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Distribution networks' observability: A novel approach and its experimental test

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HIGHLIGHTS

- Delivery to the TSO of real-time estimations of DER generation on a primary substation.
- Real-time monitoring of a limited set of power plants by always-on communication.
- Automatic Meter Reading used ex-post to collect energy measurements on users.
- Weather nowcasts to improve estimation accuracy.
- Approach best performing with solar source, but showing good accuracy also with other DERs.

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ABSTRACT

The work presents an approach devoted to improving the observability of distribution systems with a high share of Renewable Energy Sources. The proposed method, developed according to the prescriptions of Italian Resolution 646/2015/R/eel, but designed to be applied in any modern power system, provides the delivery to the Transmission System Operator of real-time estimates of the overall generation downstream an HV/MV substation. The estimation process is based on the real-time monitoring of a limited set of power plants, completed by the acquisition of weather nowcast and energy measures collected on users through the standard Automatic Meter Reading infrastructure. The approach, tested on two real Italian distribution networks, and benchmarked against an Artificial Neural Network based approach, showed a good accuracy, allowing the provision of useful information to the TSO through a simple and easy to implement architecture.

1. Introduction

The increasing share of Renewable Energy Sources (RESs) and the EU targets for the reduction of greenhouse gas emission impose a rethinking of the strategies by which power systems are designed and managed. In presence of non-programmable energy sources, novel approaches, supported by a proper evolution of the regulatory context in force, become essential to ensure adequate levels of flexibility, reliability and efficiency of the power system operation [1,2]. In this perspective, an effective coordination between the procedures adopted to manage the High Voltage (HV) system and those implemented at the distribution level is pivotal [3]. This fact is evident in the energy systems subject to a massive renewables penetration, where Transmission System Operators (TSOs) are encountering increasing difficulties in ensuring the system power balancing, due to the lack of data about the actual state of Distributed Energy Resources (DERs) connected to Medium Voltage (MV) and Low Voltage (LV) networks. Under the Third Energy Package directives, however, European electrical networks are subject to unbundling requirements which oblige Member States to ensure the separation of vertically integrated energy companies: this results in a decoupling of the various stages of the energy supply chain (generation, distribution, transmission and supply) [4]. Therefore, in this scenario, one of the main challenges is the development of tools to support an effective coordination between TSOs and Distribution System Operators (DSOs) [5,6]; this coordination is possible only through the exchange of proper information between the HV and MV systems [7], able to characterize the system operation with respect to both the real-time management and the short-term perspective.

In such a context, the Italian Energy Authority (Autorità per l'Energia Elettrica il Gas ed il Sistema Idrico, AEEGSI), through the

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Nomenclature

SaPP: a (Satellite) Power Plant not provided with a real-time metering system;
SePP: a (Sentinel) Power Plant provided with a real-time metering system;
$P_{i,t}^{sat}$ and $E_{i,t}^{sat}$ are the active power and quarter-hour active energy of the ith SaPP of a given technology estimated at time t;
$P_{m,t}^{sen}$ and $E_{m,t}^{sen}$ are the active power and the quarter-hour active energy measured on the mth SePP of a given technology at time t;
P_t^{PS} is the active power measured in the primary substation at the interface with the High Voltage system at time t;
$P_i^{sat,rated}$ and $P_m^{sen,rated}$ are the rated powers of, respectively, the ith and mth SaPP and SePP of a given technology;
P_t^{DER} is the power production estimated on the distribution network for a given electricity generation technology at time t;
$P_t^{DER,tot}$ is the overall power production from Distributed Energy Resources estimated at time t;
P_t^{Load} is the overall load estimated on the network at time t;
$E_{i,t}^{sat,AMR}$ and $E_{m,t}^{sen,AMR}$ are the quarter-hour active energies measured by the Automatic Meter Reading, respectively, on the ith and mth SaPP and SePP of a given technology at time t;
$\sigma_{m,i,p}$ is the mean square error evaluated between the production of the mth SePP and the ith SaPP, according to the metering data collected at the pth hour of the day;
$k_{m,i,p}$ is the proportionality coefficient minimizing the mean square error between the power profile of the ith SaPP of a given technology estimated using the mth SePP of the same technology, according to the historical data collected at the pth hour of the day;
α is the coefficient adjusting the degree of filtering of the SePP power profiles according to the historical error;
M is total number of SePPs of the same technology and representative of the behavior of the ith SaPP;
I and N are the total numbers of SaPPs and SePPs of a given technology on the distribution network;
I' is the total number of verifiable SaPPs (i.e. quarter-hour measured power plants) of a given technology;
T_p is the set of time steps belonging to the pth hour of the day.

Resolution 646/2015/R/eel [8], recently promoted the implementation of innovative functionalities aimed to improve the management of the energy networks in the presence of DER generation. The service named "OSS-2" is relevant to the observability of power flows and state of DERs on MV/LV grids and aims to support the TSO in managing more effectively the RES intermittency thanks to a reliable estimation of the DER production in each bus of the transmission system. The service prescribes the delivery to the TSO of real-time (20 s sample time) estimates of the overall DER production downstream each primary substation. The estimates have to be grouped according to the relevant DER: PhotoVoltaic (PV), hydroelectric, Combined Heat and Power (CHP). In spite of the fact that the OSS-2 functionality has been conceived within the Italian regulatory framework, it can be applied to the interface TSO/DSO of any electric power system. Data delivered to the TSO are beneficial because they can be exploited for the power system balancing, ensuring an optimal selection of regulating resources: TSOs, according to EU ENTSO-E Grid Code [9], shall in fact dimension frequency and replacement reserves on the basis of the principle of covering remaining imbalances that, estimated through a probabilistic approach, are deemed likely to happen in the future. Therefore, the greater are the uncertainties affecting DER production estimates, in real-time and in advance, the greater are the amounts of reserve and regulation resources that have to be collected by TSO on the Ancillary Services Market (ASM), and consequently the greater are the costs incurred by the system. As a result, with the increasing share of RESs, in the last years, the need for novel tools supporting TSO in performing a cost-effective collection of regulating resources on ASM rose. Through the OSS-2 data, the TSO will be able in the future to know the amount of RES production (and load) in each node of the HV system and accordingly to define the optimal strategy to manage the power system (e.g., congestion relief, selection of N−1 operational criteria, voltage regulation, etc.). This can be considered a great improvement if compared to the present situation, in which only the residual power exchange measured at the HV/MV interface is monitored, resulting as the difference between the local DER production and the MV/LV load (both quantities unknown in real-time in their actual value). Moreover, the differentiation of DER estimates according to the relevant production technology will allow the system operator to take into account the degree of intermittency and uncertainty of each technology during the collection and dispatching of regulating resources. In periods with high shares of PV and wind generation, for example, frequency/balance reserve to purchase on the ASM is greater than that required when the (more predictable and less intermittent) hydro and thermal generation is overcoming. The main objective of the proposed tool is to support the TSO in managing the High Voltage (HV) network; however, it is also beneficial for the DSO: providing an estimation of the active power injected by DER units, it represents a useful starting point for any algorithm aimed at performing a state estimation of the distribution network and optimizing its operation (voltage control, losses minimization, etc.).

Today, the computation of accurate and reliable estimations of DER generation is a main challenge for DSOs due to the scarce measurements available. In the future, advanced monitoring infrastructures will allow DSOs to formulate very accurate estimations of the actual and expected behavior of loads and generators on the MV/LV grid [10]. This is the direction mainly investigated in the literature, which implies to carry out a state estimation of the distribution network, often based on the detailed knowledge of the actual grid topology and of the exchange profiles of final users [11]. In [12], for example, the measurements (half-hour sampling time) collected on 384 residential smart meters are used to evaluate the voltage profile (magnitudes and angles) at each busbar of an LV network. While in [13] a state estimation model structured in two time scales is applied to a 15 kV test network, but, in this case, the 24 h active power consumptions are supposed to be known in all the 100 buses of the system. In [14], authors highlight that the state of a distribution network can be effectively estimated exploiting a method based on the transformation in a sparse domain of the voltage profile; however, the method requires the use of experimental micro-phasor measurement units (μPMUs) to be applied.

The implementation of the pervasive monitoring infrastructure needed for the distribution systems state estimation is complex and expensive; therefore, its deployment can be expected reasonably only in the long-term. As a consequence, the Italian Energy