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Electric vehicle charging algorithms for coordination of the grid and distribution transformer levels

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ABSTRACT

The need to reduce greenhouse gas emissions and fossil fuel consumption has increased the popularity of plug-in electric vehicles. However, a large penetration of plug-in electric vehicles can pose challenges at the grid and local distribution levels. Various charging strategies have been proposed to address such challenges, often separately. In this paper, it is shown that, with uncoordinated charging, distribution transformers and the grid can operate under highly undesirable conditions. Next, several strategies that require modest communication efforts are proposed to mitigate the burden created by high concentrations of plug-in electric vehicles, at the grid and local levels. Existing transformer and battery electric vehicle characteristics are used along with the National Household Travel Survey to simulate various charging strategies. It is shown through the analysis of hot spot temperature and equivalent aging factor that the coordinated strategies proposed here reduce the chances of transformer failure with the addition of plug-in electric vehicle loads, even for an under-designed transformer while uncontrolled and uncoordinated plug-in electric vehicle charging results in increased risk of transformer failure.

1. Introduction

Plug-in electric vehicles (PEVs) have been gaining popularity in recent years due to the need to reduce fossil fuel consumption and greenhouse gas emissions [1]. PEVs include plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). In Ref. [2], it is shown that meeting ambitious reduction in greenhouse gasses, such as those planned for California, requires large numbers of PEVs. According to [3] market share of PHEVs is expected to increase to 25% by 2020. This would lead to an overall PHEV penetration of about 9% of all vehicles in use. While this penetration level might seem low, concentrations of PEVs could become quite high in more affluent and tech savvy neighborhoods (e.g. Silicon Valley) [4]. This uneven distribution can occur across national boundaries. For example, the Tremove model predicts a PHEV penetration as high as 30% for Belgium by 2030 [5]. Here, it is assumed that the vehicles rely on electric power primarily, therefore the focus is on BEVs.

Interactions between large number of electric vehicles and power networks have been studied by several groups. In Ref. [6], integration of PEVs is studied with regard to reconfigurable microgrids, while [7] analyzes the impact of 100% PEV penetration on the power transmission network. Reference [8] shows that PEVs can be used as storage, in vehicle-to-grid (V2G) charging, to reduce reliance on coal/natural gas. In Ref. [9], similarly, PEVs are studied as alternative energy storage, for high renewable penetration levels, given the intermittency of renewable sources (see, e.g., [10,11] on challenges in integrating wind and solar energy into a conventional grid). In Ref. [12], PEV batteries (although only at their automotive end of life) are repurposed as stationary storage systems to integrate intermittent wind power. In Ref. [13], it is found that large number electric vehicles that recharge at night, can level the electricity demand, and increase the amount of wind power that can be used. High concentrations of PEVs, however, can also cause grid level challenges during high demand periods if vehicle charging is uncoordinated.

Large, and non-uniform penetration levels have the potential to pose additional challenges, namely at the local level through distribution transformers. These transformers are often designed and sized for the non-BEV power demand of a group of residences (e.g., a street). Large loads, extended over long periods can shorten the life, as well as increase the risk of serious damage [1] to distribution system equipment (including transformers). While transformers

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Notation

Symbols

b_n	Energy used by each BEV, between charging cycles
$C_{grid}(t_i)$	Broadcast cost from the grid for each timeslot
$C_{trans}(t_i)$	Broadcast cost from the transformer for each timeslot
I_{CD}	Cooling down period
J	Total charging cost
n	PEV number
P_{lim_i}	Desired maximum power limit for the transformer
$\overline{P_{lim_i}}$	Desired maximum power limit for the transformer with cooling down period
$p_n(t_i)$	Charging power for each BEV
$r_n(t_i)$	Maximum charging energy for each BEV n, at each timeslot
t_i	Timeslot i
$\overline{\Delta t_n(t_i)}$	Time each BEV n is plugged in during timeslot i
$x_n(t_i)$	Charging energy for each BEV n, at each timeslot
η	BEV charging efficiency

Abbreviations

AAF	Aging Acceleration Factor
BEV	Battery Electric Vehicle
BSOC	Battery State of Charge
EAF	Equivalent Aging Factor
HST	Hot Spot Temperature
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
TOU	Time-of-Use

are designed to tolerate certain levels of overload, excessive overloads can be problematic. Overloading can increase the hot spot temperature (HST), which can increase the equivalent aging factor (EAF). This would cause more frequent replacement of transformers [1] and upgrades to the distribution system.

Scheduling EV charging properly, may reduce the daily cycling of power plants and the operational cost of the electric utility [14]. The issue of accommodating the charging needs of a large number of PEVs without placing extreme stress on the electricity distribution network have been studied by a number of research groups. EV charging control strategies fall into three main categories: time-of-use (TOU), centralized control, and decentralized control [15]. In Ref. [5] quadratic and dynamic programming techniques are used to generate charging profiles for PEVs by minimizing power losses in the distribution grid. In Ref. [16] a decentralized charging strategy is proposed for the case where all EVs have identical characteristics (same charging horizon, power consumption, and maximum charging rate). In Ref. [15] another decentralized charging strategy is proposed which alleviates the necessity for the identical characteristics assumed in Ref. [16].

In this paper, the focus is on leveling the grid scale power demand by developing a smart charging strategy for high electric vehicle penetrations, while avoiding excess damage to the infrastructure (e.g., distribution transformers). Due to the communication and computational requirements for a real world application, the focus is on a decentralized approach. This paper starts with the simple algorithm proposed in Ref. [4], in which a non-iterative approach is developed that results in maximum charging rates for all charging periods, is capable of achieving valley filling (when desired), and can be modified easily to follow specific grid level demand profiles (e.g., to accommodate the integration of renewable power generation in the grid, thought that is not the main focus). It is then shown that under reasonably mild conditions, a large number of distribution transformers can operate under undesirable conditions (i.e. significantly higher than designed power levels), be it under a grid level coordination or uncoordinated charging.

Charging strategies have also been developed to improve performance at the distribution level as well. The effects of uncontrolled and off-peak charging are studied in Refs. [1,3]. Both papers find that smart charging strategies can mitigate the negative effects of PEV charging. Two smart charging strategies are proposed in Ref. [3]. The first prevents transformers from overloading by delaying charging of PEVs. The second sheds or defers non-critical household loads (e.g. water heaters and dryers) during PEV charging. Load shedding is not considered in this paper due to communication, technical, and privacy concerns. Neither algorithm addresses grid level concerns and deal with the safety of local transformers only. Another local control strategy is proposed in Ref. [17] that depends only on local network conditions and the battery state of charge (BSOC) of the PEV. A centralized control charging strategy where a single controller manages the charging rates of all PEVs is then also proposed.

In Ref. [18], Distribution Feeder Reconfiguration (DFR) is used to coordinate PEV operation in a stochastic framework. The DFR strategy is employed to minimize operational costs and increase the penetration of PEVs with the use of V2G. An application of the proposed approach demonstrates its robustness and effectiveness. In this paper, V2G is not investigated and focus is given to more readily available technologies. In Ref. [19] the integration of a high number of electrical vehicles in a renewable-dominated power system is studied. The problem is formulated using a two-stage stochastic programming model.

A critical issue that remains unresolved is that improved grid performance can negatively affect local distribution components. In Ref. [20] decentralized charging protocols are developed that use cost signals to achieve a valley filling profile at the grid. The charging strategy from Ref. [15] is expanded to develop three different iterative algorithms that incorporate capacity constraints, relying on stochastic optimization techniques using nested iterative algorithms. The capacity constraints in Ref. [20] can be used to prevent failure and/or improve the efficiency of local components (e.g. transformers).

The focus of this paper is developing a decentralized algorithm, with minimal communication and delay considerations (e.g., non-iterative) that addresses both grid level concerns (i.e., utility level economics) and local levels (e.g., safety and maintenance concerns), with priority given to local concerns. Here, the two concerns are combined by expanding the algorithm in Ref. [4], with only slight increases in communication and computation requirements. The algorithm from Ref. [4] requires modest communication between the grid operator and the BEV. As in Ref. [20], the modifications made to the algorithm from Ref. [4] requires communication between the BEV and the local distribution transformer. However, since iterative techniques are not used, the increase in computational effort (performed by the BEV) is negligible. This communication is used to prevent charging during times that could cause overloading. Naturally, the algorithm proposed here is not limited