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Performance based approach for electricity generation in smart grids

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HIGHLIGHTS

- An approach to include performance indicators in electricity dispatching is proposed.
- The analysis is based on the operational data of existing power plants.
- The results are a support for smart grid optimization algorithms and energy planners.
- The variability of operation conditions requires detailed time steps in the analyses.

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ABSTRACT

The Power Grid balance requires the organization of multiple supply plants to match the electricity demand of the users', starting from the most accurate forecasts available and with the need of continuous adjustments based on the actual demand profile. The power dispatching is currently based on a day-ahead wholesale market, which fixes an hourly price based on the offers and bids of producers and buyers. In this paper an alternative approach is proposed, with the integration of performance indicators of the electricity generation plants. Optimization algorithms at the base of Smart Grids operation could support a multi-objective approach that overcomes a simple economic optimum. The aspects that have been considered are the renewable energy share, the primary energy consumption, the global emissions (i.e. CO_2) and the local emissions (i.e. NO_X, CO, PM, etc.). A precise calculation of these performance indicators is proposed for three real natural gas combined cycles, and the results are compared with the average data for the electricity produced in Italy and supplied to the Power Grid. The strong variability of those indicators highlights the importance of performing detailed analyses with up-to-date actual operation data, as the evolution towards sustainability targets in Smart Grids require an integrated approach.

1. Introduction

Smart grids are facing the challenge of providing an enhanced capability of optimizing the entire energy system by allowing a growing integration of non-programmable Renewable Energy Sources (RES) in substitution of fossil-based power generation units. These developments are supported by the worldwide growing interest in limiting the climate change caused by CO_2 emissions, as well as decreasing the dependence on fossil fuels for geopolitical concerns and local pollution problems (related to NO_X, CO, PM and other emissions).

Smart grids development will need to face multiple aspects, including: a resilient operation against failures or attacks; the active participation of consumers through demand response; the warranty of power quality and disturbances reduction; the inclusion of all generation and storage options; the development of new products, services, and markets; the optimization of assets and an efficient and smooth operation [1]. The facilitation of RES integration into the electricity mix will need to face a number of issues, which are not limited to a technical domain. The participation of actors should be supported by institutions, which need to provide flexible regulations supporting the contributions of end-users [2].

The transition towards smart grids requires tackling a significant complexity, as the energy systems optimization entails multiple actions to be performed by different stakeholders [3]. The balance of the network is accomplished by short-term and long-term actions on the supply side, the demand side and the network itself [4]. The current balance system in the majority of countries is still relying on the availability of large, centralized and programmable fossil-fueled power plants able to operate in reserve and integration markets where the mismatch between forecast and actual demand is fixed. This process is currently leading to some redundancy and inefficiencies, and it needs structural actions to be adapted to a power network that is migrating towards an increasing share of distributed generation from RES.

Multiple solutions have already been proposed to create synergies

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with the local distributed generation system. Energy storage technologies provide significant opportunities for smart grids, as they are uniquely suited to respond quickly and effectively to demand and supply variations [5]. The storage value increases when a large share of distributed generation is operating in the grid, as there is a larger mismatch between the production and the demand [6]. An alternative approach can lay in the demand response: organized groups of users can choose to modify their consumption patterns based on optimization schemes that aim at optimizing the whole grid operation [7]. The energy management of demand-side users is subject to spatially and temporally coupled constraints, and it requires complex algorithms to provide optimum configurations [8].

Two additional possibilities are the aggregation of distributed generation from RES into virtual power plants and the sector coupling. Virtual power plants allow the integration of multiple units in a single entity that has the size and the capacity of being integrated in the current schemes of power balance markets [9]. Sector coupling includes different applications that have the common goal of transforming the power excess into other forms of energy, e.g. power-to-heat, power-to-liquids or power-to-gas [10].

All these solutions need to be included into an advanced energy management system, which should guarantee a robust control of the voltage and frequency, and facilitate demand side management and resynchronization [11]. Current power grids are operated by a centralized energy management system, but future Smart Energy Networks will reach a level of complexity that will require distributed management systems. A decentralized management and control energy management system can have important benefits, as multiple microgrids can be managed independently and guarantee higher reliability when facing system failures at different levels [12].

A wise combination of these solutions can meet the requirements of demand–supply balance, but a coherent planning framework should be defined to avoid an uncontrolled development of such technologies. While in the long term these technologies could allow a significant integration of RES generation, in the short and medium term the operation of fossil-based generation units for peak power supply remain unavoidable. Nevertheless, some actions can be performed to optimize the operation of such units. This goal requires a deeper knowledge on the operation of existing thermoelectric power plants under variable external operation conditions. Each technology shows peculiar characteristics depending on part load operation, external temperatures, heat request for CHP units, etc. [13]. Thermoelectric power plants usually allows some flexibility, depending on the fuel and the technology. For this reason, they can be used to compensate the fluctuations of the non-programmable units based on RES. However, attention must be paid on the lower performance of the plants when operating in off-design conditions, as part load operation can lead to higher fuel consumptions and pollutants emissions.

Energy generation scheduling is usually based on a wholesale electricity market, where through bids to buy and offers to sell the match between the expected demand and the scheduled supply is performed. The transition towards smart grids requires a paradigm shift of electricity dispatching, as the increase of parameters and complexity requires the implementation of innovative solutions. Rising shares of renewable sources power plants have an impact on market prices volatility, depending on the type of support scheme grated to RES [14]. Other external measures can impact the power markets, such as environmental and carbon taxes [15]. However, external measures should be carefully planned and tuned to avoid unpredicted effects on the markets, with consequences on the actual power generation mix. System governance needs to evolve to become a driver for innovation in the power sector [16].

This paper presents an alternative approach based on the calculation of performance indicators for the electricity generation, to be used in an electricity market based on a multi-objective optimization. The shift towards a distributed generation would require more complex dispatching algorithms, that could potentially incorporate optimization logics that go beyond a mere economic target. Some indicators are proposed based on the most common sustainability targets (i.e. renewable energy sources, primary energy, carbon and pollutants emissions) and applied to a case study, comparing the performance of some real power plants to the average values of the Italian Power Grid.

2. Methodology

The performance of electricity generation units can be evaluated considering multiple aspects (i.e. energy consumption, type of energy source, environmental impacts, etc.). Each unit shows different operational configurations based on a number of internal and external parameters, and it is important to provide actual data for the calculation of the real performance. A complex Power Grid connected to multiple generation units needs a comprehensive database of operation data from the monitoring systems of the generation units.

Each electricity flow supplied to the Power Grid should be associated to detailed information about its generation process. Reference indicators can be defined to allow a fast and meaningful comparison of different energy sources, technologies and operational conditions. A set of representative indicators are described in the following paragraphs, based on the most common aspects that are currently considered when dealing with the sustainability of energy generation.

The calculation of statistically significant performance indicators can provide a useful tool for the smart grids development, to avoid an optimization limited to some sections of the network, which would overlook the entire conversion system from primary energy to final users' consumption [17,18]. These indicators can be calculated from monitoring data that are usually available for power plants, but a common framework should be defined to perform a standard methodology for the calculation of indicators in each system.

2.1. Performance indicators

The key indicators considered in this study are: (1) the share of renewable energy sources in electricity production, (2) the primary energy consumption in the electricity generation process, (3) the CO_2 emissions and (4) the pollutants emissions (mainly NO_X and CO) [19,20].

2.1.1. Renewable share

The Renewable share (RES_{share}) in the electricity mix can be defined as follows:

$$RES_{share} = E_{el,RES}/E_{el} \quad (1)$$

being $E_{el,RES}$ the electricity production from renewable sources and E_{el} the total electricity production.

The share of RES in the energy mix of a country is being commonly used worldwide as a indicator, to evaluate the dependence from fossil fuels of any energy system. While the policy targets are generally set on an annual basis, this indicator shows a large variability on a daily and seasonal basis, especially for specific sources (solar, hydro) that are related to natural cycles. For this reason, policy measures cannot be developed by considering only annual values, but resources availability and energy demand must be matched with high time resolution. A balanced mix of multiple RES can mitigate the generation variability, and some programmable RES (i.e. biomass, wastes, hydro reservoirs) can support the network flexibility required by the non-programmable sources.

2.1.2. Primary energy factor

The optimization of the energy efficiency of a supply system is often performed by considering its primary energy consumption, and a relevant PEF is calculated to generalize the conversion unit performance on the energy output produced. The Primary Energy Factor can be