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ScienceDirect
Energy Reports 8 (2022) 62–69
www.elsevier.com/locate/egyr

The 8th International Conference on Energy and Environment Research ICEER 2021, 13–17 September

Electric vehicles local flexibility strategies for congestion relief on distribution networks

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Received 22 December 2021; accepted 8 January 2022
Available online 2 February 2022

Abstract

Due to the rising concern for the environment and sustainability issues, the transportation system is experiencing important changes to its paradigm, with the increasing replacement of internal combustion vehicles by electric ones. Consequently, the electric systems need to adapt to the ever-increasing load demand from the grid and the challenge to identify driving patterns in electric vehicle users' behavior. To prepare the grid for these changes, it is necessary to study the behavior of EV users and develop strategies to cope with the growing demand for electric vehicles. Knowing that electric vehicles experience long-parked periods at the charging stations (more than necessary to fully recharge the battery), this research paper proposes an EV charging strategy that intelligently explores these long-parked times. It interrupts charging of EVs that have enough charge to start their trip from certain charging stations to alleviate problems in the network in exchange for a certain incentive. This methodology is then applied in a realistic smart city to investigate its application. The results show that the proposed methodology brings benefits to the distribution network to relieve line congestion and improve the voltage magnitude at the network buses.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Energy and Environment Research, ICEER 2021.

Keywords: Distribution system; Electric vehicles; Flexibility strategies; Smart charging

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), an objective was set to limit global warming to below 2 °C relative to pre-industrial level by the end of the 21st century [1], and 195 countries will actively participate to try and reach this goal [2]. In order to reduce gas emissions and stem the rising concern about using energy in a more sustainable way, electric vehicles (EV) will replace internal combustion engines, which contribute to about 16% of the global man-made carbon dioxide emissions [3]. It is widely acknowledged that the shift from internal combustion engines to EVs has many environmental and economic advantages. However,

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https://doi.org/10.1016/j.egyr.2022.01.036

Peer-review under responsibility of the scientific committee of the 8th International Conference on Energy and Environment Research, ICEER 2021.

the increasing number of EVs requires a continued development of new infrastructure for EV charging, which leads to a growing energy demand [4,5]. These charging set-ups will put a burden on the distribution power grid [6–8], namely the high charging power of fast EV charging stations.

With the high penetration of EVs and distributed generation in the grid, the distribution network is suffering changes to its characteristics, posing new challenges to the Distribution System Operator (DSO) in terms of security and the economic operation of the grid [7]. EV owners have a specific pattern of behavior that can be exploited, e.g., they have much higher long-parked times than necessary to charge the battery fully). The DSO can use this behavior, and coordination of EV charging can be a good asset for ancillary services, therefore, keeping the grid more stable. This paper proposes a model to help the DSO improve the distribution network's stability, seeking to take advantage of the flexibility that EVs provide in their charging. As such, the methodology proposes multiple scenarios with several additional costs for the DSO that it must pay the EV user to remove its car from charging since it has enough energy to complete its trip. An optimal power flow (OPF) is implemented for the operation/reconfiguration of the distribution network to obtain network information so the DSO can know if a congestion problem is occurring and then act to mitigate it by trying to buy the flexibility of the EVs.

This paper is organized as follows: Section 2 describes the background on EVs and local markets; Section 3 describes the proposed methodology, while the case study is presented in Section 4. Finally, Section 5 presents the conclusions.

2. Related work

This section discusses the relevant work to the proposed work's topic. It shows the work that has been done and is currently being developed in the numerous subjects displayed.

2.1. Electric vehicles

The EVs are different vehicles from the ones with internal combustion. In the EVs the energy is not stored in the form of fuel, but in the battery [9]. There are 4 main EV categories: Purely Electric; Hybrids without grid connection; Plug-In Electric Vehicle (PHEV); Fuel Cell. Purely electric vehicles are constituted by electric engines without any form of combustion. Therefore, they depend exclusively on the battery and, consequently, on its connection to the grid or some other power source. Hybrids with grid connection are vehicles that have 2 engines: one electric and one combustion. The battery is recharged by the electric engine working as a generator. Alternatively, PHEVs are cars with similar characteristics to the hybrids, but PHEV batteries can be recharged through a grid connection. Finally, in Fuel Cell vehicles the electric energy originates from chemical reactions between hydrogen and oxygen, which results in electricity and water.

2.2. EVs smart charging

Due to a growing trend in the replacing of cars with combustion engines to electric vehicles as a result of a growing concern for environment preservation, sustainability, decrease in fossil resources and emission of polluting gases, there is a critical need to recharge the EV batteries in a smart and efficient way to also avoid problems from the network perspective. Charging these batteries entails costs, which is extremely relevant for users of this form of transportation. China has the largest EV park in the world. According to [10], in 2015, 60.6% of China's oil consumption came from importation and this is expected to increase to 80% by 2030. Therefore, many decisions have been made aimed at reducing these levels in order to protect the environment and provide better energy security. As the demand for automobiles in China has been growing rapidly, the Chinese government made the decision to invest in the fast growth of EVs, the replacement of fuel and the reduction of emissions from cars. Consequently, 780 charging stations were built, and 31,000 charging points were installed [10].

The authors in [11] claim that EVs have three unique characteristics that make them an excellent asset for the grid. These are: the flexibility to vary the charging power; the ability to rapidly change the charging ramp; and the ability to charge and discharge the battery. Therefore, they found that by adopting smart charging, the power to be transmitted and its direction (energy flowing from the grid to the EV or vice versa) can be continuously controlled to promote the following benefits: Reduce the charging price based on the energy price; Provide new income sources such as Vehicle-to-Grid (V2G); Increase the use of wind- and solar-based energy to charge the EV during the day and night, respectively; Reduce DN power losses; Reduce the demand peak in the grid (by charging the EV in off-peak hours); Using the fast change in the charging ramp for ancillary services; Deploy EV charger multiplexing using a single charger for multiple vehicles (to significantly reduce charging infrastructure costs).

2.3. Demand response and flexibility

Local electricity markets work to restructure the system, where individual consumers and prosumers share the management of a local grid, trading electricity in a given neighborhood. For the purpose of increasing the interaction between end-users and electricity entities, the so-called Demand Response (DR) was created, which is a tool based on the energy market with benefits for both the end-users and the grid. For the consumers, the DR enables energy saving and a reduction in the electricity bill. For the grid, the DR is beneficial for the efficiency of the energy market and the network operation and expansion by actively adapting demand to the energy supply or by providing fast reactions to contingencies in the electric system [12].

The current decarbonization of the European electricity system via the proliferation of distributed and renewable energy production sources has created a global surge of interest in local electricity markets for local energy communities [13]. In 2050, the European electricity system is expected to have millions of prosumers (consumers who participate continuously and actively in the production of energy), EVs and storage units willing to provide energy and flexibility [14].

According to [15], the term “flexibility” on an individual level is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include the amount of power modulation, duration, rate of change, response time, location, etc. The flexibility can be provided by both large-scale supply and demand, for example by combined cycle power plants, industrial and commercial consumers, smaller domestic load aggregation, distributed generation, and energy storage.

3. Proposed methodology

This section presents a detailed description of the adopted methodology, depicted in Fig. 1. It combines an EV user behavior simulator [16] with an innovative smart DLMP-based distribution network operation/reconfiguration. Since this problem is classified as mixed-integer nonlinear programming (MINLP), the Benders decomposition method was used to resolve the optimization problem [13], through the use of a specialized software such as TOMLAB. This work is an extension of the study described in [17], where the full mathematical model is presented, concerning the optimization problem, the EV user behavior simulator, network, supplier, curtailment, and energy storage system constraints.

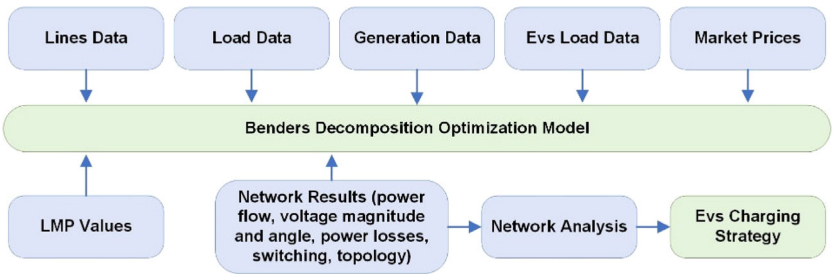

Fig. 1. Proposed methodology.

To achieve the previously stated goal, first the loads (including the EVs) and distributed generations are mapped. Then the optimization model can load and start. This optimization model provides important information such as: distribution locational marginal pricing (DLMP), network topology and switching, power flows, voltage magnitude, and power losses.

From this information, the EVs charging strategy was developed, which works according to the flowchart presented in Fig. 2.

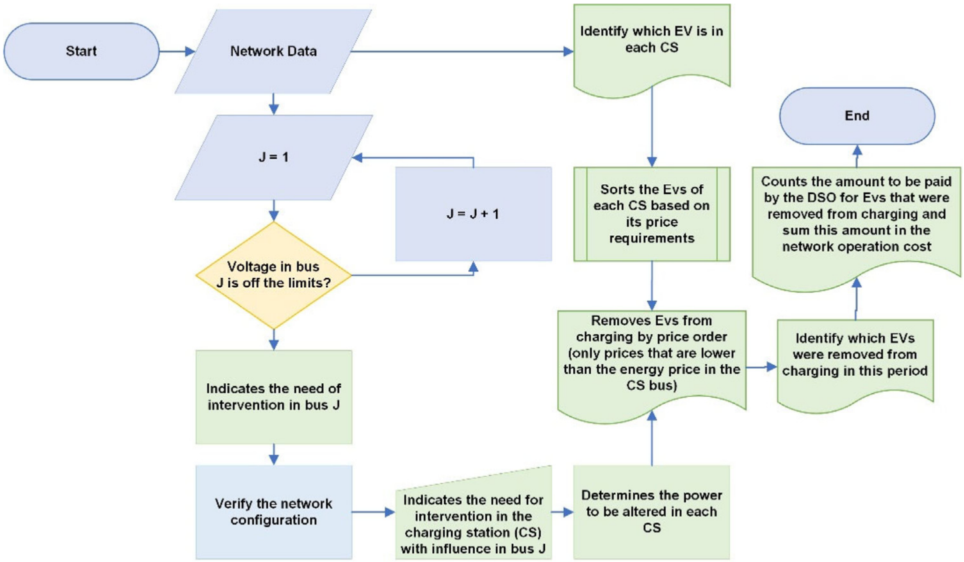

Fig. 2. Flowchart of the EVs charging strategy.

Every 15 min a network analysis is made to identify if any parameter is beyond its limits, e.g., voltage magnitude is too low or too high, overloaded lines and so on. In addition to this data obtained from the optimization model, there is also the data from the EVs, such as their locations, state of charge of the battery, scheduled trips and time needed to fully charge. Matching this information there is data of the EV users' minimum price to stop charging their EV, in other words, if the system is overloaded and the EV has enough battery to make the next trip, the EV can suspend its charging process in order to maintain the grid stable and within its limits, but, of course, receiving a certain amount of money from the DSO.

In the proposed strategy, the DSO will only make this choice if the grid is overloaded and if the price of the EV is lower than the marginal energy price of the parking lots' bus. Initially, the objective function does not take the DSO EV flexibility cost into consideration. Then, after the strategy is applied and the amount to be paid by the DSO for the EV flexibility is known, this amount is added to the objective function, in order to compare to the results with and without the EV coordination strategy. It is important to mention that in the EV behavior simulator, the EVs with the battery State-of-Charge (SoC) equal or lower than 20% are immediately sent to the nearest charging station, and, for these users, the prices of flexibility are altered to values higher than the energy price in the charging station bus. With this alteration, the DSO will never ask for them to stop charging even if the grid is beyond its limits. To enable computational speed in the simulation each EV in this work represents 5 units. The reason not to increase the numbers of the population of EVs in the grid was due to the computational burden, which was high enough with a population of 5000 EVs. So, in order to make one EV represent 5, the battery capacity of each EV, the energy spent during each trip and the EV minimum price to stop charging were all changed accordingly.

4. Case study

In this section, the case study of the work is presented in Fig. 3 based on the network mentioned above. To demonstrate the application of the proposed methodology, the BISITE laboratory's smart city (SC) mockup model was used with a 13-bus distribution network and high distributed energy resources (DER) penetration. This distribution network has one 30 MVA substation, 25 load points (not including the EV parking lots), 4 EV charging stations, 15 distributed generation (DG) units, (2 wind farms and 13 photovoltaic (PV) parks) and 4 capacitor banks of 1 Mvar, which can be seen in Fig. 3(b).

The DG penetration corresponded to 27% (10.93 MW) of the total installed power, where 24% is from wind generation and 3% is from PV. The distributed generation and loads of the buildings in each period can be consulted in [17]. As this research work only analyzed the periods of one day, the chosen day was 19 March 2017. The

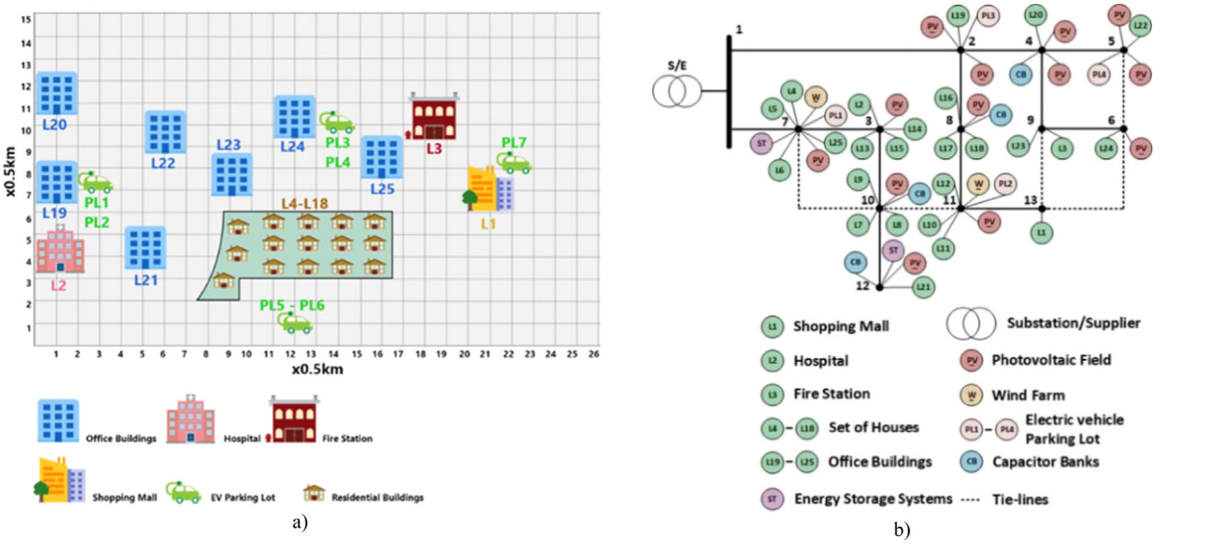

Fig. 3. (a) Smart city plan; (b) Single-line diagram of the distribution network [17].

market prices in each period were taken from the Iberian Electricity Market Operator (OMIE) in order to calculate the DLMP.

The case study was divided into 4 scenarios, with the aim to apply the presented methodology for later analyzes of the results. The scenarios are all similar, changing only the EV users' minimum price to stop charging, making it possible to observe the applicability of the strategy for different flexibility prices.

4.1. Scenario1

In this scenario, the charging strategy presented in the previous chapter was applied in the network shown in Fig. 3, in a way that the average price of the EV users that were requested to stop their charging resulted in 0.095 €/kW. The most critical period in this scenario (higher operation cost) was between 8:30 pm and 8:45 pm, with an operation cost of 424.05€ (before the strategy). Hence, we choose this period to be analyzed in all the other scenarios, in order to compare the results of the proposed methodology.

Table 1. Voltage magnitude results in scenario 1.

Bus number	1	2	3	4	5	6	7	8	9	10	11	12	13
Voltage magnitude before strategy	1	0.919	0.931	0.904	0.889	0.895	0.941	0.886	0.901	0.923	0.881	0.916	0.877
Voltage magnitude after strategy	1	0.967	0.978	0.953	0.942	0.944	0.985	0.961	0.948	0.973	0.967	0.971	0.959

To understand the results presented in Table 1, it is necessary to identify the number of EVs in each charging station before and after the strategy, to know how many EVs were removed from charging. This data in shown in Table 2.

Table 2. Distribution of EVs in scenario 1.

Charging station number	Number of EVs before strategy	Number of EVs after strategy	Number of EVs removed from charging
1 (slow)	50	35	15
2 (slow)	160	125	35
3 (fast)	100	80	20
4 (fast)	70	60	10

With this information, it was possible to calculate the amount of power altered in the network, 1581 kW. As mentioned before, the average price of flexibility was 0.095 €/kW, therefore the amount of money paid by the DSO for the EVs flexibility was 150.19 €. However, as utilizing this strategy entails a reduction in the congestion and power losses costs, which, when combined, resulted in a reduction of 38.45 €, it is clear that the strategy application with these EVs flexibility prices were insufficient to make the strategy interesting from the DSO perspective, since the operation cost after the strategy resulted in 535.79 €, while the operation cost before the strategy was 424.05 €.

This is mainly because the congestion cost (0.02 €/kW for lines with more than 50% congestions) was significantly lower than the flexibility cost. The congestion cost in this network is linear, which is not exactly accurate in the real world, because the line congestion costs normally follow an exponential function.

4.2. Scenario 2

This scenario is similar to the previous one, only differing in the average price of EV users' minimum price to stop charging, that is 0.041 €/kW (for EVs that were removed from charging). The operation cost before the strategy continues at 424.05 €. To evaluate the results of the strategy application, the voltage magnitude in all the buses before and after the strategy is shown in Table 3.

Table 3. Voltage magnitude results in scenario 2.

Bus number	1	2	3	4	5	6	7	8	9	10	11	12	13
Voltage magnitude before strategy	1	0.919	0.931	0.904	0.889	0.895	0.941	0.886	0.901	0.923	0.881	0.916	0.877
Voltage magnitude after strategy	1	0.967	0.978	0.949	0.936	0.939	0.985	0.957	0.945	0.973	0.967	0.971	0.959

To understand the results presented in Table 3, it is necessary to identify the number of EVs in each charging station before and after the strategy, to know how many EVs were removed from charging. This data in shown in Table 4.

Table 4. Distribution of EVs in scenario 2.

Charging station number	Number of EVs before strategy	Number of EVs after strategy	Number of EVs removed from charging
1 (slow)	50	35	15
2 (slow)	160	125	35
3 (fast)	100	85	15
4 (fast)	70	60	10

Comparing this scenario with the previous one, it is possible to observe that in charging station 3, 5 EVs were not removed from charging. As the process of removing the EVs from charging is made from the lower prices until the amount of power to be intervened is achieved or the prices are higher than the energy price in the parking lots' bus. Therefore, in this case, there fewer cars were removed from charging because the price of the next 5 EVs were above the price of the bus.

The power altered in the DN resulted in 1368.5 kW, therefore the amount of money paid by the DSO for the EV flexibility was 56.11 €. However, the total reduction in the congestion and power loss cost was 33.76 €, which makes the operation cost after the strategy, 446.40 €, still higher than the operation cost before the strategy. This means that the strategy is still not interesting from the DSO perspective, because the EV flexibility cost is far higher than the congestion cost.

4.3. Scenario 3

This scenario is similar to the previous ones, but now the average price of EV users' minimum price to stop charging is 0.022 €/kW (only EVs that were removed from charging). The operation cost before the strategy continues at 424.05 €. The number of EVs removed from charging in this scenario is the same as in scenario 1, meaning that the voltage magnitudes in the buses before and after the strategy are the ones shown in Table 1.

Consecutively, the distribution of the EVs in this scenario is equal to the distribution in scenario 1, presented in Table 2.

As the average price of EV users' flexibility price from the ones removed from charging was 0.022 €/kW and the power altered in the DN was 1581 kW, the amount of money paid by the DSO for the EVs flexibility was 34.78 €. As this scenario is similar to scenario 1, the congestion and power loss cost reduction is the same, 38.45 €. Therefore, in this scenario, the operation cost after the strategy resulted in 420.38 €, which is inferior to the operation cost before the strategy, 424.05 €. With this information, it is possible to state that the strategy became interesting for the DSO, because the voltage magnitudes are now better and for a lower price. We can see that even with the average price of EVs removed from charging still slightly superior to the congestion costs, the strategy became useful, because the power losses cost reduction was higher than this slight difference in the prices.

4.4. Scenario 4

This scenario is similar to the previous ones, but now the average price of EV users' minimum price to stop charging is 0.017 €/kW (only EVs that were removed from charging). The operation cost before the strategy continues at 424.05 €. The number of EVs removed from charging in this scenario is the same as from scenario 1, meaning that the voltage magnitudes in the buses before and after the strategy are the ones shown in Table 1. Consecutively, the distribution of the EVs in this scenario is equal to the distribution in scenario 1, presented in Table 2.

As the average price of EV users' flexibility price from the ones removed from charging was 0.017 €/kW and the power altered in the DN was 1581 kW, the amount of money paid by the DSO for the EVs flexibility was 26.87 €. As this scenario is similar to scenario 1, the congestion and power loss cost reduction is the same, 38.45 €. Therefore, in this scenario, the operation cost after the strategy resulted in 412.47 €, which is inferior to the operation cost before the strategy, 424.05 €. With this information, it is possible to state that the strategy became interesting for the DSO, because the voltage magnitudes are now better and for a lower cost. With this scenario it became evident that as EV flexibility prices start to approach the congestion costs, the strategy starts to become interesting from the DSO perspective.

5. Conclusions

In this research, the authors investigated if the coordination of the charging process of EVs on a smart DN could result in a lower operation cost of the grid. To this end, an EV behavior simulator was combined with an innovative smart DLMP-based DN operation/reconfiguration.

The results showed that it is possible to make the grid perform with a lower operation cost mainly in scenario 4 where the minimum price to stop charging is the lowest of all the proposed scenarios being lower than the sum of the congestion and power loss costs. This situation is the most beneficial for the DSO because network efficiency improves, and the operation costs are also reduced. But, to make this strategy interesting for both the DSO and the EV users, it is necessary to make sure that the removal of the EV from charging in this period will not affect the scheduled trip from these EVs, and that the owners of these EVs receive a certain amount of money for their available flexibility.

The main contributions of the conducted study is that the EVs do not need to start charging at the moment that they arrive at the charging station, because with the knowledge of the next scheduled trip of the EV user and the energy prices in the network, the charging periods of each EV can be optimized by charging the battery in periods with lower energy prices, saving money for both the DSO and the EV users and avoid more congestion in the electrical lines.

CRediT authorship contribution statement

João Soares: Conceptualization, Investigation, Formal analysis, Validation, Writing – original draft, Project administration, Funding acquisition. **José Almeida:** Formal analysis, Validation, Writing – review & editing, Writing – original draft. **Lucas Gomes:** Conceptualization, Data curation, Investigation, Writing – original draft, Writing – original draft. **Bruno Canizes:** Formal analysis, Data curation, Writing – review & editing. **Zita Vale:** Supervision, Writing – review & editing, Project administration, Funding acquisition. **Edison Neto:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research has received funding from FEDER funds through the Operational Program for Competitiveness and Internationalization (COMPETE 2020), under Project POCI-01-0145-FEDER-028983; by National Funds through the FCT Portuguese Foundation for Science and Technology, under PTDC/EEI-EEE/28983/2017 (CENERGETIC), UIDB/00760/2020; João Soares is also supported by CEECIND/02814/2017 FCT grant.

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