Use of Storage

Storage systems

The increased awareness of the environmental impact and of the carbon footprint of all energy sources have motivated the recent widespread adoption of Renewable Energy Sources (RES). However, the intrinsic intermittent and not-schedulable nature of such naturally generated energy introduces a new source of uncertainty in the operation and planning of electric power systems. This poses a critical threat to the power grid since its stability relies on the balance between energy production and demand [1]. Therefore, as the installed capacity of RES keeps increasing, the need to compensate the fluctuations caused by non-dispatchable energy sources has become one of the most compelling driver of research in the power-grid scientific community.

There are many ways to mitigate the variability of power generation from RES. On the one side, there have been many efforts in improving the accuracy of power generation forecasts from renewable sources. Most notably, recent efforts in this direction can be found in [2-3], and in the book [4]. Another possibility to handle the intermittent nature of RES is to use conventional (i.e., dispatchable) power plants as back-up to improve the resiliency and the flexibility of the overall mix of power plants in the power grid. Obviously, this solution brings back the pollution issues, associated with the usage of conventional power plants [5-6]. A further opportunity can be provided by hydro power plants, as they can respond quickly and absorb some of the energy fluctuations; however, hydro resources are limited by their availability and their unsuitability to handle frequent charge-discharge cycles.

According to the previous discussion, there is a general consensus that Energy Storage Systems (ESSs) may provide a viable way to systematically support power generation from RES, as they represent a cost-effective, flexible and quick tool to smooth and regularize intermittent power generation [7]. The next sections describe the main technologies employed to build storage devices, their main applications in power grids, and the main mathematical methods that are used to solve grid-related optimization problems when storage devices are also explicitly taken into account.

Technology

The physical characteristics of a storage system must be adapted to the particular service of interest. For instance, an ESS that has to provide primary frequency regulation will present different characteristics from one that is desired to provide the local supply to a private house. Accordingly, storage techniques can be divided into four categories [8]:

- Low power applications (e.g., transducers, private houses)
- Medium power applications (e.g., individual electrical systems, town supply)
- Peak levelling and network connection applications
- Power-quality applications

For the first two categories, we consider small-scale systems in which energy can be stored in the form of a flywheel (kinetic energy), fuel cells (hydrogen), or supercapacitors. The last two categories are instead large-scale applications and the most used technologies rely on storing the energy in the form of gravitational energy (e.g., hydraulic systems), thermal energy or compressed air. Finally, note that Electric Vehicles (EVs, either in terms of Fully Electric Vehicles or Plug-in Hybrid Vehicles) have been recently assimilated to ESS, due to their ability to behave as a battery when the vehicle is idly connected to the grid. Given the special characteristics of EVs (whose main purpose is clearly to serve as mobile vehicles, and not to serve as batteries), a specific and more detailed discussion about their usage is given here (add a link to the wiki entry to electric vehicles).

For a more detailed discussion on storage technology and their technical characteristics, we refer to [7-8] and to the more recent [9-10].

Technical and economic advantages

The use of ESSs, due to their versatility and flexibility, can lead to a number of advantages for the power grid, both from a technical and an economic perspective. In what follows we list the main services that storage technology can bring. For a more detailed discussion the interested reader can refer to [7-11], and especially to [9, Section 3].

- ***Ancillary services***: ESSs can help regulate the active power supplied by non-dispatchable generation and provide primary frequency and voltage control, therefore improving the transient response of the power grid. This would remove the need to keep expensive dispatchable back-up power generation and would greatly facilitate the penetration of wind and solar power. Examples of technologies in the ESS for ancillary services segment are pumped storage for longer duration applications such as load following, reserve capacity and spinning reserves, or flywheels for high-power, short-duration applications such as frequency regulation.
- ***Energy arbitrage***: ESSs would allow to purchase inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be used as a substitute for the expensive primary power used in peak-load power stations. Alternatively, ESSs could store excess energy production, which otherwise would be lost, from RES. A typical example would be Pumped storage. The principle is that during periods when demand is low, these stations use electricity to pump the water from the lower reservoir to the upper reservoir. When demand is very high, the water flows out of the upper reservoir and activates the turbines to generate high-value electricity for peak hours.
- ***Network savings***: Power consumption during the day is characterized by high fluctuations, meaning that the minimum level of consumption is usually much lower than the maximum daily peak (especially during summer and winter). This leads to over sizing the production units and transmission lines, and the necessary equipment, that are tailored to absorb the peak demand. On the other hand, the usage of local supply in the form of ESS, would help compensating load variations and would make possible to operate transmission and distribution networks with lighter designs, closer to the average daily consumption rather than to the peak demand.

Due to the aforementioned diverse applications, the mathematical problems associated with ESSs that are of utmost interest for the power grid, correspond to their optimal *siting* (i.e., finding the most convenient location where to install them) and *sizing* within the power grid [9]. The next section reviews the most used techniques to address such problems.

Mathematical tools to analyse ESS and the power grid

Different models, with different levels of accuracy, have been developed in the literature to model the functioning of storage devices. The level of detail usually depends on the particular application of interest, and in general on the level of detail with which other power grid devices have been modelled. When accurate models of the batteries are not required, in some cases simple first order linear equation may be used (see [12-14]). Such simple models can be used when one is not interested in the point-wise behaviour of the system (as the low-level electrical behaviour of the ESS is neglected) but, for example, when the aim of the study focuses on the effects of the transient behaviour of a power grid [12-13]. More sophisticated and realistic models can be found in [15-16], where many other low-level details of a storage unit are also taken into account (e.g., life cycle, ageing, dc link, specific technology).

While simultaneous determination of the optimal location and size of ESS is known to be a non-deterministic polynomial-time hard problem (see [9]), yet different strategies have been adopted to tackle it. This includes the use of Monte Carlo simulations, more analytic approaches (like dynamic programming, mixed integer-linear programming and second-order cone programming), and other heuristic methods (e.g., genetic algorithms, particle swarm optimization).

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Contributor

Dr. Emanuele Crisostomi, University of Pisa

Dr. Pietro Ferraro