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

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ABSTRACT

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.

$$SETT_{cool}^{Adjusted} = T_{cool}^{Normal} + \beta_{cool}c \tag{1}$$

where

$T_{cool}^{Adjusted}$	:	Adjusted cooling set point (°C)
T_{cool}^{Normal}	:	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

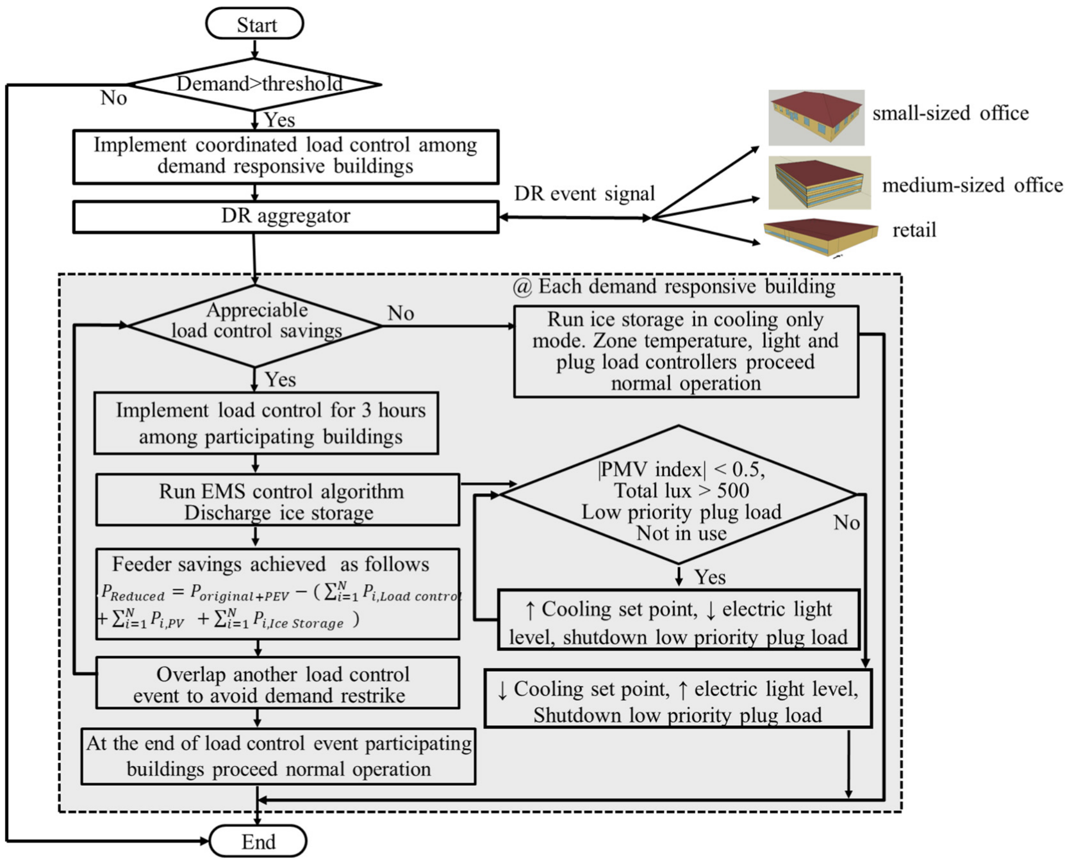

Fig. 1. Load control strategy for the distribution feeder.

order to achieve more savings with good adaptability to the changing daylight conditions. At each time step, the electric and daylight illuminance together are sensed, if daylight illuminance value is greater than 500 lx than the zone light control actuator completely shuts down the zone electric lights by setting the adjustment factor in Eq. (2) to zero. If the daylight illuminance level is less than 500 lx than the EMS zone light control actuator increases or decreases the electric lighting level as per Eq. (2) by varying the adjustment factor.

$$SETP_{light}^{Adjusted} = P_{light}^{Normal} \cdot S_{light} \cdot \beta_{light} \tag{2}$$

where

$P_{light}^{Adjusted}$	:	Adjusted lighting load power (W)
P_{light}^{Normal}	:	Normal lighting load power (W)
S_{light}	:	Normal lighting load schedule
β_{light}	:	Adjustment factor for lighting load

2.2.3. Strategy for plug load control

The plug load control algorithm allows key plug loads to be individually controlled and shut down by the EMS. In particular, electric plug loads are shut down by EMS zone plug load control actuators as per Eq. (3). The adjustment factor is 0.5, which allows shut down of 50% miscellaneous equipment in each zone, and zero for shutting down all low priority plug loads during a load control event.

$$SETP_{plug}^{Adjusted} = P_{plug}^{Normal} \cdot S_{plug} \cdot \beta_{plug} \tag{3}$$

where

$P_{plug}^{Adjusted}$	:	Adjusted plug load power (W)
P_{plug}^{Normal}	:	Normal operating plug load power (W)
S_{plug}	:	Normal operating plug load schedule
β_{plug}	:	Adjustment factor for plug load

2.2.4. Strategy for ice storage charge/discharge control

Some demand responsive buildings have ice storage systems integrated with their packaged air-conditioning (AC) units which can be controlled to discharge fully or partially [22] and provide space cooling, thereby further reducing the cooling load. For demand responsive buildings with ice storage systems, their mode of operation is changed to discharge-only mode (full storage discharge) or cool and discharge mode (partial storage discharge) as needed by the EMS during the 3 h load control event so that building's cooling energy consumption can be reduced through storage discharge.

2.3. Calculation of distribution feeder demand

The distribution feeder's demand is reduced per Eq. (4).

$$P_{Reduced} = P_{original+PEV} - \left(\sum_{i=1}^{N} P_{i,Loadcontrol} + \sum_{i=1}^{N} P_{i,PV} + \sum_{i=1}^{N} P_{i,IceStorage} \right) \tag{4}$$

where $P_{Reduced}$ is the distribution feeder's reduced demand in kW that needs to be shed due to PEV penetration, $P_{original+PEV}$ is the feeder's original demand with PEV penetration, $P_{i,Loadcontrol}$ is the optimized demand value in kW for the ith demand responsive commercial building participating in load control; $P_{i,PV}$ is the demand reduction in kW by the PV system for the ith demand responsive commercial building participating in load control; $P_{i,IceStorage}$ is the demand reduction in kW by the ice storage system for the ith demand responsive commercial building participating in load control.

2.4. Mitigating demand restrike

By performing load control in buildings, demand restrike can occur after a load control event when buildings proceed with their normal operation and instantaneously reduce cooling set points and ice storage switches to conventional cooling, causing an increase in electric cooling consumption. While demand restrike can be managed locally at each building by slowly bringing back the cooling set points, the proposed strategy chooses to mitigate demand restrike by managing demand in a different group of buildings. This will reduce the overall occupant discomfort, especially in buildings that already participated in a load control event for three hours.

Lastly, if load control strategy (including ice storage control) is not able to absorb PEV penetration, the proposed strategy will suggest appropriate sizes and number of rooftop PVs to help absorb PEV penetration.

3. Methodology

In this section the commercial building, PEV, PV and ice storage and distribution feeder models used in this study are discussed.

3.1. Commercial building models

Three types of demand responsive buildings were considered in the modeled distribution feeder, namely small-sized office buildings, medium-sized office buildings and standalone retail stores. Building operations were modeled in EnergyPlus, a building energy simulation tool, based on the already validated building models [23] [24]. These models are explained in detail in [25,26]. In this study, these buildings were integrated into the modeled distribution feeder, and thus their power consumption was scaled down to match with the existing load and distribution transformer ratings. See Fig. 2, which shows the scaled down power consumption profiles of three types of simulated commercial buildings for a summer day.

In particular, the small- and medium-sized office buildings originally have an area of 5500 ft^2 and 53,628 ft^2, respectively; and the retail building's original area is 40,500 ft^2. In order to accommodate these buildings in the distribution feeder, their areas were scaled down by a factor of three, hence their power consumption was reduced accordingly.

With respect to building operation, both small- and medium-sized office buildings follow typical occupancy patterns, with peak occupancy between 8 am and 5 pm on weekdays. Occupancy is limited beginning at 6 am and extended until midnight to include janitorial function and after-hours work. During peak occupancy, lights and equipment usage is also at its maximum with a decrease during lunch time, i.e., between 12 pm and 1 pm. These buildings have a scaled down peak load of 10 kW (at 4 pm) and 74 kW (at 4:10 pm) for small- and medium-sized offices, respectively. On the other hand, the retail building has the peak occupancy between 11 am and 1 pm and 5–7 pm on weekdays. Lighting and equipment usage is high from 9 am to 9 pm. The building's power consumption profile has spikes due to the on and off cycling of the electric water heater. The retail building has a scaled down peak load of 73 kW at 7:50 pm due to additional power consumption by the external lights along with high internal loads.

3.2. Electric vehicles models

In order to accurately determine the impacts of PEVs on the distribution feeder, PEV models indicating real world charging scenarios are needed. PEV models used in many studies are based on assumptions ignoring either vehicle types, diversity of usage, multiple charging events over the day, dynamics of PEV arrivals and departures in real time, or driving habits [27]. In this study, real-time PEV charge profiles monitored over a year at both residential and public charging stations (courtesy of Dominion Electric) were used. Charging power consumptions of different PEVs including, Nissan Leaf, Chevrolet Volt and Tesla Model S at various residential sites were monitored along with aggregate PEV charge profiles for charging stations located at a retail site. The monitored data represents varying driving distance, vehicle class (sedan, small car, SUV, etc.), driving cycle (city, highway, congested) and the driver style (aggressive, passive) for residential and public PEVs.

Table 1 shows the type, number and rating of PEV charge stations assumed to be available at each type of demand responsive buildings.

In particular, workplace PEVs are charged with Alternating Current (AC) level 2 chargers. These chargers use 208 V or 240 V and can deliver up to 19.2 kW maximum power [28,29]. California Green Building Standards Code [30] recommends buildings with less than 9 parking spaces to install one PEV charge station and those with parking spaces around 10–25 to install two PEV charge stations. Based on this recommendation, this study assumes that: a

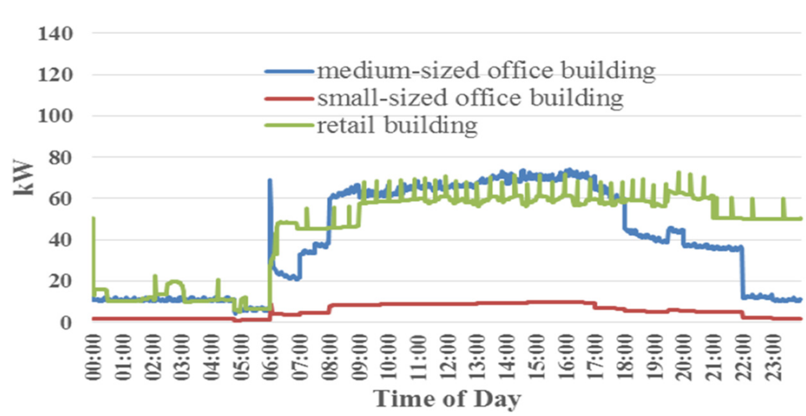

Fig. 2. Scaled down power consumption profiles for the commercial buildings used in this study for a summer day.

Table 1
PEV Charge Stations for Demand Responsive Buildings.

Buildings	Type of charge station	No. of charge stations	Maximum charging power (kW)
Small-sized office	AC level 2	1	19.2
Medium-sized office	AC level 2	2	19.2
Standalone retail	DC fast charge	1	50

Table 2
Demand Responsive Buildings Peak Demand w/ and w/o PEV.

Buildings	Peak demand without PEV	Peak demand with PEV	% increase
Small-sized office	10 kW @4:00 pm	20 kW @2:30 pm	100%
Medium-sized office	74 kW @4:10 pm	93 kW @4:10 pm	26%
Standalone retail	73 kW @7:50 pm	119 kW @11:58am	63%

small-sized office building has one AC level 2 PEV charging station; a medium-sized office building has two AC level 2 PEV charge stations; and a retail site has a 50 kW DC fast charging station.

The PEV charge profiles were added to the buildings' existing electric service, i.e., the buildings' existing power consumptions. Fig. 3, shows examples of power consumption profiles with PEV for the modeled commercial buildings. These profiles are slightly varied for respective building types to depict diversity. A survey [6] shows that PEV owners primarily recharged their vehicles upon arrival at work, and charging at public stations takes place throughout the day. Hence it is assumed that PEV owners in office buildings plug-in their cars upon arrival in the morning and unplug during lunch time to allow other PEV owners to charge their PEVs. Hence PEV charging consumption is high from around 8am to 12 pm and from around 1 pm to 5 pm. Random DC fast charging of PEVs at retail sites mostly occurs in the afternoon and evening hours while owners do shopping. PEV charging consumption is higher from around 11 am to 1 pm and 5 pm to 7 pm when retail building's occupancy is also high. Hence, PEV charging at different buildings in the distribution network occur simultaneously.

Table 2 shows the demand responsive buildings peak demand with the selected PEV charge profiles shown in Fig. 3. As shown, small and medium-sized office and retail buildings' peak demand increases by 100%, 26% and 63% respectively with PEV penetration.

3.3. Solar photovoltaic models

Distribution Engineering Workstation (DEW) [31] was used to model grid-tied PVs with actual PV output profiles in one-minute resolution from the PV units installed at the Virginia Tech – Advanced Research Institute in Arlington, VA. In this study, the rating of rooftop PV is dependent upon the building's available roof space as explained in [32,33]. PV covers about 40–65% of the buildings' roof area. Inter-row spacing between PV modules is calculated based on site's latitude, the desired solar window and the PV modules' height and tilt angle to avoid tops of tilted row of PV modules shading the bottom of behind row.

A typical sunny day has been considered but as the demand responsive buildings are located at various sites in the distribution feeder, PV output profiles of these buildings vary from location to location due to scattered clouds. Fig. 4 shows example PV profiles with varying output for each type of demand responsive building in the distribution feeder. As shown, peak PV output, for the small-sized office, medium-sized office and retail building are 3 kW, 35 kW and 41 kW, respectively. Demand responsive buildings located elsewhere in the feeder have slightly different PV profiles.

3.4. Ice storage model

Ice storage models were developed in EnergyPlus, providing modeling of ice storage system integrated with packaged air conditioning (AC). Usually ice storage systems are integrated with chillers. Mostly small and medium-sized commercial buildings have packaged AC units and if ice storage systems can be integrated with these, its deployment potential could be high. Ice storage system provides peak load shifting, i.e., changing the timing of energy consumption for space cooling. For ice storage system integrated with packaged air condition unit charging and discharging involves circulating a heat transfer fluid between ice storage system's refrigeration cycle equipment and its storage section. The main components of ice storage system integrated with packaged air conditioning are compressor, condenser, evaporator and ice storage tank. The model operates in different modes of operations including the off mode, cool-only mode, cool and charge mode, cool and discharge mode, charge-only mode and discharge-only mode. As load control events are planned ahead of time and building owners are made aware of them hence, the storage is fully charged before the start of a load control event. During a load control period the ice storage system can be made to operate in either discharge-only mode (full storage discharge) or cool and charge mode (partial storage discharge) where both ice storage and packaged AC meet building cooling needs. In this study, medium-sized office buildings are equipped with ice storage systems. Each of the building's three floors has its own ice storage system with a storage capacity of around 6GJ.

As an example, Fig. 5 shows the demand responsive medium-sized office building load profiles with and without ice storage.

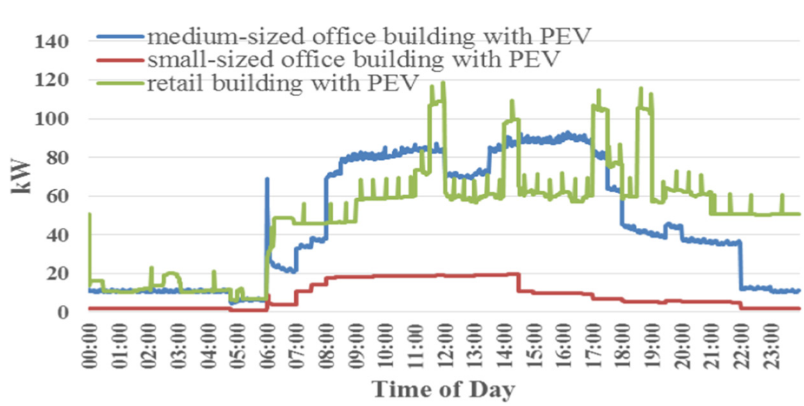

Fig. 3. Scaled down building power consumption profiles with PEV.

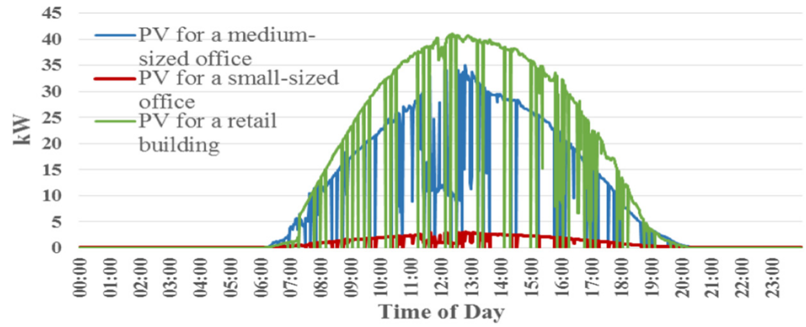

Fig. 4. PV profiles for the demand responsive buildings used in this study.

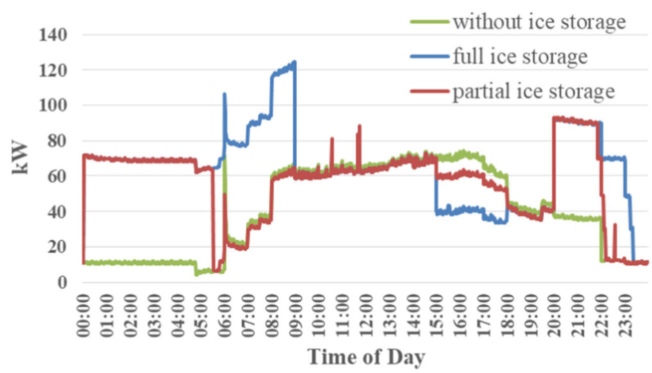

Fig. 5. Demand responsive medium-sized office building load profiles w/o and w/ ice storage used in this study.

The figure shows full and partial ice storage discharge for a load control period from 3 pm to 6 pm during which ice discharge reduces building's electric cooling consumption. At the end of the load control period, building's demand increases as the ice storage operates in cooling only mode, i.e., packaged AC alone meets the building's cooling demand. Ice storage shifts building's demand to off-peak periods.

3.5. Distribution feeder model

A real world distribution feeder model, shown in Fig. 6, was used for analysis purposes in this study. This distribution feeder was modeled in DEW software and simulations were performed using its power flow applications [34]. The main feeder is about 5272 ft long with branching laterals. The 3-phase voltage at the substation is stepped down from 69 kV to 13.2 kV. The circuit has a total of 97 load buses with both commercial and residential customers. 25 load buses are supplied by phase A; 12 by phase B; 18 by phase C; and 42 buses have a 3-phase supply.

Commercial customers connected to 21 load buses in the feeder were replaced with dynamic demand responsive building loads as discussed in Section 3, representing a penetration of about 22%. These demand responsive buildings include 8 medium-sized office buildings, 7 stand-alone retail buildings and 6 small-sized office buildings. The load buses selected to be replaced by the demand responsive buildings originally had commercial loads connected to them with peak demand similar to that of the new demand responsive buildings and the building transformers can accept additional building load. The demand responsive buildings are connected to the 3-phase load buses except for two buildings which are connected to the load buses supplied only by phase A.

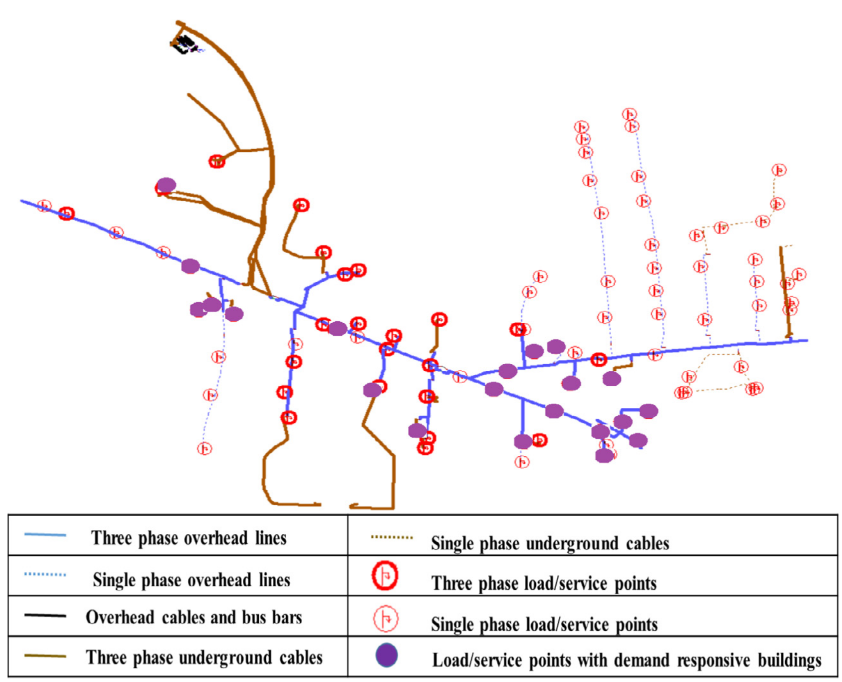

Fig. 6. Distribution feeder model used in this study modeled in DEW.

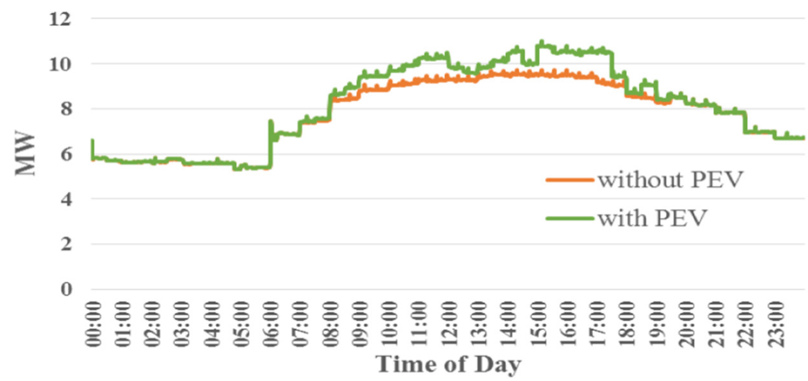

Fig. 7. Distribution feeder's load profiles w/o and w/ PEV penetration.

For the base case, PEVs were present (charged) at all demand responsive buildings representing 100% penetration. Fig. 7 shows the load profiles at the substation with and without PEV penetration.

Without PEV penetration the distribution feeder has a peak load of 9.75 MW at 3:59 pm. With 100% PEV penetration, the feeder's demand increases and gets quite high at times when PEV charging is higher as described in Section 3. The distribution feeder has a new peak load of 11.01 MW at 3:08 pm, an increase of 13.4% from the original peak load. Also PEV penetration increases the losses and lowers the load factors as discussed in the next section. This problem can be overcome by introducing load control strategies, discussed in Section 2, in demand responsive buildings to control their end-use loads without sacrificing occupant comfort and perform ice storage control. If load control alone is unable to improve the feeder's profile and bring it back to the threshold value then rooftop PV units can be recommended.

4. Simulation results and discussions with the proposed load control strategy

This section presents the simulation results for the load control strategy for the distribution feeder to absorb PEV penetration and at building level. The simulations were performed for a summer day at a resolution of 1-min intervals.

4.1. Case study description

For the base case (i.e., 100% PEV penetration in all 21 demand responsive buildings), to evaluate the ability of the proposed load control strategy to absorb PEV penetration, end-use building loads in all buildings were controlled, and ice storage units (if available) were discharged. Table 3 summarizes the participation by different types of demand-responsive buildings.

In this study, small-sized office buildings were made to participate together in the load control from 3 pm to 6 pm during their high demand period. Together, they could provide appreciable load control savings. Medium-sized office buildings and retail buildings were utilized in the late morning and afternoon hours to absorb PEV penetration due to the nature of their building operation. Retail buildings were made to participate during the morning to late evening hours due to their longer operating hours and potential to provide load control savings during these periods. To avoid demand restrike, the next group of buildings about to participate in load control overlaps their end-use loads control with those already participating in load control.

4.2. Feeder-level load profile (w/ and w/o control)

This section presents the simulation results for the distribution feeder with the designed strategy for absorbing PEV penetration with load control, ice storage and PV systems. Fig. 8 shows the distribution feeder's load profiles without PEV and with PEV plus load control. With all 21 buildings participating in reducing the feeder peak demand, the distribution feeder's peak load with PEV penetration is reduced from 11.01 MW to 10.44 MW, a decrease of 5.18%. Feeder demand in the evening, from around 5:30 pm to 6 pm, gets lower than the threshold value as occupancy in office buildings gets lowered and load control in these buildings provides more savings. Similarly, demand from 7 pm to 9 pm is also lower

Table 3
Demand Responsive Buildings Participation.

	Small-sized office building	Medium-sized office building	Stand-alone retail store
Load control participation duration: Maximum three (3) hours for each building	All six (6) small-sized office buildings control end-use loads from 3 pm to 6 pm	One (1) building: end-use loads control from 9 am to 12 pm	One (1) building: end-use loads control from 11 am to 2 pm
		One (1) building: full ice storage discharge from 10 am to 1 pm	Three (3) buildings: end-use loads control from 4 pm to 7 pm
		One (1) building: end-use loads control from 1 pm to 4 pm	Three (3) building: end-use loads control from 5:30 pm to 8:30 pm
		One (1) building: end-use loads control from 3 pm to 6 pm	
		Four (4) buildings: discharge partial ice storage plus end-use loads control from 3 pm to 6 pm	

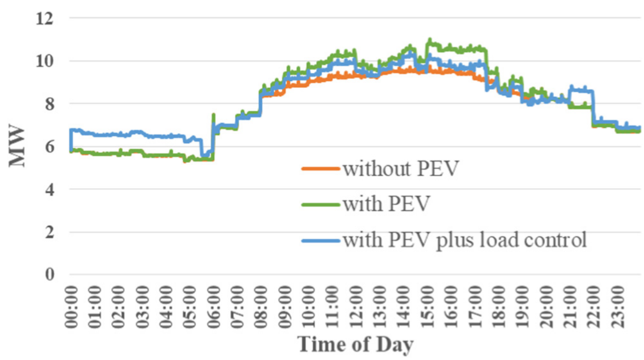

Fig. 8. Distribution feeder's load profiles w/o PEV and w/ PEV plus load control, including ice storage discharge.

or close to the threshold value since the retail buildings occupancy lowers and load control in these buildings achieves more savings. The result indicates that load control alone is unable to bring the distribution feeder's demand to its threshold limit at all times. Also with load control off-peak electricity consumption increases from around midnight to 5:30 am in the morning and from 9 pm to 10 pm, as shown in Fig. 8, due to charging of full and partial ice storage systems.

As load control alone is unable to bring the distribution feeder's demand to its threshold value hence, the proposed strategy recommends the deployment of 13 rooftop PVs, about 62% penetration, among the demand responsive buildings to bring the distribution feeder's load profile to its threshold value and improve the load

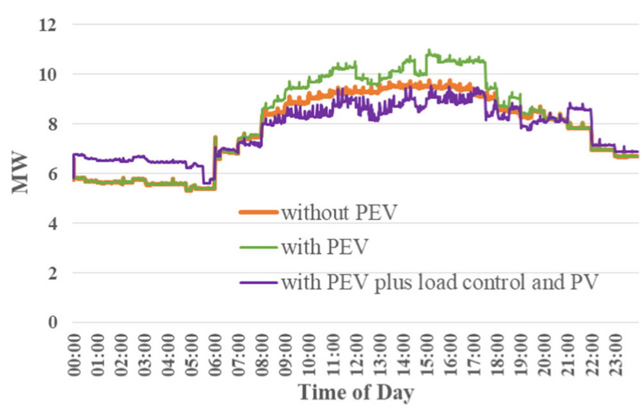

Fig. 9. Distribution feeder's load profiles w/o PEV, w/ PEV, load control and PV.

factors and further reduce losses. Fig. 9 shows the distribution feeder's load profiles without PEV and with PEV, load control and PV together. With load control and PV, the feeder has a peak demand of 9.53 MW at 3:11 pm, a decrease of 13.4% from the 11.01 MW demand with PEV penetration alone.

PV along with load control brings the distribution feeder's demand close to the threshold limit, in fact demand gets quite lower than the threshold value in the afternoon hours from around noon to 3 pm due to high PV output. PV output is both variable and intermittent due to weather changes and therefore varies on a daily basis. Hence, the peak load will vary between Figs. 8 and 9 due to PV output changes.

4.3. Building-level load profile (w/ and w/o control)

This section presents the load control strategy at building level using a medium-sized office building for experimentation. Fig. 10 shows the medium-sized office building's power consumption profiles with and without end-use loads control by the EMS during the load control event from 3 pm to 6 pm. All zones lights, cooling set points and plug loads are controlled to achieve maximum savings possible while maintaining occupant comfort needs.

It can be seen that the end-use load control reduces the building peak load at 4:10 pm from 74 kW to 42 kW, representing a 43% decrease. Lighting control achieves the most savings as it also reduces the building cooling load, followed by HVAC control. In particular, about 34% of the building peak load can be reduced with lights-only control; about 18% of the building load can be reduced with HVAC-only control; and about 4% of the building peak load can be reduced with plug load-only control.

As an example, Fig. 11 shows the medium-sized office building perimeter zone's cooling set points and PMV index and Fig. 12 shows the electric lights power consumption and illuminance levels with and without end-use loads control event from 3 pm to 6 pm. For HVAC control, it is observed from simulation results that the PMV index and peak load savings remain unaffected beyond 27 °C as the sensible cooling rate, i.e., cooling delivered by HVAC, is the same for the temperature offset greater than 3 °C from the original 24 °C cooling set point [21]. Hence temperature set points are altered between 24 °C and 27 °C. For the perimeter zone, as shown in Fig. 11, 27 °C cooling set point can be maintained till 3:30 pm, which provides maximum peak load savings. From 3:30 pm onwards cooling set point can be increased by 1 °C higher than the normal operating temperature of 24 °C, i.e., at 25 °C, due to rapid increase in the PMV index [35]. For lighting control, electric lights are completely shut down if the daylight illuminance exceeds 500 lx. Hence electric lights power consumption is altered between zero and their normal operating values. Fig. 12 shows the

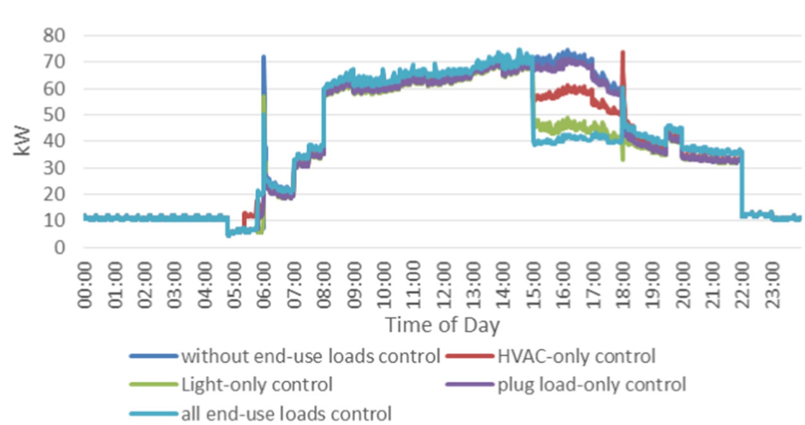

Fig. 10. Demand responsive medium-sized office building load profiles w/o and w/ end-use loads control used in this study.

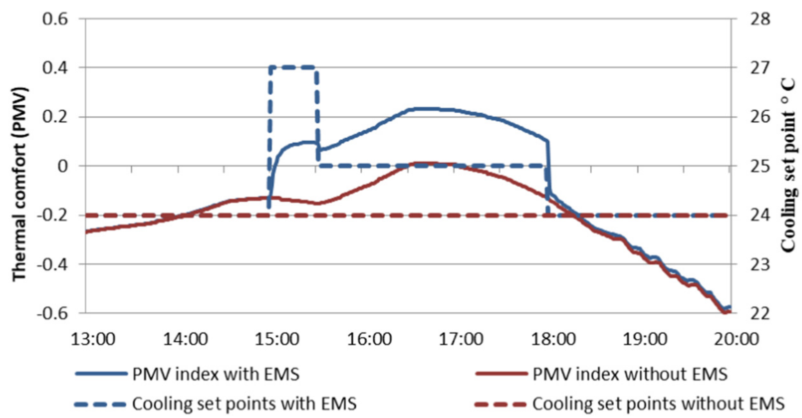

Fig. 11. Bottom perimeter zone's cooling set points and PMV index w/o and w/ end-use loads control in a demand responsive medium-sized office building.

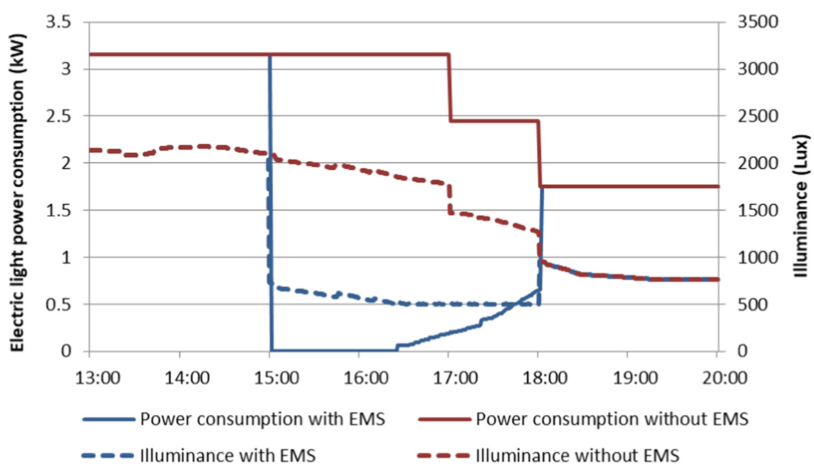

Fig. 12. Bottom perimeter zone's electric light power consumption and illuminance levels w/o and w/ end-use loads control in a demand responsive medium-sized office building.

perimeter zone which receives daylight. As long as the daylight illuminance level is higher than 500 lx, all zone's electric lights remain turned off until 4:25 pm. As the daylight illuminance level gets lower than 500 lx gradually electric lights are turned on to maintain the overall illuminance level of 500 lx. Low priority plug loads in each zone are turned off during the load control event.

4.4. Results and discussion

Table 4 summarizes the peak loads, load factors and power losses for the distribution feeder under study without PEV and with PEV, load control and PV.

- Quantifying peak demand reduction potential with the proposed load control strategy
  For the base case, 100% PEV penetration among demand responsive buildings increases the distribution feeder's peak load from 9.75 MW to 11.01 MW, or 12.9%. Implementing load control in all demand responsive buildings and PV are able to reduce the peak load with PEV penetration from 11.01 MW to 9.53 MW, representing a 13.4% improvement. This new peak demand is lower than the original demand without PEV penetration by 2.26%.
- Impact of the proposed strategy on distribution system load factor
  Load factor is defined as the ratio of the average load to the peak load. The original load factor without PEV is 79.7%. With 100% PEV penetration, the original load factor decreases to 73.6%. With the introduction of load control and PV together, the load factor is improved to 81.6%, representing a 10.9% improvement. In fact, the load factors are slightly higher than the original load factor without PEV penetration.
- Impact of the proposed strategy on distribution system losses
  100% PEV penetration increases the feeder losses from 317 kW to 362 kW, or 14.20%. When load control and PV are introduced, feeder losses with PEV at 362 kW are reduced to 320 kW, representing an 11.6% loss reduction.

Table 4
Summary of distribution feeder's peak loads, load factors and losses without PEV, with PEV, Load control and PV.

	Without PEV	With PEV	With PEV + Load control	With PEV + Load control and PV
Peak load	9.75 MW	11.01 MW	10.44 MW	9.53 MW
Load factor	79.7%	73.6%	78.2%	81.6%
Feeder losses	317 kW	362 kW	339 kW	320 kW

Table 5
Sensitivity analysis considering different percent of buildings with PEV charge stations.

% of buildings with PEV charge stations (no. of buildings with PEV charge stations)	No. of buildings needed to participate to absorb PEVs	No. of buildings with PVs needed to absorb PEVs
Base case 100% (21)	21	13
75% (16)	21	9
50% (10)	21	0
35% (7)	18	0
25% (5)	7	0
15% (3)	0	0

5. Sensitivity analysis

In this section, sensitivity analysis is performed to analyze how the proposed load control strategy can contribute to reducing distribution feeder peak load with PEVs, thereby making the PEV penetration transparent to the grid. This study was carried out by varying the number of buildings with PEV from the base case, considering mixed type of buildings and PEV charge stations, where all 21 demand responsive buildings (100%) have PEVs to 15% where only 3 buildings have PEVs.

For the base case, all 21 demand responsive buildings are needed to participate in load control, i.e. 100% load control, along with 13 buildings recommended to install rooftop PVs, i.e. 62% PV penetration, to absorb PEV penetration. Table 5 summarizes the number of buildings needed to perform load control and to have PV in order to absorb different PEV penetration levels. As shown, load control alone is able to bring the feeder demand to its threshold value for PEV penetrations above 15% and up to 50%. 75% PEV penetration needs around 9 demand responsive buildings with PVs to help absorb PEV penetration along with load control. The distribution feeder is able to absorb PEV penetration of up to 15% without load control and PV.

6. Conclusions

The analysis presented in this paper shows that random and large-scale Plug-in Electric Vehicle (PEV) penetration in a distribution feeder results in the increase in system losses and reduction in load factors. By evaluating the issues generated by PEV penetration, utilities and building owners can better understand and develop approaches that will better optimize the distribution system.

In this paper, a coordinated load control strategy, among participating commercial buildings in a distribution feeder to control buildings' end-use loads without sacrificing occupant comfort and ice storage discharge, along with strategically deployed PV is presented to absorb PEV penetration. Demand responsive commercial building load profiles and field recorded PEV charging profiles have been added to a real world distribution circuit to analyze the effects of PEV penetration, together with real-world PV output profiles. Results indicate that 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 PEV penetration above 50%. Having been validated on several types of commercial buildings in a distribution feeder with summer peaks, the developed strategy has been proven to be scalable and applicable to any type, size and number of commercial buildings in a distribution feeder including hospitals, strip malls, apartment buildings, etc. Results of implementing the developed strategy in a distribution feeder show the improvement in overall system load factor and reduction of system losses due to PEV penetration. The analysis has been performed for a typical hot (thus sunny) day of the year, which results in high building peak demand. The utility concerns about the peak day (only) and this strategy helps the most on those days. Additional analysis considering winter peaking utilities can also be studied where buildings have electric heating during winters. Battery storage can also be considered to cover PV variability. Further analysis can be made on how battery storage can contribute to peak demand reduction in buildings and subsequently a distribution feeder.

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