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Coordinated control of building loads, PVs and ice storage to absorb PEV penetrations

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A B S T R A C T

Plug-in Electric Vehicles (PEVs) are active loads as they increase the distribution network's demand during charging and can have potential impacts on the network. This study discusses the impact of PEV charging on a distribution feeder serving commercial customers and proposes a mitigation strategy to make PEV penetration transparent to the grid. The proposed strategy relies on coordinated control of major loads in demand responsive commercial buildings, ice storage, along with strategically deployed solar photovoltaic (PV). A real world electrical distribution feeder serving a number of commercial buildings is used for analysis purposes. Rather than looking at individual building's economic benefits, the proposed approach considers overall technical and economic benefits of the whole distribution network, focusing on enhancing distribution-level load factor and reducing feeder losses. Results indicate that by performing load control in selected commercial buildings, along with utilizing capability of existing ice storage units and strategically deployed PV, the proposed approach can absorb 100% PEV penetration, and result in 13.4% decrease in the peak load; 10.9% improvement in the load factor; and 11.6% reduction in feeder losses. Sensitivity analysis shows that both load control and PV are needed to absorb any PEV penetration above 50% level.

1. Introduction

Utilities generally meet peak demand through expensive peaking units which are operated only for short periods of time. At the same time the growing demand for Plug-in Electric Vehicles (PEVs) in the U.S. impacts the already burdened distribution network during peak hours. PEVs are active loads as they increase the distribution network's demand when charging. PEV charging may bring about several challenges to the distribution network, including reduced load factors, potential transformer overloads, feeder congestion and violation of statutory voltage limits.

With respect to the current literature, most studies have analyzed PEV charging at residential sites [1–6] and have focused on controlling residential PEV fleet charging to reduce the distribution network's peak load or improve its power quality [7–9]. Authors in [10,11] point out that un-coordinated PEV charging increases transformer losses, thermal loading on the distribution transformer, voltage deviations, harmonic distortions and peak demand and requires additional investments on distribution side reinforcements. Authors in [12] charge the PEVs when electricity prices are low to keep the energy cost low and by using stored energy from an aggregate PEV battery from electricity process are high. Authors in [13] optimally schedule PEVs in a distribution network to maintain grid constraints. Studies [2,14] demonstrate that controlled PEV charging can improve the distribution feeder's voltage profile and reduce the power losses. However, controlled PEV charging delays PEV charging to night time which could prevent distribution assets, such as transformers, from cooling down overnight, reducing their lifetime [15]. Also at the end of controlled charging some PEVs may not be charged to the desired State of Charge (SOC) level [16]. Authors in [17] develop an approach to optimally locate PEV charging stations in a distribution network. Public PEV charge stations are expected to be located at dense population centers most convenient for the consumers such as parking lots, hotels and other publicly accessible locations [15]. And, these public charging stations would typically require Direct Current (DC) fast charging to allow PEVs to be fully charged within less than half an hour [18]. Such fast charging would significantly increase peak demand on an electric power distribution system especially during hot summer days [15]. Unlike residential PEVs with 6–8 h available for recharging, controlling PEV charging at public parking/commercial sites to reduce their impact on the grid is not applicable [7]. There are studies which have analyzed solar photovoltaic (PV) to relieve grid's stress conditions due to PEV charging. Authors in [19]

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demonstrate increase in reliability indices due to PEV penetration and conclude that absence of renewable generation worsens the scenario. Authors in [20] use renewable generation, as an alternative to upgrading the distribution network, or controlled PEV charging, to accommodate high penetration of PEVs in the distribution network.

Overall, a thorough literature search shows that, while majority of previous work pays attention to the impacts of PEV penetration in residential distribution networks, there is a lack of studies analyzing impacts of PEV penetration in distribution networks serving primarily commercial customers. Load control strategies till now have been implemented and analyzed in individual commercial buildings for their own economic benefits. However, researchers have overlooked load control implementation to a group of commercial buildings to efficiently reduce grid's peak load and improve distribution system load factor. There are studies which discuss management of PEV charging demand. Different PEV charging scenarios have been analyzed including uncontrolled charging, delayed charging based on utility signals and off-peak charging to reduce grid impacts. In this study instead of controlling or delaying PEV charging to reduce grid stress conditions, a coordinated load control strategy for controlling end-use building loads including ice storage discharge, along with strategically deployed solar rooftop PV systems in groups of participating commercial buildings are employed to absorb PEV penetration using real world charging scenarios. A real world electricity distribution feeder model developed in Distribution Engineering Workstation (DEW) software is used in order to assess impacts of integrating PEVs to the grid.

2. PEV absorption strategy for the distribution feeder

To absorb PEV penetration, control of major loads, ice storage discharge, along with PV are introduced in demand responsive commercial buildings. The flowchart in Fig. 1 illustrates the overall strategy for PEV demand absorption in a distribution feeder. The objective of the proposed strategy is to keep the distribution feeder's peak demand unchanged with PEV penetration.

To accomplish this, a threshold value is selected, which is the distribution feeder's original peak demand (kW) without PEV, load control, PV and ice storage systems. If the distribution feeder's peak demand gets higher than this threshold due to PEV penetration, the excess load will be shed by performing control of major loads in participating demand responsive commercial buildings. The control of major loads will be arranged to spread over the day and hence minimizing demand restrike – Here, demand restrike refers to a sudden increase in building load due to set point adjustments after a building participation in load control [21].

2.1. Strategy to decide level of participation from each demand responsive building

The level of load control implemented in each building depends if they can provide appreciable load control savings which is mainly based on buildings' operating schedules and load control savings potential during the operating hours. In this study, load control savings potential was evaluated through simulation studies by simulating each building type in EnergyPlus for different time periods of the day with the designed load control algorithm (discussed below). Based on this insight, buildings with smaller operating hours were made to participate first in load control and those with longer operating hours participate later in load control. For instance, office buildings need not to participate in load control during late evening hours, when their occupancy is low, and can only provide limited load control savings. Whereas more retail buildings can participate towards late evening hours due to their longer operating hours and ability to still provide appreciable load control savings. This method is further elaborated by using a case study as discussed in Table 3, Section 4.1.

The resulting EnergyPlus simulation also reveals the relationship between the size of a building and the amount of load control savings a building can provide. That is, load control savings of small-sized office buildings are less than other demand responsive buildings. These buildings can absorb only a small portion of excess demand. Hence, they can participate when PEV charge impacts are limited. If a building cannot provide appreciable load control savings, then it will not participate in load control and continues its normal operation.

2.2. Strategy for controlling major loads and ice storage in a building

Upon receiving a signal indicating excess load due to PEV charging, it is assumed that a third party DR aggregator, such as EnerNOC, sends signals and communicates with multiple buildings to obtain their DR potentials. Based on potential savings each building can provide through end-use load control and ice storage discharge, they are carefully selected to participate in the load control event. Each participating building manages its end-use loads - i.e., Heating Ventilation and Air Conditioning (HVAC), lighting, and plug loads, including PEVs - and controls ice storage charge/discharge to achieve maximum demand reduction (kW) while maintaining a comfortable indoor environment. This control algorithm was designed using EnergyPlus Energy Management System (EMS). A building was assumed to participate in load control for no more than 3 h to limit occupant discomfort. In each participating building its end-use loads including HVAC, lighting and plug loads are controlled by the EMS at a time step of 1-min for the entire 3 h duration while maintaining occupant comfort requirements. The strategy for controlling each major loads, including HVAC, lighting and plug loads, is discussed below.

2.2.1. Strategy for HVAC load control

In this study, the algorithm designed for space temperature set point control adjusts each thermal zone's cooling set points to achieve peak load savings and maintain occupant thermal comfort, i.e., Predicted Mean Vote (PMV) index, in each zone within comfortable limits. At each time step, each zone's cooling set points are adjusted repeatedly until a value is obtained at which the PMV index lies between −0.5 and +0.5 and maximum peak load savings can be achieved. Once judgment has been made as per the EMS program instructions, EMS zone temperature control actuators implement the adjustment in thermostat cooling set points for all zones as per Eq. (1). The offset varies at each time step, depending upon how much the cooling set points should be increased or decreased in order to maintain the PMV index within comfortable range.

$$SETT^{Adjusted}_{cool} = T^{Normal}_{cool} + \beta_{cool}c \tag{1}$$

where

$T^{Adjusted}_{cool}$	:	Adjusted cooling set point (°C)
T^{Normal}_{cool}	:	Normal operating cooling set point (°C)
β_{cool}	:	Adjustment factor for cooling load (°C)

2.2.2. Strategy for lighting load control

The algorithm designed for lighting load control in EMS provides a tighter control of light levels, integrated with daylight, to maintain the illuminance at the desired set point (i.e., 500 lx) in