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Studying the feasibility of charging plug-in hybrid electric vehicles using photovoltaic electricity in residential distribution systems

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ABSTRACT

Recently, interest has grown in using photovoltaic (PV) electricity to charge plug-in hybrid electric vehicles (PHEVs). This paper investigates the feasibility of such a charging alternative, from a distribution system performance perspective. To achieve this goal, it is first necessary to determine the resulting aggregated impacts for both technologies when they operate in parallel. Although extensive research has explored the individual impacts of PHEVs and PV electricity on distribution networks, far too little study has been made of the interaction between these two technologies and the resulting aggregated impacts when both operate together.

This paper fills this gap by developing a probabilistic Monte Carlo (MC)-based benchmark that can be used to assess the resulting impacts when PV arrays are used to charge PHEVs. Finally, the authors compare the resulting aggregated impacts with those resulting when PHEV charging demands are met solely from the medium voltage network, in order to draw conclusions on the feasibility of such a charging alternative.

1. Introduction

While plug-in hybrid electric vehicles (PHEVs) are a promising technology that produces considerably lower amounts of greenhouse gas emissions and achieves greater fuel economy than conventional vehicles, they are considered by many researchers to be the next challenge facing the utility industry. PHEV adoption rates in the United States may reach 28% of the total vehicle market share by 2031 [1,2], consequently representing a charging load of about 860 GWh per day [3]. The situation is made worse by the natural coincidence between peak electricity demand and the hours during which the majority of these vehicles are parked at residences and are thus probably being charged [4]. This natural coincidence leads to significant distribution equipment overloads [4–7], especially at secondary distribution levels where the diversity benefits are not as significant as at higher system levels [8,9].

One straightforward accommodation for this increased demand is to upgrade the generation, transmission and distribution infrastructure, which would be very costly and require many years to obtain the permits required [2] in this unsettled regulatory environment and with the current "not in my backyard" mentality. Adopting smart (coordinated) charging schemes for PHEVs provides another feasible solution, by shifting PHEV charging demands to off-peak periods [10–12]. Smart charging, however, is outside the scope of this research and will not be addressed in this paper.

In response to concerns about climate change, energy security and oil-depletion, several countries are encouraging the development of small-scale renewable distributed generation (DG) units. As a result, the future power system is expected to include a significant penetration of these units. A third viable alternative to accommodate PHEVs would be using these renewable DG units, already existing in distribution networks close to load centers to meet the extra charging demands. Theoretically speaking, any micro-generation resource can be used to do so. However, in practice, photovoltaic (PV) arrays are expected to be the most widely used DG technology in residential distribution networks. This expectancy is based on the fact that PV arrays exemplify a clean source of energy that can be easily installed on rooftops (without needing bureaucratic city land-use approvals) to generate electricity and at the same time protect the environment. Residential customers also prefer solar-based DG units due to the generous incentives often offered by governments to facilitate the widespread adoption of solar electricity. For example, in Ontario, the microFIT program (funded by the Ontario Power Authority

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to encourage the development of micro renewable generation in the province) offers 80.2 cents/kWh for PV-generated electricity, whereas the same program offers only 19 cents/kWh for wind-generated electricity [13]. As a result, 1856 proposals out of the 1858 microFIT proposals received up to November 2013 are for rooftop PV systems [14].

A large and growing body of literature has investigated the possibility of charging PHEVs using PV electricity. Reference [2] suggested a methodology for determining the optimal size of a PV array that can be used to charge a PHEV driven for 40 miles daily. Another study [15] proposed a design for a grid-connected residential PV system that can be used to charge a PHEV as well as to supply existing household loads. Bedir et al. [16] demonstrated experimentally how a solar-powered, net zero-energy house equipped with a battery energy storage system (BESS) can be used to charge a PHEV and to reduce dependency on the grid. An interesting study [17] discussed the economic feasibility of charging PHEVs using renewable energy sources (such as PV arrays). In that study, a configurable eco-system with PHEVs, renewable energy resources and storage devices is modeled using data for the State of Ohio that includes the cost of energy, anticipated photovoltaic capacity and government regulations and incentives. Study results showed that using renewable energy resources to charge PHEVs is economically feasible as it has the potential to reduce the operational costs of PHEVs, increase the economic viability of PV electricity and reduce the environmental impacts in terms of CO_2 emissions. These promising results led to increased interest in the topic by several entities; for example, Hydro One-the largest distribution utility in Ontario-is funding a $295,000 research project that aims to develop a PHEV charging station employing PV arrays. The U.S. Department of Energy is funding a similar $200,000 research project that aims to maximize the synergy between PHEVs and PV arrays.

From previous discussion, it becomes evident that previous researchers focused mainly on studying the feasibility of charging PHEVs using PV electricity from a device-level perspective, and did not analyze the aggregated system-level impacts.

The main focus of this paper is to investigate the feasibility of using PV electricity to charge PHEVs, from a system performance perspective, or in other words, to determine whether charging PHEVs using PV electricity will negatively affect the performance of the distribution network or not. This task, however, necessitates accurate determination of the resulting aggregated impacts when both technologies operate together. Although extensive research has been carried out on the individual impacts for PHEVs and PV electricity on distribution networks, far too little attention has been paid to studying the interaction between these two technologies and the resulting aggregated impacts when both operate in parallel. Moreover, previous researchers who have conducted research on the same topic failed to provide adequate models for different uncertainties present in the system. For example, the authors of [18] studied the aggregated impact of PV arrays and PHEVs in terms of network voltages and power losses. However, the paper has several drawbacks: PV intermittency was not considered in the analysis, and individuals' driving habits that may impact the charging process were not modeled properly. For example, PHEV home arrival times were simply assumed to follow a normal distribution centered at 6 pm, with a 2-h variance. Also the stochastic nature of electrical loads was completely ignored; only one load shape was used in the analysis.

In this paper, the authors address the above-mentioned drawbacks by developing a probabilistic Monte Carlo-based benchmark for assessing the resulting aggregated impacts of PV arrays and PHEVs accurately, satisfying the following requirements:

i. To consider the intermittent nature of PV array outputs.
ii. To consider the stochastic nature of existing loads.
iii. To utilize transportation data to obtain an accurate probabilistic representation for individuals' driving habits that impact PHEV charging.
iv. To assess comprehensively the anticipated impacts on different distribution system components (primary feeders, secondary distribution transformers, voltage regulators, single phase laterals and service drops).

The remainder of the paper is organized as follows: Section 2 describes the proposed benchmark, Section 3 outlines the Monte Carlo simulation procedure, Section 4 presents the simulation results for a range of scenarios, and finally Section 5 concludes the paper.

2. Description of the proposed benchmark

Assessing the aggregated impacts of PV arrays and PHEVs on residential distribution networks is basically a probabilistic load flow (PLF) problem; best solved using Monte Carlo simulation. This is; however, a difficult task due to different uncertainties characterizing the probabilistic loads present in the PLF problem.

Previous research adopted several unbacked assumptions and approximations while modeling these uncertainties, either due to a lack of a reliable data or to simplify the analysis, which may have affected the accuracy of the performed analysis. That is, according to Monte Carlo simulation theory [19]: if the inputs for a certain process are sampled (randomly generated) following their actual probability distributions, the output will be random as well; yet, the probability distribution for the estimated output will follow that of the true output with acceptable error (given an appropriate stopping criterion) and both probability distributions will coincide after infinite number of simulations (according to the law of large number (LLNs) [20]). However, if the process inputs are generated in a totally random fashion (without following their actual probability distributions), there is no guarantee that the estimated output will actually represent the true output.

Providing adequate modeling for different uncertainties characterizing the probabilistic loads present in the PLF problem is another contribution of this paper; instead of relying on unbacked assumptions, the authors performed statistical analysis for the available load and transportation data to extract probability functions describing different uncertainties in the system as precisely as possible, thus providing more truthful results.

This section provides an overview of the probabilistic models used in this research to describe different uncertainties present in the system.

2.1. Modeling uncertainties related to PV arrays output

In this research, the authors use their approach described in [21,22] to model the probabilistic output of PV arrays. Hourly insolation and temperature data provided by the Solar Radiation Research Laboratory are used to estimate PV arrays' DC power output using the empirical model described in [23]. The equivalent AC output power is computed using a typical inverter efficiency curve [24]. The 24 data points representing the PV electrical output in one day are assembled in a data segment. The resulting 365 data segments representing the whole year are evaluated for similarities using principle component analysis, and then similar segments are grouped into one cluster using clustering techniques. For each cluster, a representative segment is selected, and the probability of occurrence of each segment is computed. The results of the clustering process reveal that the complete dataset can be represented using only 19 representative segments (instead of 365) while retaining temporal variations within the data, thus, reducing