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Demand flexibility: the unlocked capacity in smart power systems

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Abstract

In the next years, it is expected a deep growth of world primary energy and electricity demand. The scenarios prospect a positive rate in all the sectors, especially in the residential one. In particular, residential sector is one of the major consumer of electricity and this situation will be intensified by the awaiting spread in large scale of electric vehicles and heat pumps.

For what concerns the generation of electricity, the penetration of not programmable renewable energy sources (NP-RES) is significantly increasing, especially photovoltaics resources (PV) are experiencing a large distribution between small consumers, as small commercial and residential. The presented energy scenario is leading the grid operators to face issues in managing the grid due to both the uncertainty in the load profiles and in the generation production from NP-RES. Furthermore, the deeper use of NP-RES, such as PV, introduced new critical situations that must be solved by the grid operators in order to run the system in a safe and reliable way. One of these situations is well depicted in the *duck curve*, which represents the system net load in CAISO (California Independent System Operator), where are highlighted both the *overgeneration risk* and the *high rate ramps* problem. The former occurs when the *net load* is close to the *base load* generation units total capacity, whereas the latter occurs during the sunset in which the PV panel generation decreases quickly, driving the *net load* to increase in a short period of time. The uncertainty, the ramp risks and all the issues related to the strong penetration of NP-RES, led grid operators to involve more balancing generation units with a consequence increase of the energy price. A more sustainable and economic solution is the deployment of flexible resources in the grids, such as energy storage resources and demand flexibility. By using these technologies and techniques, the grid operator can achieve a stronger control on the grid and through their coordination, it can manage the grid in a more efficient and reliable way to face all the events in the grid and guarantee the equilibrium between generation and demand around the clock.

In this PhD dissertation, the focus is on demand side flexibility and how it can be managed from grid operators, from transmission to low voltage distribution grids.

In order to use demand side flexibility, demand response programs (DR) have been introduced. DR programs are mostly diffused in energy markets and therefore they impact on transmission grids in terms of congestions, expected unserved energy (EUE) and loss of load probability (LOLP) parameters. In USA the use of DR resources (DRRs) is well regulated and they actively participate in the energy markets to get economic benefits such as reduction of the energy prices (locational marginal prices). Furthermore, there is a strong regulation about their remuneration (FERC Order No. 745) and as consequence, the presence of DRRs is quickly increasing. DRRs are also involved in emergency situations, for example when grid issues occur. In this dissertation, the focus is on economics DR programs and their impact on transmission grid reliability, economics and emissions metrics. The performed study aims at providing insights into the impacts of deepening penetration of DRRs under different intensity levels in the presence of energy storage systems (ESSs), as pumped-hydro storage and compressed-air energy storage, and wind power plants. The results show that with a high number of DRRs and using the maximization of the social welfare as clearing optimization criterion, the performance of the system in terms of reliability metrics (EUE and LOLP) gets worst, instead in terms of economics and emissions parameters there is a significant positive impact. The research results show that if the number of DRRs is not less than 20% of the total number of the

transmission grid buses, all the metrics (reliability, economics and emissions) are positive, ensuring a relief effect on the system.

If DR programs are well described and regulated in the energy markets and therefore they influence the transmission grid as both scheduled and real time resources, in the low voltage distribution grid, DR programs are still not available by grid operators as balancing or reserve resources. This is mostly due to the high percentage of residential customers in low voltage distribution grids whose daily power consumption is strongly related with their behaviors and they put their comfort on the foreground. Furthermore, the almost total absence of DR aggregators for residential customers and the lack of technological devices make the residential sector be a locked capacity for the distribution system operators (DSOs). Literature and some pilot projects (for instance the European project ADDRESS and the UK project CLASS) aim at investigating the opportunity offered by this sector and exploring techniques and technological solution to exploit its flexibility in balancing the distribution grids. In particular, in literature it is investigated the opportunity to modulate the dwellings power by modifying the supplying voltages, as by using Conservation Voltage Reduction (CVR) technique. This approach is developed according to the relationship between voltage and power, described by the exponential and polynomial model, called ZIP model. In literature, the power modulation is achieved modifying the position tap of *on load tap changer* (OLTC) primary distribution transformer in order to modulate the voltages over the feeders. Even if this approach shows a good level of power reduction in low voltage distribution grids with high penetration of residential units and customers do not notice any lack of quality service in the supplied voltage, the main limitation of this technique is its centralized nature. It is applied to the primary substation and therefore it involves all the customers connected to the grid and since the supplied voltages must be inside the limits set by the standard CEI EN 50160, downstream users are the bottle neck of this technique because they set the lower limit of the voltage regulation.

In this dissertation it is applied a fully decentralize power control (FD-PC) based on a decentralized voltage control in order to achieve the active power modulation by residential end-users when the DSO needs (for instance, when the cables or transformers are overloaded). Voltage modulation can be executed inside a single or cluster of residential units; here a smart home energy management system (SHEMS) to be installed inside a dwelling and able to receive signal from the DSO is suggested, in order to modulate the dwellings voltage using AC/AC converters. The FD-PC is tested on a LV distribution grid and compared with a CVR based solution applied to the secondary distribution transformer. The FD-PC shows better results in terms of power reduction compared with the centralized technique since it applies a different percentage of voltage reduction according to the voltage values measured at the selected points. In this way, it is possible to use all the regulation range set by the standard. In addition, the voltages over the feeders are not directly involved in the voltage regulation as in the centralized technique, therefore the system has better performance in terms of voltage security margins. Another interesting result is obtained in LV grids characterized by low voltage levels (close to the standard lower limit) on the feeders. It is analyzed the case study in which the OLTC secondary distribution transformer is set equal to 1.05 p.u. in order to increase the voltages in the feeders and assure that the upper and lower limits are respected. In this situation, the FD-PC gains better results, providing an active power reduction almost double compared to the base case. All the simulation studies are performed using a Monte Carlo approach in order to define random residential demands and allocation of PV panels, when included in the network. The simulation period is one day and the simulation step is equal to 10 minutes.