



Determining the size of PHEV charging stations powered by commercial grid-integrated PV systems considering reactive power support



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HIGHLIGHTS

- Penetration of commercial grid-connected PV and PHEVs for minimizing energy losses.
- Sizing of PV powered workplace charging stations and their reactive power support.
- Consideration of the probabilistic characteristic of PV generation.
- Impacts of time-varying voltage-dependent charging load models on PV penetration.
- Analyses of probabilistic voltage distributions and peak load demand reduction.

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ABSTRACT

Due to low electricity rates at nighttime, home charging for electric vehicles (EVs) is conventionally favored. However, the recent tendency in support of daytime workplace charging that absorbs energy produced by solar photovoltaic (PV) panels appears to be the most promising solution to facilitating higher PV and EV penetration in the power grid. This paper studies optimal sizing of workplace charging stations considering probabilistic reactive power support for plug-in hybrid electric vehicles (PHEVs), which are powered by PV units in medium voltage (MV) commercial networks. In this study, analytical expressions are first presented to estimate the size of charging stations integrated with PV units with an objective of minimizing energy losses. These stations are capable of providing reactive power support to the main grid in addition to charging PHEVs while considering the probability of PV generation. The study is further extended to investigate the impact of time-varying voltage-dependent charging load models on PV penetration. The simulation results obtained on an 18-bus test distribution system show that various charging load models can produce dissimilar levels of PHEV and PV penetration. Particularly, the maximum energy loss and peak load reductions are achieved at 70.17% and 42.95% respectively for the mixed charging load model, where the system accommodates respective PHEV and PV penetration levels of 9.51% and 50%. The results of probabilistic voltage distributions are also thoroughly reported in the paper.

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1. Introduction

Solar photovoltaic (PV) has received remarkable worldwide attention over the past decade [1]. The global installed capacity was approximately 178 GW at the end of 2014 and this amount is expected to be more than 540 GW by 2019. Meanwhile, the usage of electric vehicles (EVs) has been growing in many parts of the world such as the United States, Japan, China and Europe due to their environmental benefits, advancements in the technology, battery cost reductions, and government incentives [2]. It has been reported that the total worldwide EVs stock was over 0.02%

(0.18 million units) of the total passenger cars through 2012. This figure is projected to increase to 2% (20 million) by 2020. Furthermore, an online survey has been recently conducted in the United States to evaluate the possibility of the economic and environmental benefits obtained from EV and renewable energy deployment [3]. This investigation indicated that there would be an increase of 433% in the usage of public charging stations if renewable energy resources, including solar PV generation were offered.

The widespread adoption of intermittent solar PV sources can increase the pressure on the distribution system, especially power fluctuations, reverse power flows, voltage rises and high power losses [4]. In contrast, the distribution system would potentially face excessive voltage drops, feeder overloads and high network

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losses caused by high EV penetration [5]. However, EV charging loads can support high PV penetration while mitigating dependence and impacts on the power grid, the intermittency of PV production and emissions as well [6,7]. This coordination is also expected to meet the demand for daytime charging at workplace parking infrastructures [8–10].

The study of EV charging stations consuming energy produced by grid-connected PV panels at workplace parking areas during the daytime has been conducted in a number of recent research efforts [11–27]. This model has comprehensively reported to bring multiple technical and economic benefits to vehicle and garage owners and power utilities. In [11], the benefits of EV charging facilities powered by PV panels were quantified using an optimal charging algorithm, which was developed based on dynamic programming and rule-based control. This analysis showed that daytime charging based on solar PV at workplace generated a lower charging cost than nighttime home charging without solar energy while the garage owner gained a reasonable profit. Other possible benefits included lower emissions and power consumption from the grid and higher PV penetration. Moreover, a research [12] emphasized that coordinated operation of both PV and PHEVs during the mid-day can enable higher penetration levels of not only PV, but also EVs during low demand periods and less curtailment of surplus PV production. Meanwhile, a study [13] designed a charging facility supplied by PV panels to maximize the consumption of PV power while minimizing voltage deviations in distribution networks. In this work, a real-time fuzzy logic controller that incorporates a probabilistic model was proposed to forecast PV generation and PHEV charging loads. Such a method was also employed to control multiple charging stations to minimize charging costs, network power losses and voltage deviations in MV industrial/commercial power networks [14]. In [15], an optimal EV charging approach based on forecasted PV generation load demand was also presented to reduce the electricity cost in commercial buildings. Similarly, a mixed-integer linear programming approach was presented to minimize the annual energy cost and emission while enabling high PV penetration in commercial buildings involving EVs [16]. An concept of a future smart city was also developed in [17], where EVs are charged using power generated from PV panels to reduce electricity demand. Recently, a study [18] reported a heuristic operation approach that accommodate EVs and PV panels to enhance the self-consumption of PV power in commercial buildings and a research [19] showed optimal EV charging using PV panels to reduce dependency on the grid and maximize the usage of solar energy as well. A coordinated charging approach was proposed to enable operational synergy between PV generation and EV charging and subsequently reduce emissions in an urban distribution network [20]. An online energy management for PV-assisted charging stations was developed to maximize the self-consumption of PV and decide the power supplied from the grid under time-of-use pricing [21]. A smart charging model was presented to increase the self-consumption of PV power using EV charging loads and reduce peak load demand [22]. In [23], a PV-powered charging station was proposed to reduce the intermittency of PV production and the cost of energy trading to the charging station. In [24], economic operation of a microgrid-like EV parking deck powered by PV panels was also presented to minimize the intermittency of PV generation while maximizing the total revenue. In addition, an experiment on a microgrid-connected charging station, which involves solar and wind sources and energy storage buffers, demonstrated a reduction in energy exchange between EV charging and the main grid [25]. Another experimental study showed that PV-powered charging stations significantly declined the energy consumption from the grid [26]. More importantly, an uncoordinated charging approach was successfully developed using a stochastic model that considers load

demand, EV charging and PV generation in an urban power network [27]. This study observed that daytime charging combined with PV generation can enhance load and voltage profiles despite the fact that no optimal charging algorithms and control devices were employed.

The aforementioned survey shows that sufficient work has been done with respect to the optimal control of EV charging stations powered by grid-connected PV systems; two key shortcomings unresolved, however, were identified. Firstly, the existing studies have assumed that the sizes of PV units and charging stations are pre-specified. Such an assumption may lead to a possibility of an under/over-estimation of the penetration of PV and EVs. Consequently, the power network may experience excessive increases in reverse power flows, power losses and voltage variations. Secondly, the ability to provide probabilistic reactive power support by PV units and EVs was also neglected in the above-reviewed studies. The immediate concern is that given high intermittent PV penetration with active power provision only together with sharply increased charging loads, the deficiency of reactive power support may exist in the distribution network. Switchable capacitor banks are conventionally employed for reactive power compensation. Nevertheless, they are not adequately fast to compensate for transient events as a consequence of the intermittency of PV generation and the voltage rise that occurs due to reverse power flow when the generation of PV exceeds the local demand [28,29]. As fast response devices, inverter-based charging stations powered by PV panels are permitted to regulate reactive power to stabilize load voltages while charging EVs as a primary task [30,31]. Overall, depending on the nature of loads, if properly sized, PV powered charging stations that are capable of reactive power provision may have positive effects on reducing energy losses and stabilizing bus voltages as well.

The contribution of this paper is to propose a new analytical approach to determine the size of PHEV charging stations powered by different levels of grid-connected PV penetration that considers probabilistic reactive power support for energy loss reduction. To this end, expressions are first developed to estimate the size of PV powered charging stations that can provide reactive power support for minimizing energy losses while considering the probability of PV generation. The proposed expressions are achieved by significantly expanding the previous work [32], where an analytical expression was derived from an exact loss formula for DG allocation only at the peak load to reduce power losses without consideration of EVs and their probabilistic reactive power support. The proposed approach is further extended to study the effect of charging loads on PV penetration. Various charging levels (i.e., normal, fast and mixed) are defined by time-varying voltage-dependent commercial charging load models. Moreover, the paper shows the importance of charging loads and the reactive power response of charging stations in reducing energy losses, peak loads and voltage deviations. Some interesting findings of PHEV and PV penetration levels with various commercial charging load models are reported as well.

The rest of this paper is organized as follows: Section 2 describes commercial load, PHEV and PV modeling. Section 3 presents the impact of PHEVs and PV on network power and energy losses. An analytical approach to model charging stations with PV units is explained in Section 4. Section 5 shows numerical results along with discussions, followed by the conclusions and contributions of the work in Section 6.

2. Commercial load, PHEV and PV modeling

This study considers a MV power distribution network that delivers electricity to commercial customers. Their buildings are

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