2008 up to 2012. As it can be seen, against a general invariance of thermoelectric and hydroelectric installed power and against a slight gain in the wind energy exploitation, there is a significant increase in PV (photovoltaic) power installations, which grows from 430 MW in 2008 up to 16,420 MW in 2012. Cause of this trend can be related to the important policy mechanism, introduced by Italian Government in February 2007 [25–28], designed to accelerate investment in PV technology with a feed-in premium. This incentive campaign ended in July 2013 (for new installations) with the simultaneous depletion of state funds allocated to incentivize those power plants.

Within the thermoelectric sector, as highlighted in Fig. 2, CC (combined cycle) technology has the leading role with a higher than 45% share of the installed capacity in the years 2011–12. Moreover, it can be noted that the installed capacity of CST (condensing steam turbine plants) dropped by 5%, from 2008 to 2012, whereas the installed capacity of RP (repowered power plants), GT (gas turbines) and ICE (internal combustion engines) was left unchanged. Even with such a sharp decline in installed capacity CST power plants are still the second power generation technology in Italy.

In order to further analyse the evolution of the thermoelectric sector in the observed period, data about production, consumption and efficiency are provided hereinafter. Figs. 3 and 4 show, respectively, gross and net produced electric energy for each kind of fuel used in thermoelectric plants. For clarity, gross production is