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Energy storage for PV power plant dispatching

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ABSTRACT

Energy from the sun is weather-dependent. In modern electric grids that is a shortcoming; generation (and load) has to be regulated accordingly. This issue is a cornerstone for an effective transition to a renewable-based energy system. Weather forecast algorithms can predict photovoltaic production but, in real life conditions, their reliability is only partially effective with respect to the actual grid operation requirements. In the paper, Energy Storage Systems are adopted to compensate the mismatch between the injections of a photovoltaic power plant and the day-ahead market power schedule: the final goal is to achieve the full programmability of the photovoltaic resource by minimizing energy imbalances, as defined in the Italian regulatory framework, on an hourly basis. In particular, the optimal design of the storage apparatus (nominal power and capacity) is defined according to the regulating performances required. Moreover, three forecast models are tested to evaluate the impact of weather prediction accuracy on the ESS design. Finally, the benefit/cost ratio of the ESS application is assessed according to the main economic and technical parameters (ESS cost, round trip efficiency, lifespan). The analyses are performed on data measured on a real power plant, with hypotheses consistent with the actual Italian scenario.

1. Introduction

Renewable Energy Sources (RESs) are a key driver for a new, sustainable, energy ecosystem. Nevertheless, RESs introduce some drawbacks in the operation of electric networks, which must be properly addressed in order to avoid deteriorating power quality, reliability and supply efficiency [1,2,40]. In particular, one of the main RESs issues is their unpredictability, which reduces the programmability of the energy flows on networks. The energy balance between load and generation has to be respected in real time, acting on the injections of some flexible power plants able to accept dispatching orders from the system operator (i.e. conventional generators). Increasing cost in the selection of conventional power plants is being caused by the rising RES exploitation and the consequent production fluctuations, in order to respect the operational security margins of the system. In fact, in the past, (cheap) base load power plants (e.g., coal, fuel oil, etc.) could satisfy most of national load requirements, thanks to the small daily/seasonal variability of the load profile; in addition, being the energy consumption easily predictable, only a small amount of dispatching resources were collected from (expensive) peaking power plants (e.g., natural gas, etc.). Today, the situation is substantially different: the increased variability of load profiles, often incompatible with the operating constraints of base load power plants, together with the need to compensate in real time RESs fluctuations, caused a rising exploitation of peaking power plants [3]. Consequently, in the last few years, the improvement in dispatch capability of RESs and their better coordination with the other production (and consumption) resources is of increasing interest. Presently, in the liberalized markets (e.g., in Italy [4], Germany [5], Spain [6] and UK [7]), if RES power plants do not meet the submitted schedule for output power, they face financial penalties. In Italy, if mismatches between actual and scheduled production exceed the given tolerance, the energy injections out of the tolerance band are charged of imbalance penalties, with an approach similar to that applied to conventional generators. However, on the contrary of conventional power plants, which can be dispatched conveniently to meet the submitted schedule, non-programmable RES generators cannot avoid penalties. The unique way the user has to prevent undesirable imbalance costs is to adopt suitable expedients to make the RES power plant more programmable. In order to achieve such a challenging target, Energy Storage Systems (ESSs) are one of the most promising options.

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Nomenclature

ANN	artificial neural network
BCR	benefit/cost ratio of the investment
DG	dispersed generation
DR	discount rate
ESS	energy storage system
FM	forecasting method
LRWF	linear regression and weather forecast
NNWF	neural network and weather forecast
PV	photovoltaic
RES	renewable energy source
SRC, *SRP*	storage rated capacity/power
E_t	energy stored in the battery, expressed with respect to the storage rated capacity, at the hour *t*
EI_t	energy imbalance affecting the PV production at the hour *t*
c^C	ESS CAPEX coefficient w.r.t. the energy capacity
c^E	energy price, assumed constant over time
c^F	ESS deployment fixed costs
c^I	imbalance penalty applied to the amount of energy exceeding the tolerance limit
C_t^I, $C_t^{I\_ESS}$	imbalances penalty applied to the user, without and with ESS, at the hour *t*
c^P	ESS CAPEX coefficient w.r.t. the nominal power
e_t^{UP}, e_t^{DW}	imbalances affecting the PV production exceeding the tolerance threshold, at the hour *t*
$e_t^{UP\_ESS}$, $e_t^{DW\_ESS}$	residual imbalances after the ESS compensation exceeding the tolerance threshold, at the hour *t*
G_t	linear regression proportionality coefficient between the PV power production and solar radiance, at the hour *t*
heq	PV plant equivalent hour of operation at the nominal power
I_t	forecast of solar radiance at the hour *t*
η^C, η^D	ESS charge and discharge efficiency
ρ_t^C, ρ_t^D	charge and discharge rates of the ESS at the hour *t*
$\rho_t^{C\text{-}MAX}$, $\rho_t^{D\text{-}MAX}$	maximum charge and discharge rates of the ESS according to the technical limits
$\rho_t^{C\text{-}REF}$, $\rho_t^{D\text{-}REF}$	ideal charge and discharge rates
$\rho_t^{C\text{-}TOL}$, $\rho_t^{D\text{-}TOL}$	maximum ESS injections, positive or negative, that cause no imbalances (e.g., to keep the energy stored in the battery at the reference value), at the hour *t*
p_t^E	estimated power production of the PV power plant at the hour *t*
p_t^{AM}	average measured power production of the PV power plant at the hour *t*
Tol	tolerance admitted for the prediction

The paper focuses on the Photovoltaic (PV) dispatching feasibility by the exploitation of electricity production Forecasting Models (FMs) and ESSs. In particular, Section 2 reports an analysis of the literature, with a discussion about several issues relevant for the problem under study; Section 3 describes the approach proposed; Section 4 focuses on the forecast models adopted in the work; Section 5 illustrates the ESS design procedure developed; Section 6 reports the numerical applications performed on a real PV power plant; in particular, the performances of the FMs adopted are described. The results depicted in Section 6 are used in Section 7 to apply the ESS design procedure; the economic feasibility of the investment involving the ESS is assessed w.r.t. the main economic and technical parameters in Section 8; finally, some conclusions are provided in Section 9.

2. Related works

RES dispatching affects several areas, ranging from production prediction methods (typically based on weather forecast procedures) to regulatory issues, while technological aspects related to PV generation, ESS design and storage technologies have to be addressed, too.

Regarding forecasting, the RES production related to PV power plants has been addressed in several papers and projects. In particular, PV prediction requires the estimation of both the weather conditions (first of all the solar radiation) and the PV modules parameters (to evaluate the production efficiency).

In the literature, different methods have been proposed for the production estimation: in Ref. [8] ARIMA models, k-NN models, ANN and ANFIS models are used to assess the production based on a numerical prediction model and on historical data, in Ref. [9] Medium-Range Weather Forecasts and a detailed PV simulation model are exploited, while in Ref. [10] a Multi-Layer Perception network is used. Despite the accuracy of these methods in estimating PV production, the wide set of data about weather and PV plant that they require could be an issue, especially where small users (domestic users) are involved. For example, in Ref. [8], surface sensible and latent heat flux, surface downward shortwave and longwave radiation, top outgoing shortwave and longwave radiation, and temperature are used to estimate PV production up to 39 h in advance. In Ref. [9], to refine the irradiance forecasts provided by the ECMWF model (e.g., by spatial averaging and temporal interpolation, improved clear sky forecasts and post processing with ground data) deriving site-specific hourly forecasts, additional data about the PV plant are needed, such as location, orientation and PV panels characteristics. Similarly, in order to evaluate the PV production of the next day, the Multi-Layer Perception model proposed in Ref. [10] processes global radiation (subdivided into direct, diffuse and ground-reflected radiations), pressure, nebulosity, ambient temperature, (peak) wind speed, wind direction, sunshine duration, relative humidity and rain precipitations.

In conclusion, nowadays, there are many models able to provide good PV production estimations, however they do not seem to be decisive: they typically require a wide set of information about the PV power plant technology, its installation site and the weather conditions acting on it [11]. Therefore, reliability for "on field" uses might not be as good as depicted in theoretical studies.

In order to guarantee the real feasibility of PV dispatching, ESSs are today identified as the most promising solution. In Ref. [12] a general overview about the applicability, advantages and disadvantages of various ESS technologies for large-scale RES integration is provided.

Typically, the literature has focused on ESSs coupled with wind power plants [13]: this is because wind farms have rated power up to hundreds of MW, i.e. they significantly impact on the energy flows on the main grid. Unfortunately, wind production is quite intermittent resulting in a complex (expensive) ESS design. PV production forecast is more effective; consequently, the use of ESSs for this application is increasingly considered a feasible option [14].

Today, coupling PV power plants with ESSs is being widely discussed, from both the regulatory point of view (incentive schemes and economic feasibility), and the technical point of view [15–19,41]. Focusing on the issues under analysis [20], and [21] report a detailed energetic analysis of ESS design in order to