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Multi-objective optimization control of plug-in electric vehicles in low voltage distribution networks

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HIGHLIGHTS

- A new smart charging method for PEVs in LV distribution networks is proposed.
- The methodology relies on minimizing the load variance and charging cost.
- A novel approach to reduce voltage drops and unbalances is developed.
- Electric vehicle battery degradation is limited when V2G is used.
- The new method has been simulated using real data of a LV distribution network.

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ABSTRACT

The massive introduction of plug-in electric vehicles (PEVs) into low voltage (LV) distribution networks will lead to several problems, such as: increase of energy losses, decrease of distribution transformer lifetime, lines and transformer overload issues, voltage drops and unbalances. In this context, this paper proposes a new multi-objective optimization algorithm in order to reduce the mentioned problems. At the same time, users' interests in terms of charging cost and privacy have been taken into account. The proposed multi-objective optimization is based on minimizing the load variance and charging costs by using the weighted sum method and fuzzy control. The use of vehicle to grid (V2G) concept and load forecast uncertainties have been also considered. Furthermore, an innovative method for mitigating voltage unbalances has been developed. The effectiveness of this methodology has been tested using real data of a LV distribution network, located in Borup (Denmark). Simulation results show that this approach can reduce both energy losses and charging costs as well as it allows a high PEV penetration rates (PEV-PR).

1. Introduction

Currently, society is more concerned about environmental issues such as global warming and urban air pollution. Transport sector is one of the largest contributors to global warming. In 2011, 71% of the petroleum consumed in the world was due to the transport sector. In addition, the 93% of the energy consumed by the transport sector depends on petroleum [1]. In this context, electric vehicles have emerged as a possible alternative to reduce pollutant emissions as well as oil-products dependency. Thus, governments of different countries are encouraging the purchase of electric vehicles by subsidizing or financing them and implementing other actions, such as: tax exemption, tax deductions, transit and parking facilities [2].

Among the different types of electric vehicles, plug-in electric vehicles are gaining more interest due to the possibility of being charged from the electric grid. According to the U.S. Department of Energy, a PEV can be defined as a light vehicle which draws electricity from a battery, with a capacity of at least 4 kW h, and is capable of being charged from an external source [3]. However, electric vehicles have some drawbacks that should be overcome such as their high cost, short autonomy and slow charging times. Nevertheless, PEV sales have been steadily grown in the last years. As an example, in 2014 PEV sales have increased up to 69% in USA and around 120% in China [4].

Moreover, the arrival of plug-in electric vehicles is a great challenge to electric distribution networks. The charge of a large amount of PEVs represents a significant new load demand which

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should be satisfied. In this context, researchers have analyzed the possible impacts that a large deployment of PEVs can have on electricity markets [5] but also in electric distribution networks [6–8]. Among the expected impacts, the most mentioned ones are the increase of voltage deviations, voltage unbalances and energy losses, overload of lines and distribution transformers and degradation of the distribution transformer lifetime [9].

However, a proper charging control of PEVs could reduce the mentioned impacts and, improve the operation of electric grids, by increasing the load factor and allowing the integration of more intermittent renewable generation [10]. Such objectives can be achieved due to the possibility of programming when PEVs should be charged. In addition, PEVs can also be used to inject energy to the electric grid [11]. This concept is known as vehicle to grid. This way, energy storage capacity of PEVs can be used to provide ancillary services such as spinning reserve [12]. However, an intensive use of V2G will impact on expected battery lifetime [13]. Thus, it is necessary to limit the energy injected back to the grid.

In addition, the application of a smart charging control should be beneficial for all stakeholders. On the one hand, utilities would like to improve the load factor to dispatch more energy using the same infrastructure. Furthermore, they would like to reduce the potential impact on the electric grids as much as possible. On the other hand, users of PEVs will not give the charging control of their batteries if no economic incentive is provided.

Two main control architectures can be considered to implement a smart charging control: the centralized and the decentralized architecture. In the centralized control architecture, a central controller, aggregator or fleet operator (FO) is in charge of acquiring data from PEVs and other entities, executing the control algorithm and sending the calculated charging set-point of each PEV under its governance. The central controller has to take into account numerous aspects such as electricity prices, PEV users' preferences and distribution network status. In this approach, each user will give up the direct control of the charging process of its PEV.

In contrast, the decentralized control, also known as distributed or local control, is based on managing locally the charging process of the PEVs, according to the users' preferences and external data received. This way, users maintain the control of the charging process of their PEVs. Additionally, decentralized architectures present several advantages such as scalability, fault tolerance, constant computational effort, reduced communication requirements and improved privacy of PEV users.

In this context, this paper presents a smart charging algorithm which reduces the charging cost for PEV users as well as improves the load factor and voltage levels in LV distribution networks. The developed solution is achieved by solving a multi-objective optimization problem, which is composed by two different objective functions: charging cost and load variance. In addition, several constraints are applied to meet the technical limits and PEV user requirements. Furthermore, the proposed algorithm is ready to V2G operation, including a constraint to limit the quantity of energy to be delivered to the grid. This way, battery degradation is limited. The proposed smart charging algorithm has been implemented through a centralized coordination architecture located at LV network level. However, charging set-points of each PEV are calculated locally. That is, the intelligence is located on-board of each PEV. This way, reliability, scalability and user's privacy of the presented solution are improved.

This paper is organized as follows. Section 2 presents a literature review about charging control techniques in LV distribution networks. Section 3 introduces the necessary system architecture to implement the proposed methodology. The mathematical formulation of the proposed algorithm is explained in Section 4. Section 5 shows the LV distribution network used to test the proposed algorithm and the simulation results. Finally, the main conclusions and future works are presented in Section 6.

2. Literature review

Currently, due to the poor market penetration level of PEVs, no integration strategy is performed (dumb or uncontrolled charging) or a passive strategy is implemented. Among passive strategies, the most widely used is the off-peak charging, using time-of-use (TOU) tariffs, that encourages the charging of PEVs during night. However, this solution has the drawback of producing sudden power demand increases because all PEVs charging processes would begin almost simultaneously [14]. Thus, researchers have developed and proposed a wide range of methods to achieve a better integration of PEVs.

One of the most used decentralized methods is the implementation of a droop control to modify locally the charging power of PEVs. The droop control is based on measuring the voltage and frequency at the connection point and controlling the active and/or reactive power of PEVs in order to provide voltage and frequency regulation. Considering that the R/X ratio of LV distribution networks has a relatively high value, it is more efficient to apply an active power control [15].

Many authors have used this useful technique of control. In references [16,17], PEVs with droop control method have been used to reduce voltage deviation in residential distribution networks. Possibilities of droop control to maximize intermittent RES integration, using PEVs and V2G in islanded grids, is researched in [18,19]. A more complex solution is developed in [20] using an adaptive droop control to take into account the charging level required by PEV users. Other approaches use fuzzy control to develop a smart charging controller which takes into account the user's requirements [21]. And important advantage of these decentralized methods is that they are easy to implement and cost-effective solutions.

However, a drawback of droop control methods is the lack of coordination. Thus, the effective gain of the control is affected by the number of connected PEVs. In addition, the droop control method alone does not provide some important benefits given by the optimized methods, such as load levelling, peak shaving, congestion management and charging cost reduction.

Therefore, researchers have proposed different optimal strategies to charge PEVs efficiently. These methodologies usually require communication systems and a certain level of computing power. As a result, their implementation will be more expensive compared to decentralized solutions. However, it is expected that most of future vehicles will be connected to Internet and on-board computing units of these vehicles will be powerful enough to solve any optimized charging algorithm.

Jian et al. present a centralized solution for optimizing load variance in [22]. This solution uses V2G and load forecasting in order to flatten the load profile of a distribution network. Authors achieve good results in load variance reduction but some aspects of the proposed framework can be problematic. First, the centralized nature forces to PEV users to send information about the actual state of charge (SOC) of the battery, departure time and the amount of energy required for the next trips. This last information can be difficult to know beforehand for PEV users. Second, V2G operation is not limited. Third, there is no incentive for PEV users to participate in the proposed solution. Fourth, as number of PEVs increases, the optimization problem will be more and more complex to solve, due to centralized nature. Finally, voltage issues are not mentioned in this paper.

In [23] a multi-objective scheduling strategy is formulated for a MV/LV distribution networks. In this paper, two different objective functions are presented: total operational cost of a distribution