MANAGEMENT OF ELECTRIC VEHICLES CHARGING PROCESSES IN A DSO CONTROL CENTER

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ABSTRACT

Today, it is well known that the Electric Mobility is a key point toward a more sustainable transportation system. However, the deployment of Electric Vehicles (EVs) will bring new challenges for the electric power systems, to be properly faced in order to fully benefit of this new strategy of mobility. The paper presents a method, based on a tight interaction between a scheduling policy and a load flow procedure for the real-time management of EVs charge requests. The proposed method aims to limit the peak load and to increase the number of rechargeable EVs. Simulations are carried out on a real electricity distribution system of a medium-sized Italian city.

INTRODUCTION

Nowadays, for a transition of the energy sector toward a low carbon framework, a huge evolution in the transportation sector is envisaged. Transport emits about 24% of all Greenhouse Gases (GHG) in the European Economic Area member countries; 17% of which can be attributed to road transport [1]. To improve the sustainability of transportation, the European Commission adopted a roadmap [2] with the target for 2050 to cut 60% of transport emissions. By 2030, this action is expected to achieve a 20% reduction compared to 2008. In this scenario, Electric Mobility (in the following, e-mobility) will play a main role in the reduction of GHG emissions. From the point of view of the electrical system, however, Electric Vehicles (EVs) deployment is a great challenge. Moreover, in recent years the increasing awareness for the environmental topics, and the consequent spreading of Dispersed Generation on MV/LV grids, introduced further challenges for the power system [3][4]. Centralized management of energy will be replaced by a dispersed approach and, consequently, coordination needs will rise in order to guarantee the same level of quality we have today [5].
This paper proposes a novel approach to manage the e-mobility in a urban scenario deeply affected by EVs penetration: the final goal is to reduce the impact of the EVs power flows on the electric system, minimizing energy losses, reducing peak loads, and increasing the number of EVs that can be supplied by the electrical network, without exceeding the technical limits (voltages, ampacity). The envisaged method schedules the charge processes of EVs connected to the distribution network: the coordination policy is based on control algorithms, in the perspective, suitable to be integrated on the Distribution Management System (DMS) of the DSO (Distribution System Operator). The DMS receives all the information relevant to the charge processes and the energy flows on the MV network, and consequently computes (in real-time) a scheduling strategy for the pending Charging Requests (CRs). The operation of the system is based on the availability of a suitable communication network, essential to perform the necessary exchange of information between the control center and the peripheral devices.
The paper is organized as follows. Initially, the architecture proposed to manage the CRs of EVs is presented. Then, the case study adopted to assess the performance of the developed control strategies (a real Italian MV distribution grid) is detailed, focusing on the modelization of drivers' behavior. Eventually, the results of numerical analyses performed are depicted and conclusions are drawn.

THE ARCHITECTURE PROPOSED

The scheduler implemented in the DSO's control center operates according to the logic reported in Figure 1. When an EV is connected to a charging station, all relevant information is collected and sent (through the communication system) to the DMS. Such information is:

1. the electric power required by the CR;
2. the initial State of Charge (SoC) of the battery;
3. the minimum desired SoC after the charge (fill level);
4. the time before which the CR must be completed (deadline).

The control logic exploits the data collected by the charge point, together with the data about load and generation, and weather forecasts, in order to accomplish an allocation of each EV's CR fitting with the needs of the distribution system. In detail, a load flow procedure is run to check if electrical constraints on the distribution network are met, considering all the CRs previously allocated and the new CR request. The load flow evaluation is performed up to 24 h ahead, taking into account the prediction of the load that cannot be explicitly controlled by the DMS (MV/LV load, dispersed generation). Given this prediction, the control algorithm defines the best time interval, compliant with the deadline specified by the user, to satisfy the CR. This procedure is applied in real-time to each CR.

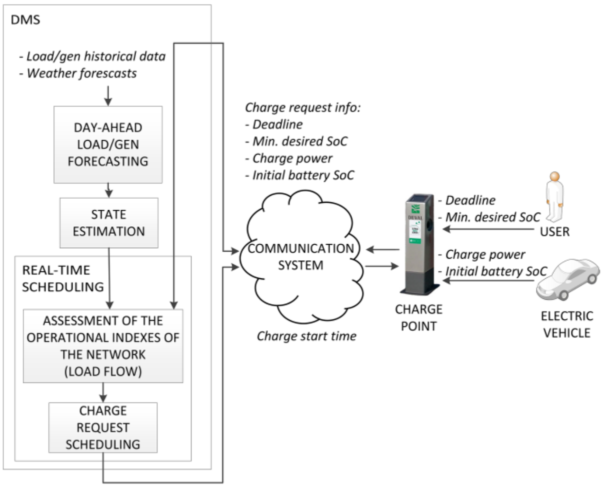

Figure 1. Scheme of the infrastructure proposed.

In detail, the scheduler selects the charge interval such that simultaneous charge processes are avoided, if not strictly necessary: i.e. the logic uses a "valley filling" approach to determine the best candidate starting time. For all time slots of the considered interval, the load flow computes the power exchanges in all buses of the network, assessing possible violations of electrical constraints or overloading conditions. If no violations/overloads are detected, the CR is enabled, filling the battery up to the desired level before the imposed deadline. If violations are forecasted, or the CR happens during peak-hours, the logic tries, if possible (long deadline), to differ the CR. The technical limits taken into account concern the voltage profiles on MV buses and the current transits on lines and HV/MV transformers. In detail, EN 50160 [6] states that voltage profiles on MV/LV networks must be kept within 10% of rated voltage. In this study, voltages are assumed acceptable if included between 96% and 110%. The inferior limit is set to 96% to give an allowance for voltage drops on the LV network. The transit limit is set to 80% of the rated ampacity of conductors and HV/MV transformers, in order to avoid an excessive aging of components and reduction in energy transport efficiency. If the scheduling system cannot find a suitable charging interval according to the technical constraints of the network, the CR is rejected. It is worth noting that the control logic does never modify the schedule of already allocated CRs.

THE STUDY CASE

The control architecture envisaged in this study is designed in a DSO perspective. In particular, the work has been developed thanks to a close cooperation with Deval SpA [7], an Italian DSO having in charge the management of the distribution network of the Valle d'Aosta region, in the North of Italy. Recently, Deval started the project Strade Verdi, aimed at supporting the deployment of the e-mobility in the Alps, through the installation of a network of public and private charging stations, and the use of EVs as company cars (Figure 2). Actually, the control center of Deval has been integrated with some novel features devoted to the management of the e-mobility (e.g., monitoring of the ongoing CRs). The value of the project lies, on the one hand, in fostering a proper standard for the access to the network, ensuring also the integration with respect to the solutions adopted at national level; on the other hand, on the peculiar scenario of application: a mountain region with stringent environmental constraints.

Figure 2. EV deployed in the Strade Verdi project.

In such a framework, the assessment of the performance of the proposed architecture has been carried out on a real distribution network operated by Deval. The network under study supplies the city center and the neighborhood of Aosta, the capital of the Valle d'Aosta region, with a population of 35,000 inhabitants (Figure 3). The MV network has a radial structure, starting from a HV/MV primary substation equipped with two 132/15 kV transformers, each one rated 25 MVA. Each MV grid underlying a MV busbar acts independently of the other, and has 9 and 7 feeders, respectively. The considered scenario refers to a urban area in a mountain region. Therefore, the penetration of dispersed generation is limited: 5 power plants (3 CHP, 1 photovoltaic and 1 hydro) are connected to the MV grid.

Power injections of LV power plants (mainly photovoltaic) are negligible. As for electric calculations, the grid model is implemented in Matlab. All energy flows in the grid are represented on an hourly basis.

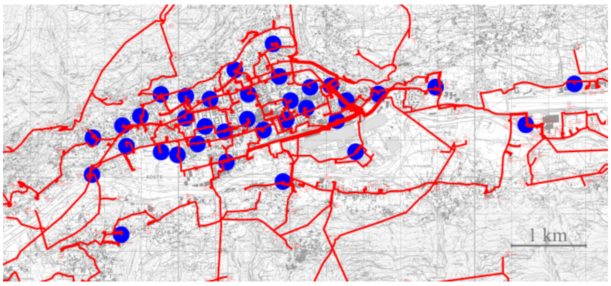

Figure 3. The MV network under study (MV feeders in red; charge points as blue dots).

MV and LV active/passive users are modeled with specific exchange profiles, obtained from historical data measured on the distribution network (e.g. energy exchange profile at the HV/MV interface; historical measures on MV users). Loads and generators are introduced in the model as equivalent power withdrawals/injections at the MV/LV interfaces. According to Italian regulations [8], all loads are assumed to absorb electricity with a power factor 0.9 lagging.

It is supposed that 35 charging stations are installed on the grid. Their location has been defined according to the needs envisaged for users in a scenario of full deployment of the e-mobility in the area of Aosta. Therefore, they are mainly located in the central area of the city, as the residential and industrial districts, and in the airport area.

In order to evaluate the effects of the e-mobility on the power system and the benefits of the proposed scheduling approach, a realistic EV traffic model was developed, aiming at reproducing the common behavior of users. In this model, each EV is associated with its own daily route on the road network. In each simulation, the EV traffic is generated, over one or more days, through a stochastic approach. The main parameter to be set is the penetration level of the e-mobility: i.e., the number of EVs considered in the simulation. According to the model developed, in the morning, each car departs from a charging station where it was parked overnight (Figure 4); in the evening, the car returns to the same station. During the day, cars travel in the city: they can stop in car parks equipped (or not equipped) with charging points. In defining the movement of EVs between car parks, the EV traffic model takes into account the constraints related to the distance from park to park. This approach allows an accurate estimation of the energy consumption of EVs, and of their arrival times to charging stations. The car behavior is shaped according to a set of statistical parameters defined through data collected in real life applications (on the DEVAL car fleet, over year 2011): e.g., daily journey length equal to 39.02 km (standard deviation 10.99 km; minimum value 10 km), average departure time from the base charge point 7 am, arrival time 7 pm; duration of each stopover (on average, 1-2 stopovers per day) defined according to a pdf with mean value equal to zero and standard deviation 0.3 h. As a simplifying assumption, all EVs are supposed to have the same technical parameters: a power withdrawal equal to 20 kW (assumed to be constant during the whole charging process) and a battery capacity of 40 kWh. The energy consumption of the car during use is 0.2 kWh/km.

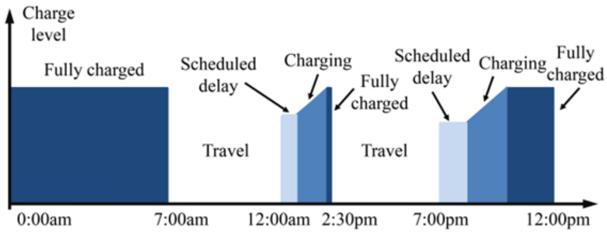

Figure 4. Example of EV behavior, and the corresponding battery's SoC, during the day.

NUMERICAL ANALYSES

The scheduling algorithm to be implemented on the DMS has been tested by the mathematical models developed to simulate the MV distribution network and e-mobility traffic. Simulations have been performed by computing the movements of EVs in the urban area of Aosta and by tracking the batteries' SoC and the users' CRs. The analysis has been carried out with different levels of EV penetration. A total number of EVs ranging from 2,000 up to 20,000 is assumed. Since each EV may require more than one charge during the simulation time, the number of CRs (i.e., the workload) is usually higher than the total number of EVs. Under different workloads, the simulation evaluates the operational efficiency of the grid, the scheduling process efficacy, and the customer satisfaction (full charge accomplished). For each level of EV penetration, 30 different scenarios are simulated. This number of attempts is a suitable trade-off between degree of convergence of results and computational effort. Each simulation is carried out on a one-day time horizon.

Three scenarios are implemented and compared:

- Scenario #1: No scheduling logic - no technical limits. In this case, no scheduling logic is used to manage EVs' CRs. Therefore, battery charging starts when the user plugs the car into a charging station. Moreover, an ideal grid is assumed, able to accept all the EV CRs. This scenario is useful for comparison: it is the best possible condition that could be achieved by adequate investments in network development.

- Scenario #2: No scheduling logic - technical limits in place. This is the reference case (existing system). As above, no scheduling operation is performed. The DSO sheds the load if needed, by inhibiting EVs charging during grid overloading.
- Scenario #3: Scheduling logic - technical limits in place. The EV charging is managed by the logic implemented within the DMS in order to improve the grid operation (avoid overloading and efficiency lowering) and to match user constraints regarding the desired charging time (i.e., deadlines).

A first important factor for the scheduling algorithm performance evaluation is the quality of service guaranteed to users, i.e. the number of CRs accepted, or rejected, due to technical limitations and electrical constraints. Figure 5 reports the average number of CRs that are satisfied in the three scenarios simulated.

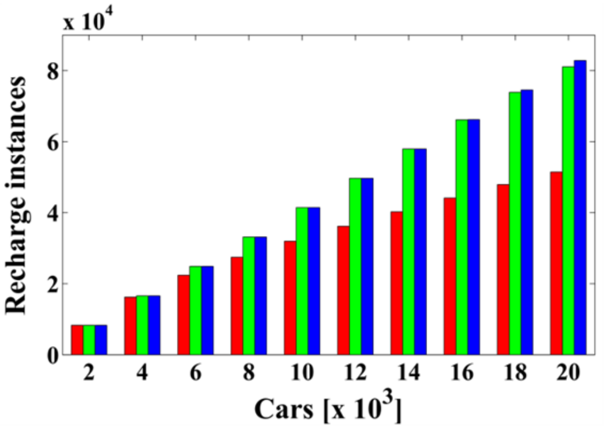

Figure 5. CRs accepted in the EVs' scenarios. The blue bar refers to the scenario #1, the red bar to the #2, the green bar to #3.

The effectiveness of the scheduling logic increases with the EV penetration level. When 2,000 EVs are simulated, there are 10,000 CRs per day. In this case the grid is always able to satisfy all the CRs (with and without the scheduling logic the same results are obtained). If the EVs population grows, the energy flows generated by battery charges can cause violations of the electrical constraints of the grid. Without scheduling actions, some CRs must be rejected to preserve the good functioning of the grid (the instances accepted in the scenario #2 are less than those in the scenario #1). On the other hand, in the scenario #3, the logic schedules EV CRs (according to the deadlines imposed by users) in order to avoid the network overloading and to better fulfill users' needs; in particular, in this case, all the CRs could be satisfied up to a population of 15,000 EVs. For example, with 15,000 EVs (equivalent to about 60,000 instances) nearly 33% of the CRs cannot be accepted without scheduling. If the EV population rises further, some CRs are also rejected in the scenario #3. For example, considering a population of 20,000 EVs (about 80,000 charge instances), the DSO must reject about 2.14% of the CRs, while in the scenario #2 this percentage increases to about 38%.

The actual peak shaving action performed by the scheduling logic is illustrated in Figure 6. Figure 6-a shows the daily profile of the active power at the HV/MV interface of the distribution network in the scenario #2, i.e. the case in which no control action is performed to limit the effects of the e-mobility on the grid operation (only the energy load of the EVs actually charged is considered). Figure 6-b reports the same quantity in the scenario #3.

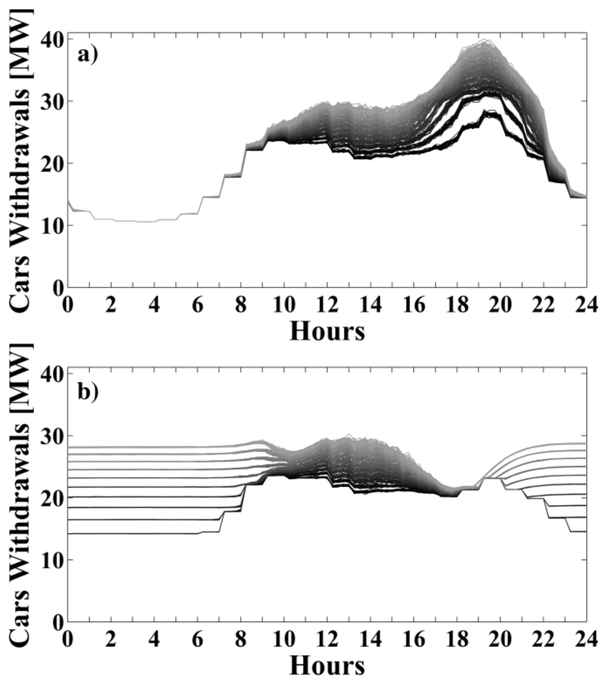

Figure 6. Daily power absorption profile measured at the HV/MV interface of the network without (a) and with (b) scheduling logic (scenario #2 and #3) [MW]. The darker is the line, the smaller is the EVs penetration level.

The comparison highlights that the scheduling action provides a clear improvement on the peak load. For example, in the 20,000 EVs scenario, the daily peak in the case #2 is about 40 MW, while in the scenario #3 is lower than 30 MW. In the latter case, when the e-mobility penetration is great (e.g., more than 4,000 EVs) the load requirements can lead to overload conditions on the grid (violations of transit and voltage limits), especially in the evening. With 20,000 EVs, in fact, the uncoordinated EV charging would bring to a peak load of 50 MW in the absence of adequate counter-measures; therefore, many CRs must be rejected, affecting the quality of service provided to EV users. Using the scheduling logic, i.e. in the scenario #3 (depicted in

Figure 6-b), the nighttime is exploited to better distribute the energy requirements of the EVs charging. In compliance with the deadlines set by users, several EVs' CRs are postponed to smooth the energy exchanges at the HV/MV interface and to avoid the violation of the network technical constraints.

Figure 7 shows the improvement of the network operation in terms of energy losses occurring on MV conductors and HV/MV transformers. The figure reports the daily energy losses in the MV lines conductors and HV/MV transformers according to the EV penetration in the grid, in the three scenarios considered. The scenario #3 presents higher losses w.r.t. the case #2. However, this is due to the higher number of CRs that are satisfied. A better comparison can be performed between the scenario #3 and the #1 (almost the same number of EV CRs satisfied). As reported in Figure 7, the efficiency begins to appreciably improve at low EV penetration levels (2,000÷4,000 cars). It further increases with the increase in the energy flows on the network. For example, considering the case with 20,000 EVs, in the scenario #3 97.9% of CRs (81,057 in Figure 5) are accepted and losses are 6.05 MWh/day, which is 67.3% of losses in the scenario #1. In the scenario #2, only 37.9% of EV CRs are satisfied. In this case, energy losses are 4.8 MWh/day, which is 53.3% of losses in the case #1.

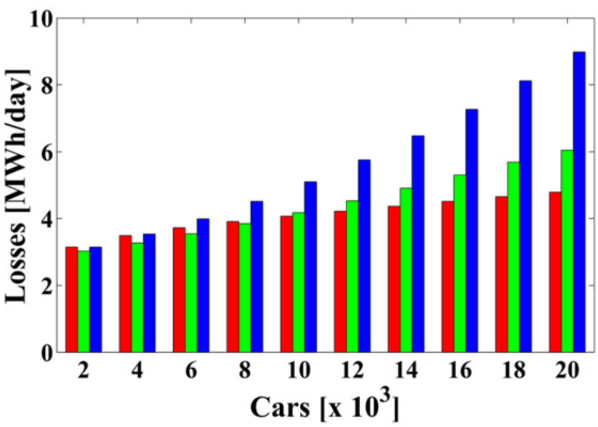

Figure 7. Energy losses in grid conductors and HV/MV transformers. The blue bar refers to the scenario #1, the red bar to the #2, the green bar to #3.

CONCLUSION

In this paper, a novel control strategy to coordinate the charge of EVs on a distribution network is proposed. The strategy envisaged is based on a scheduling approach, which delays the CRs with less binding time requirements (farther deadlines) in off-peak hours (for example, from evening to nighttime).

The numerical analyses performed show that, by this method, a significant peak shaving of the power consumption profile of the electrical network can be achieved, guaranteeing the technical constraints of the distribution infrastructure. Therefore, the investments needed for the network development (refurbishment of MV feeders and HV/MV transformers) can be postponed, improving the exploitation of transmission and distribution assets and generation capacity. In addition, the scheduling of CRs ensures a better quality of service provided to EV users, in fact the number of CRs that can be satisfied is increased (the EV charge is postponed in compliancy with the deadline set by the user). Also the efficiency of the transmission and distribution systems benefits of the e-mobility scheduling, with a significant reduction of energy losses. The experimental analyses show that the computational resources required are quite limited (each CR is processed in real-time, with an average processing time of about 50 ms).

In perspective, this will allow an effective integration of the proposed control logic in the Distribution Management System of the DSO.

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