EV Charging Stations and RES-Based DG: a Centralized Approach for Smart Integration in Active Distribution Grids

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Abstract- Renewable Energy Sources based (RES-based) Dispersed Generation (DG) and Electrical Vehicles (EVs) charging systems diffusion is in progress in many Countries around the word. They have huge effects on the distribution grids planning and operation, particularly on MV and LV distribution grids. Many studies on their impact on the power systems are ongoing, proposing different approaches of managing. The present work deals with a real application case of integration of EVs charging stations with ES-based DG. The final task of the integration is to be able to assure the maximum utilization of the distribution grid to which both are connected, without any upgrading action, and in accordance with Distribution System Operators (DSOs) needs. The application of the proposed approach is related to an existent distribution system, owned by e-distribuzione, the leading DSO in Italy. Diverse types of EVs supplying stations, with diverse diffusion scenarios, have been assumed for the case study; various Optimal Power Flow (OPF) models, based on diverse objective functions, reflecting DSO necessities, have been applied and tried. The obtained results demonstrate that a centralized management approach by the DSO, could assure the respect of operation limits of the system in the actual asset, delaying or avoiding upgrading engagements and charges.

Keywords smart distribution grids; dispersed generation; electrical vehicles; optimum power flow; power flow; planning and operation; renewable energy sources.

1. Nomenclature

Distribution System Operator (DSO); Electrical Sub-Station (ESS); Electrical Vehicles (EVs); Energy Management System (EMS); High Voltage (HV); Low Voltage (LV); Medium Voltage (MV); Objective Function (OF); On-Load Tap Changer (OLTC); Optimal Power Flow (OPF); Power Flow (PF); Photovoltaic (PV); Renewable Energy Sources based (RES-based) Dispersed Generation (DG).

2. Introduction

Renewable Energy Sources based (RES-based) Dispersed Generation (DG) and Electrical Vehicles (EVs) charging systems are key components on the way to more sustainable electrical power systems. The European policies on environmental and energy sustainability enforce a diffusion of RESs and EVs that is ongoing in all the European Countries. Simultaneously, the EVs spread is happening for many reasons: the growth of fossil fuels prices, the problem of the urban pollution and thanks to the progress on the technologies of storage. It is well known that the EVs and RES-based DG diffusion has huge effects on the distribution grids planning and operation, particularly on MV and LV distribution grids. A number of studies on the impact of EVs on the power systems have been performed, highlighting the importance of focusing on detailed aspects of the matter, e.g. new planning methodologies, operation standards and charging managing structures, usually containing probabilistic methods [[1]-[6]]. The interaction of EVs and RES within a smart grid environment is discussed e.g. in [[7]-[9]]; a review is presented e.g. in [[10]]. In addition, a number of studies focus on the European context. Reference [[11]] investigates the influence of EVs charge on a typical distribution grid in Hungary, taking into account charging scenarios and penetration levels. Reference [[12]] compares approaches for the EVs spread in Italy and Norway. The integration of EVs into a smart grid requires both hardware (infrastructures and ICT) and software (control strategies) advancements; this is discussed e.g. in [[13]], where possible solutions are presented. A focus on charging stations is presented e.g. in [[14]]. The coordination of EVs charging has been investigated, e.g. using fuzzy logic [[15]-[16]], in order to mitigate the impact on grid utilization. On the other hand, EVs charging has been regarded as an opportunity for users, as in the Vehicle-to-Grid approach [[7], [17]-[19]]. Recent papers investigate details of this concept, e.g., models for the simulation of EV utilization [[20]], coordinated charging for time-of-use price [[21]], effect of EVs penetration on system reliability and use of response resources for further penetration [[22]]. The common task of the proposed charging managing approaches is the deferral of distribution grid advancements, through exploitation management.

On this context, the originality of the present work is to suggest, and to prove on a real distribution system, the value of a smart management approach of EVs charging stations, also coordinated with DG, mainly RES-based. The proposed approach can be used by a DSO for guaranteeing the extreme use of the power system, without additional investments of its own structure. It is essential highlighting that the proposed approach is founded on the DSO viewpoint. The basis of the proposal can be so summarized: if the DSO itself or an outdoor service provider, by means of an economic contract with the DSO, is the owner of EV charging system, there could be the auspicious chance to modify the available power amount in the charging points that are linked to the unrespect of grid operation limits. The final task is to avoid additional expenses for advancement on the system. To check the anticipated approach and its welfares from DSO perspective, Power Flow (PF) and Optimal Power Flow (OPF) simulations have been used for the application to an existing distribution system of e-*distribuzione*, the most important Italian DSO.

The work includes 6 paragraphs. Paragraph 2 describes the approach proposed and show PF and OPF algorithms applied for testing it on a real system. Paragraph 3 includes the main figures of the case study, concerning electrical grid topology and its operation data. Paragraph 4 deals with different types of EVs charging stations and their spread scenarios. Paragraph 5 summarizes the results, and finally paragraph 6 reports the conclusions.

3. Proposed Approach and PF and OPF Algorithms

A smart management approach of EVs charging stations, also coordinated with DG, mainly RES-based, can be used by a DSO for guaranteeing the extreme use of the power system, without additional investments of its own structure. The statement at the basis of the proposal is that: if the DSO (or an outdoor service provider, by means of an economic contract with the DSO) is the owner of EVs charging system, there could be the auspicious chance to modify the available power amount in the charging points that are linked to the unrespect of grid operation limits. The final task is to avoid additional expenses for advancement on the system.

The suggested approach has been verified by means of PF and OPF models implemented in *MatLab* [[23]]. In particular:

- PF analysis lets exploring the hosting capacity of the present network, pointing out criticalities, when the system is managed without any modulation action on the EVs charging points.
- OPF lets examining the usefulness of smart managing of EVs charging points, i.e. the chance to use the present hosting capacity through an appropriate centralized scheduling and dispatching of EVs charging points.

OPF models, including the maximization of the EVs charging points available power, with varied Objective Functions (OFs), would represent diverse DSO necessities. In particular, the proposed OFs are: the minimization of network power losses without dispatching priorities on the EVs public charging points (Case 1); the minimization of network power losses with dispatching priorities on the EVs public charging points (Case 2); the minimization of the reverse power flow to the HV grid (Case 3). The reasons at the basis of the choices are detailed the dedicated sub-paragraphs dedicated to each Case.

3.1. *Case 1 and Case 2: maximization of available power at EV charging points and losses minimization, w/wo priorities*

The first algorithm aims at assessing the maximum power availability of EVs charging stations in the network, without violating voltage and capacity constraints, and minimizing the losses overall grid. The OPF problem wants to take into account and simulate an energy efficiency approach, typically applied by DSOs. The control variables are the available powers in EVs charging points in time. For each EVs charging point, a cost function is defined, in function of the available power of the charging station:

$$C_{st}^{i} = f_{st}^{i}(P_i) \tag{1}$$

where C_{st}^{i} is the cost associated to the i-th station, f_{st}^{i} a cost function, P_i the available power of the i-th station.

The optimization problem can be stated as:

$$\min_{\theta,V_m,P_i} \sum_{i=1}^{n_{st}} f_{st}^{i}(P_i) \tag{2}$$

s.t.:

$$P_{min} < P_i < P_{MAX}, i = 1, \ldots, n_{st} \tag{3}$$

$$V_{min} < V_m < V_{MAX}, i = 1, \ldots, n_b \tag{4}$$

$$h_{fi}(\theta, V_m) < 0, i = 1, \ldots, n_l \tag{5}$$

$$h_{ti}(\theta, V_m) < 0, i = 1, \ldots, n_l \tag{6}$$

with the following quantities:

- θ voltage angle
- V_m voltage magnitude
- P_{min}, P_{MAX} power constraints at each station
- n_{st} stations number
- V_{min}, V_{MAX} voltage constraints at each bus
- V_i voltage at the i-th bus
- n_b buses number
- h_{fi}, h_{ti} suitable functions that express the grid constraints
- n_l number of lines

The phasor angles constraints are mistreated, as there are no issues of angular stability in distribution grids (because of their limited extent).

The cost function of the single EVs charging station (and consequently of the sum) must be decreasing with increasing available power, so that minimum cost corresponds to maximum available power:

$$\frac{\partial f_{st}^{i}(P_i)}{\partial P_i} < 0 \qquad \forall\, P_{min} < P_i < P_{MAX}. \tag{7}$$

The simplest function is:

$$C_{st}^{i} = -b_i P_i \tag{8}$$

where $b_i > 0$ is the marginal benefit coefficient. However, this constraint refers the allocation of availability to marginal benefit coefficients (allocating a greater availability to those stations with a higher coefficient). Lacking specific requirements, a useful criterion would be to allocate availability in order to minimize grid losses. To this purpose, it is necessary to set the same coefficient for all stations and introduce an additional cost function, for the slack bus, defined solely as a function of the sum ofP_i:

$$\sum_{i=1}^{n_{st}} P_i = P \tag{9}$$

$$C_{slack} = f_{slack}(P). \tag{10}$$

To minimize losses, the slack bus cost function must be increasing with increasing supplied power:

$$\frac{\partial f_{slack}(P)}{\partial P_i} > 0 \qquad \forall\, P_{min} < P < P_{MAX}. \tag{11}$$

Finally, the objective is:

$$\min_{\theta\, V_m\, P_i} \left(f_{slack}(P) + \sum_{i=1}^{n_{st}} f_{st}^{i}(P_i)\right) \tag{12}$$

s.t. (3)-(6).

The first order condition of the optimization problem dictates that the derivative of the overall cost function has to be null:

$$\frac{\partial f_{slack}(P)}{\partial P} + \frac{\partial}{\partial P_i} \sum_{i=1}^{n_{st}} f_{st}^{i}(P_i) = 0, \tag{13}$$

i.e., when the total marginal benefit of station availability equals the marginal cost of the power supplied by the slack bus:

$$MC(P) = -MB(P_i). \tag{14}$$

However, this condition does not ensure the maximization of availability (as it is possible to reduce losses by reducing available power in any case). In order to maximize availability and minimize losses at the same time, it is required that marginal benefit is larger than slack bus marginal cost:

$$MC(P) < -MB(P_i). \tag{15}$$

By setting cost functions according to (15), the algorithm maximizes availability, compatibly with voltage and power constraints (as the marginal benefit of the available power is larger than the cost of supplying such power via the slack bus). When the grid cannot provide full availability, the algorithm decreases availability to respect constraints and distributes availability among stations to minimize losses. In Case 1, all fast charging stations are subject to modulation, without priority, with the same marginal benefit coefficient. In Case 2, some stations are assumed to have priority and marginal benefit coefficients are set accordingly.

3.2. Case 3: minimization of the reverse flow to the HV grid

The distribution network with huge RES-based DG can be characterized by a significant reverse power flow, i.e. a flow of energy going from the MV side to the HV side. This phenomenon has to be controlled by DSO for the coordination activities with the TSO, as highlighted in [[24]]. In this framework, the second OPF algorithm aims at dispatching the availability of EVs charging stations in order to obtain a power exchange profile with the transmission system non-negative. In addition, in this case, (13) express the first order condition. If a parabola is assumed as a cost function for the slack bus, with minimum in the origin and marginal cost constantly null for each station, the solution of the optimization problem is the power vector such that null power supplied is by the slack bus.

4. The Case Study: E-*distribuzione* Grid

The application deals a portion of a real distribution grid, owned and managed by *e-distribuzione*. It includes an electrical network fed by MV half bus bars of a HV/MV electrical sub-station (ESS). The zone supplied is extra-urban and contains two cities (10,000 inhabitants). Figure 1 shows the single-wire chart of the ESS.

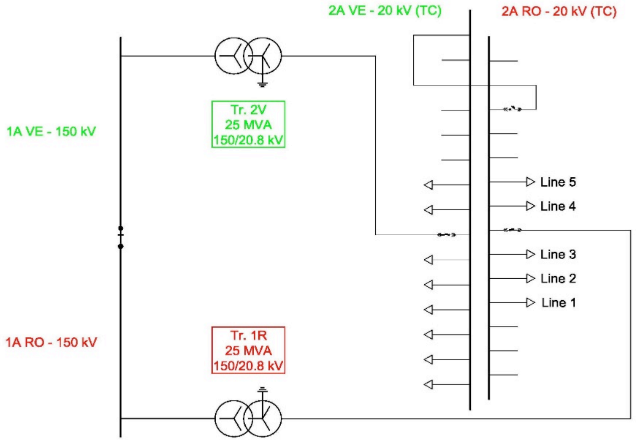

Fig. 1. HV/MV station single-wire scheme and main electrical data.

The MV half bus-bar object of study deliveries 5 lines (mainly overhead), all supplying 67 MV/LV ESS, some MV loads and local RES-based DG (only PV systems). Except for one line, load clusters are grouped in the last part of the lines. The MV/LV ESS are equipped with 400 kVA transformers, with 20/0.4 kV of rated voltage ratio and with an On-Load Tap Changer (OLTC). The LV network is made of: 169.48 km of power lines (mainly overhead cables); 7,910 end-users (80% are domestic loads); 77 photovoltaic generation plants (671.81 kW capacity). More details on the grid can be found in [[25]-[27]]. For each day of a year, the operation data of the grid, with a 15 minutes time step, are obtainable by an *e-distribuzione* database. For the analysis here presented, any MV/LV ESS, MV end-user and MV DG (PV system) has been characterized with the active and reactive power load/generation curve. The time horizon of the analysis has been set at 2030, consistent with Europe policies on the distribution of EVs and charging structures. So to evaluate the effect of the EVs charging points in an extended time, 12 representative days (weekday, Saturday and Sunday in the 4 seasons) have been simulated.

5. EVs Charging Stations Types and Spread Scenarios

IEC 61851 and IEC 62196 European standards handle EVs charging systems [[28]-[29]]. According to them, later 2003, *Enel* has promoted two types of EVs charging stations: home charging points, with 2 plug kinds (Type 2 and 3a), but allowing only one charge at the time; second-generation fast public charging points, that are 3-phase 43 kW, using Mennekes sockets. Only these last can be modulated in available power amount, by an Energy Management System (EMS) for DSO objectives [[30]], and thus are simulated as controllable in the case study application.

An important matter in e-mobility analysis is to quantify the amount and the physical location of EVs charging stations. In our case study, home charging stations have been set as a result of the geo-referencing task available in *e-distribuzione* database and the quantity has been chosen on the base of many analyses on EVs diffusion forecast and of European directives [[31]-[32]]. For a well-meaning simulation of home stations load profile, a daily curve has to be considered, calculated with a statistical algorithm done by the authors in *MatLab* [[25]-[27]].

For the EV fast stations scenario, the first assumption is to have 3×43 kW charging points associated to MV lines for each charging station [[33]-[35]]. Because of the absence of traffic numbers, to evaluate the quantity and site of fast charging stations was not possible. Therefore, the position has been supposed in function of areas of interest, e.g. gas stations, big stores, plazas and public edifices close to MV lines. As a result, 12 EVs public charging stations have been simulated, i.e. 36 charging points, and located in the points presented in Fig. 2, where also the MV/LV ESS, the MV customers with their own MV/LV ESS and RES-based MV power plants (that are only PV systems) are reported.

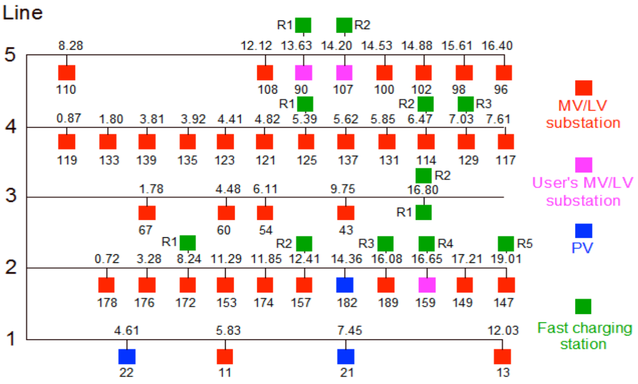

Fig. 2. Case study MV distribution grid and fast EVs charging stations in the future scenario.

Table 1 summarized the chief information on EVs public fast charging stations.

Table 1. EVs fast charging stations data

MV Line N.	N. EVs fast charging stations per MV line	N. charging points per EVs fast charging station	Maximum available power for each charging point (kW)	Maximum available power for each line (kW)
2	5	3	43	645
3	2	3	43	258
4	3	3	43	387
5	2	3	43	258

6. Simulation Outcomes

6.1. PF simulation results in present scenario

In the present scenario, a PF analysis has been done, for checking the initial criticalities on the existing grid without EVs charging stations introduction. These results have point out some key issues.

First of all the half bus bar is characterized by an inverse power flow for about 610 hours per year. The annual peak load (3.4 MW) occurs in winter on weekday. The annual peak value of the reverse power flow (1 MW) is on summer Sundays. No station has critical conditions at present (supposing a load exceeding 80% of the nominal power). In particular, on Line 1 and 3 MV/LV transformers have a medium use similar the average value in the whole grid (33.8%), whereas on Line 4 and 5 it is equal to correspondingly 44.5% and 18.5%. The maximum value of voltage drop is inferior to 5% (voltage limit respected).

6.2. PF simulation results in future scenario

Also in the future scenario, the condition of the grid can be assessed just with a PF calculation, in case of lack of management of EV charging stations. The results highlight that overload happens in 6 MV/LV ESS. Even though the overloads are rare, 13 critical conditions are noticed linked to presence of the home charging points. The expected peak load in the time horizon of simulation (2030) anyway does not involve criticalities on the primary ESS, in normal and in (N - 1) conditions. Instead, EVs public fast charging points involve limits violation on those lines already critical for the presence of home charging points, in particular Lines 2 and Line 4. On Line 4 previously charged at 95% of its capacity, the fast EVs charging points introduce an overload on the segment between MV bus bars and the first public charging station, in all the seasons, on all the days, typically in the hours close to the evening peak load. Figure 5 displays the load curves in the critical branches, in winter and summer season, as a percentage of the apparent power limit of the line. On Line 2, there was a noteworthy margin, but the presence of fast EVs charging points influences the voltage, producing drops, superior to the 5%, at the termination of the line. The extreme voltage drop happens during peak hours of winter weekdays, whereas in winter weekend days, the violation is modest. In autumn season, the violation only happens in weekdays; in spring and summer days there is no voltage violation.

6.3. OPF simulation results in future scenario for Case 1

For the modulation of the available power of the EVs fast charging stations, a minimum value of 22 kW was set. In Case 1, the results of OPF gave the results represented in Fig. 3, where the maximum available power due to the modulation is drawn. The curves are related to the EV charging stations on the Line 2 (that are R3, R4 and R5, as shown in Figure 2) and on the Line 4 (that are R1, R2 and R3, as shown in Figure 2).

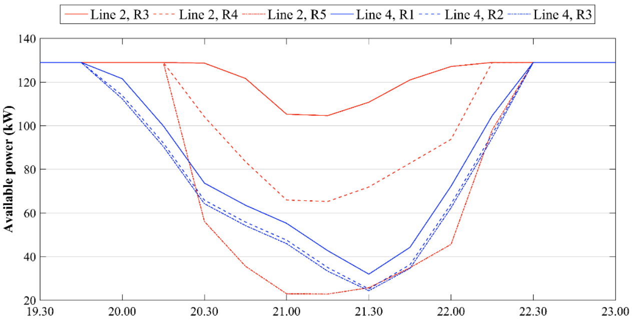

Fig. 3. Maximum available power at three fast EVs charging stations on Line 2 (red curves) and on Line 4 (blue curves)

Line 4 suffers a larger decrease of power available on its three fast EVs charging stations, because of the small margin to capacity. In total, the drop is about 305 kW at the peak hours. The decrease is bigger for the EVs charging stations more distant from the MV bus bars, under the 22-kW limit, whereas the one next to the bus bars is decreased just to 32 kW. With this modulation, Line 4 rests loaded at full capacity in the time of peak load. Line 4 EV charging stations are always involved in the modulation in the time of peak load, for each day and season.

On Line 2, 3 of its 5 fast EVs charging stations are included in the modulation in order to reduce the voltage drop. In addition, in this case, the discount falls incrementing the distance from the bus bars. At peak load, the EVs charging stations cut the availability of 194 kW in total. For winter weekend days, the performance is similar to that for weekdays. The EV charging stations modulation on Line 2 as well happens in fall weekdays and is completely lacking in the further seasons.

6.4. OPF simulation results in future scenario for Case 2

In Case 2, fast EVs charging stations located at line end are expected with a priority in the modulation, with the propose to investigate an allocation that is contrary to the optimum allocation found in Case 1. The results are here summarized.

On Line 2, prioritizing rises the overall modulation rate, reducing the energy not supplied (400 kWh, 14% increased) and the modulation of other 2 EVs charging station, not required in Case 1, is necessary. This is because of the Line 2 features, that is a long line, and of the type of violation, that is the voltage drop at line end. It implicates a reduction of the power available at other EVs charging stations, of a percentage greater than the increasing at the EVs charging stations with priority. Anyway, it is likely to assure the full availability of the two last EVs charging stations.

On Line 4, the available power at EVs charging station n. 1 is decreased for a important time, though, energy not supplied is nearly unchanged (490 kWh vs. 478 kWh), and the perceptual modulation is almost unaffected. This is linked to Line 4 features, i.e. short and very loaded, and to the violation type, i.e. the saturation of capacity of some branches. The power available at the modulated EV charging stations on Line 2 and 4 is shown in function of the time in

Fig. 4. For comparison, the power available in Case 1 in also reported.

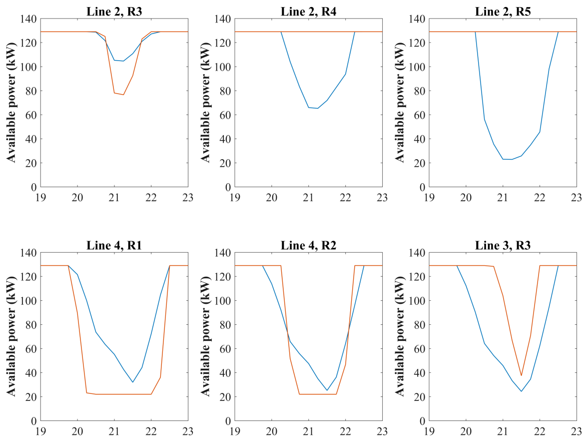

Fig. 4. Available power profile in time for modulated EVs charging station in Line 2 (top figures) and Line 4 (bottom figures), in Case 2 (red curves) and Case 1 (blue curves).

6.5. OPF simulation results in future scenario for Case 3

In Case 3, the objective function is the reverse power flow to the HV grid minimization. An availability of 43 kW is fixed for every EVs public fast charging station (33% of the installed capacity). In summer Sundays, when maximum reverse power flow happens, the results are summarized in Fig. 5 that shows the power exchange curve to the HV network and the total available power at EVs public charging points.

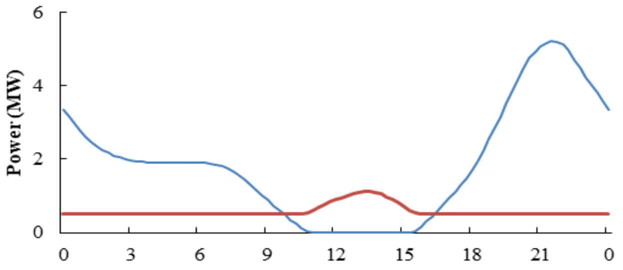

Fig. 5. Power exchange curve to HV network (blue curve) and total available power at EVs public charging stations (red curve).

When the maximum reverse flow occurs, EVs public charging stations have a peak total availability about 1.12 MW, superior to the set rate (0.516 MW), nevertheless inferior to installed power value (1.54 MW). This happens only since the reverse power flow is just curtailed and so violations escaped: the network is so able to exploit totally RES-based DG. Each charging station gives a different contribution to the reduction of reverse power flow, in function of the position, particularly in reference to DG power plants. EVs fast charging stations on Line 2 get a larger increase of available power, due to the proximity of charging station 1 to PV plants. At peak reverse power flow time, Line 2 charging stations have a 246% availability increasing, in respect of the base case (316 kW). EVs charging stations on Line 4 give an inferior contribution to reverse power flow reduction compared to the Line 2. At peak reverse power flow time, they are characterized by an increasing availability of 92%. The increasing of available power, anyway denotes a superior supplied energy compared to the other cases, in particular other 6.86 MWh per week in spring season and other 1.35 MWh per week in summer season.

Two important positive concerns of this type of approach are:

- the installed EVs charging capacity can be considered working as a "demand response" resource. It can be indorsed by financial programs of support, like variable service pricing, particularly in case EVs charging stations placed in public facilities or places of work.
- In the timeframe with a reverse power flow minimized, the MV networks is as a quasi-zero energy system, i.e. the point of delivery on the HV grid is used only for regulation services.

7. Conclusions

The paper deals with the effect of the diffusion of EVs charging stations in an existing distribution grid, and how a centralized smart management approach, by a DSO, can guarantee the safe operation of the system, without upgrading engagements. If the fast EVs charging stations are owned by the DSO, consenting a flexibility in the available power, it is promising to coordinate the value of this power to other loads, so that to safeguard a safe operation of the system, minimizing network investments and maximizing the exploitation of RES-based DG.

The outcomes of the analysis show that:

- EVs home charging stations can be root of criticalities for MV/LV ESS transformers, whereas EVs fast charging stations can be cause of violations in the MV grid;
- Controlling the available powers at the fast EVs charging stations, it is possible to reach the objective of respecting the limits of operation of all the components of existing distribution system (i.e. no new network investments), with newtwork efficiency objective functions (Case 1 and Case 2) or with maximum exploitation of RES-based DG (Case 3).

The suggested approach could be implemented in a real-time energy management system or in software, helping economic valuations on e-mobility by DSOs.

The control of available powers in public EVs charging points and the possible necessity of financial support programs (e.g. modulation of prices) is a potential economic limitation of the proposed approach. On the other hand, if the EVs charging system is taken into account in DSO planning and operation strategy, avoiding grid investments can pay off this limitation.

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