Method for Mitigating Plug in Electric Vehicle Charge Cycling Observed in a Charging Control Strategy Developed for a Third-Party Aggregator

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Authorization to Submit Thesis

This thesis of Don Scoffield, submitted for the degree of Master of Science with a major in Electrical Engineering and titled "Method for Mitigating Plug in Electric Vehicle Charge Cycling Observed in a Charging Control Strategy Developed for a Third-Party Aggregator," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

This thesis builds on and improves a Plugin Electric Vehicle (PEV) charging control strategy developed for a third-party aggregator. This charging control strategy was developed with an emphasis on shifting residential PEV charging load from peak to off-peak hours. When the initial control strategy was designed the most important design criteria was scalability and computational efficiency. It is very important to be able to control the charging of a very large number of PEVs, in a very small amount of time using an ordinary PC. After the control strategy was successfully implemented and demonstrated the author recognized the need for further refinement of the control strategy. The original control strategy is not able to limit or control the amount of PEV charge cycling. PEV charge cycling occurs when one PEV stops charging and another PEV starts charging in its place. Limited charge cycling can be a beneficial mechanism to start charging PEVs that need to start charging, but excessive charge cycling may contribute to grid problems. The amount of charge cycling that is allowed is a decision that must consider these tradeoffs. This thesis modifies the original control strategy to be able to limit, and control the amount of PEV charge cycling.

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Dedication

To my wife and children,

who give my life happiness, meaning, and purpose.

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Chapter 1: Introduction

Over the past several years there has been a move to more fuel-efficient and alternative energy vehicles in the United States, due in part to concerns regarding reliance on foreign oil and global climate change. Federal, state, and local government regulation and incentives have also played a role in motivating this shift. Plug-in electric vehicles (PEVs) with low emissions and high energy conversion efficiency are promising options for future transportation systems [1][2]. Most, if not all, major automotive manufacturers have already produced or are in the process of producing plug-in hybrid electric or all-electric vehicles. In anticipation of a widespread adoption of PEVs in the future, the U.S. Department of Energy (DOE) has funded and continues to fund many projects to study the charging infrastructure required to support future PEV charging needs [3]. Some of these projects investigate the problems that widespread uncontrolled charging might have on the grid, as well as the benefits that controlled PEV charging might provide to the grid [3]. Two DOE-funded projects that the author has personally worked on extensively over the past seven years are The EV Project and the Grid Modernization Lab Consortium (GMLC) project titled “Systems Research for Standards and Interoperability” [4][5][6].

The EV Project was a large-scale electric vehicle charging demonstration that collected data from over 7,000 Nissan Leafs and Chevrolet Volts and over 10,000 charging systems operating in 19 different metropolitan areas across the United States. The EV Project was awarded in 2009 and led by ECOtality who partnered with Nissan North America, General Motors, and Idaho National Laboratory (INL). INL was tasked with collecting and analyzing the data from the electric vehicle chargers and vehicles in the project [4].

Through analysis of data collected in The EV Project, many things were learned about the charging behavior of PEV owners and implications of that behavior for PEV charge load management. First, most PEV charging occurred at home. For example, individuals who drove Nissan Leafs charged at home 84% of the time when work-place charging was not available, and 65% of the time when work-place charging was available [7]. Second, uncontrolled residential PEV charging in the evening hours was coincident with the peak of the non-PEV residential load. This increased both the peak and rate of ramping present in the residential load, both of which are undesirable from the perspective of the electric utility [8]. Third, individuals tended to plug in their PEVs shortly after the last trip of the day but did not unplug their PEVs until the morning, just prior to the first trip of the next day. As a result, PEVs typically were plugged in all night with the opportunity to charge that entire time [5]. It became obvious during The EV Project that residential PEV charging could be made much more grid-friendly by shifting the PEV charging energy from peak-load hours into early morning hours when the non-PEV load is at its minimum, as shown in Figure 1.1.

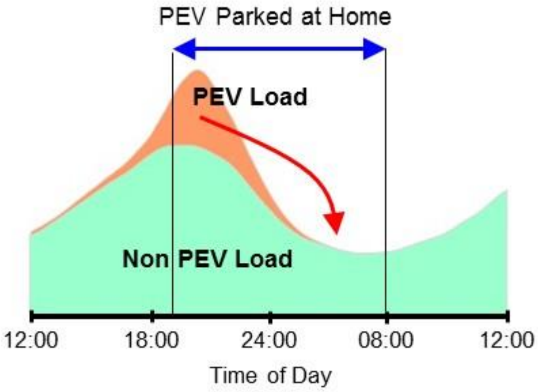


Figure 1.1: Uncontrolled residential PEV charging is coincident with non-PEV residential load because individuals tend to plug in their PEVs after the last trip of the day and an uncontrolled PEV charger begins charging immediately after a PEV is connected. PEV charging could be made grid friendly by shifting the PEV charging into the early morning hours.

Another insight gained from The EV Project was that time-of-use rates could make PEV charging more problematic than uncontrolled PEV charging [5]. Time-of-use rates are commonly used by utilities to shift energy use from peak hours to off-peak hours. Unfortunately, when there were time-of-use rates, PEV owners in The EV Project tended to program their PEVs or residential charging stations, also called electric vehicle supply equipment (EVSE), to begin charging at the beginning of the off-peak rate period. This eliminated the natural diversity in the charge start times, creating a step change in PEV charging load [5].

The project “Systems Research for Standards and Interoperability,” nicknamed “GM0085,” has also produced significant findings related to PEV charging impact on the grid. This project is being conducted by DOE’s Grid Modernization Laboratory Consortium. This consortium is described as, “… a strategic partnership between the U.S. Department of Energy and 13 National Laboratories to bring together leading experts and resources to collaborate on national grid modernization goals” [9]. The goal of GMLC is to achieve the visions, goals, and outcomes of DOE’s Grid Modernization Initiative and to integrate and coordinate the activities across the DOE offices and the national laboratories. The GMLC is also intended to strengthen partnerships with key stakeholders such as electric utilities, equipment manufacturers, and state governments [9].

The author has participated in the GM0085 project since it started in 2016 and has been the Principle Investigator of the project for the last two years of the project. Five National Laboratories are participating in the GM0085 project: Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory

(PNNL), Lawrence Berkley National Laboratory (LBNL), and Argonne National Laboratory (ANL). The GM0085 project is focused on understanding the impact of widespread AC Level 2 PEV charging (i.e., charging at 240 VAC) on a distribution feeder. The GM0085 project studied PEV charging in two separate contexts: PEV charging at residences, and PEV charging at commercial buildings [6] [10]. For each of these contexts, PEV charging is investigated using the following steps:

1. Understand the impact of uncontrolled PEV charging
2. Develop a methodology to control the PEV charging
3. Quantifying the benefits of controlling the PEV charging

PEV charging at residences was studied first in the project. As part of the project, research scientists from INL, NREL, and LBNL developed a PEV charging control strategy that could be used to control residential PEV charging. During the development process the following design criteria were established for the residential PEV charging control strategy:

- The strategy should control the charging of individual PEVs directly with an emphasis on shifting overall residential PEV charging from peak to off peak hours.
- The strategy should ensure that the PEVs are charged in a way that maximize charging efficiency and power quality.
- The strategy must be scalable; it should be capable of controlling the charging of hundreds of thousands of PEVs.
- The strategy should be computationally efficient. A single PC should be able to perform the calculations necessary for controlling the charging of hundreds of thousands of PEVs.

- The strategy should not be sensitive to internet latency. It should not require low latency communication to function.
- The strategy should prioritize PEV owners' need for transportation over the interests of the grid, meaning that the strategy must ensure all PEVs charging needs are met.

A charging control strategy for residential PEV charging that meets all of the design criteria described above has been successfully implemented in software and demonstrated via an RTDS simulation as part of the GM0085 project [10] [11]. A paper describing this control strategy is in development as of this writing. After the control strategy was implemented, it was demonstrated to successfully shift the PEV charging load to off peak hours which in large part mitigated the need for capacity upgrades to residential feeders as PEV penetration increases. This met the project deliverable for residential charging and the focus of the project shifted to studying PEV charging at commercial buildings.

After the focus of the project shifted to studying PEV charging at commercial buildings, the author recognized the need for further refinement of the residential control strategy. The residential control strategy is not able to limit or control the amount of PEV charge cycling. PEV charge cycling occurs when one PEV stops charging and another PEV starts charging in its place. Limited charge cycling can be a beneficial mechanism to start charging PEVs that need to start charging, but excessive charge cycling may lead to grid stability problems. The amount of charge cycling that is allowed is a decision that must consider these tradeoffs. This refinement can be incorporated into the residential control strategy by adding the following additional design criteria:

- The strategy should limit and control the charge cycling of PEVs.

The objective of this thesis is to modify the residential PEV charging control strategy developed in the GM0085 project to incorporate this additional design criteria.

The work in this thesis is organized as follows. Chapter 2 gives an overview of the residential control strategy developed in the GM0085 project. Chapter 3 describes how the original control strategy leads to charge cycling; charge cycling occurs when one PEV stops charging and another starts charging in its place. Chapter 4 presents a methodology that limits and controls the charge cycling of PEVs. A comparison of the original and improved control strategies are presented in Chapter 5. Finally, Chapter 6 discusses the conclusions of the thesis and describes important areas of future work.

Chapter 2: Overview of PEV Charging Control Strategy

The PEV charging control strategy developed in the GM0085 project uses a centralized control element that will be referred to as the aggregator in this overview and a decentralized control element that will be called the front end controller. The aggregator interacts with PEVs directly to determine the times during the day each PEV should be charged. The aggregator functions in the 'energy domain' by dividing each day into time segments and calculating the optimal amount of PEV charge energy for each time segment. In this document each of these time segments will be referred to as time steps. In the project, a 5 minute time step was used.

The aggregator's primary purpose is to ensure PEV charging needs are met and to meet grid objectives that require shifting PEV charge energy in time such as shifting PEV charging energy to off peak times. The front end controller is a decentralized control element that interacts with the aggregator. Each PEV has its own front end controller that translates the energy set point calculated by the aggregator into a power profile over the duration of the time step. The front end controller's primary purpose is to maximize charger efficiency, maximize charger power quality, and to provide grid services that require fast response such as voltage support, or frequency regulation. Each PEV make and model has unique charging characteristics [12-16], so the front end controller settings are different for each PEV make and model. The modified control strategy, developed in this thesis does not involve the front end controller. For this reason, the remainder of this overview will focus on the aggregator.

The control strategy requires bi-directional communication between the aggregator and each PEV. This communication can be summarized in the following three steps as shown in Figure 2.1:

1. Each PEV sends its charging needs to the aggregator
2. The aggregator calculates an energy set point for each PEV for the next time step
3. The aggregator sends an energy set point to each PEV

This communication sequence occurs every time step, allowing the aggregator to use the most recent PEV charging needs information. Since the communication sequence only occurs once every 5, 10, or 15 minutes; this strategy is not sensitive to internet latency and does not require low latency communication.

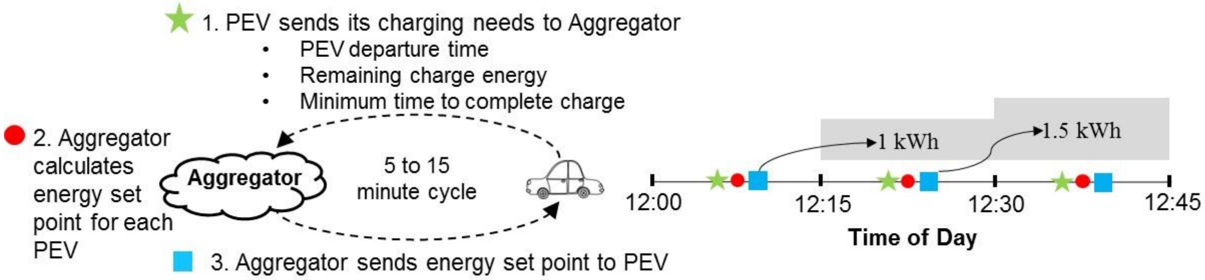


Figure 2.1: The bi-directional communication between the aggregator and each PEV occurs once every time step. In a given time step the aggregator calculates energy set points for each PEV for the next time step.

When designing the aggregator in the GM0085 project, the dominant design criteria was scalability and computational efficiency. The aggregator needed to be able to calculate the energy set points for hundreds of thousands of PEVs on an ordinary PC in less than one minute. In order to achieve this it became obvious early on that the optimization model could not represent individual PEVs. If each PEV is explicitly included in the optimization model, the number of decision variables is the product of the number of PEVs and the number of time steps in the prediction horizon. For example, as shown in (1), an optimization model including 300,000 PEVs with a prediction horizon of 24 hours and time step of 10 minutes would have 43.2 million decision variables. This is a huge optimization problem.

$$num\_PEVs = 300{,}000 \quad \text{(1a)}$$

$$num\_timesteps = \frac{prediction\ horizon\ duration}{time\ step\ duration} = \frac{24 * 60}{10} = 144 \quad \text{(1b)}$$

$$\begin{aligned} num\_decision\_variables &= num\_PEVs\ * num\_timesteps \\ &= 300{,}000 * 144 = 43.2\ million \end{aligned} \quad \text{(1c)}$$

The optimization problem can be made much smaller if the PEVs are represented collectively and not individually in the optimization model. When PEVs are represented collectively, their individual constraints are aggregated into a single set of constraints. Their individual energy set points over the prediction horizon are also aggregated into one set of aggregated energy set points. The number of decision variables in this type of reduced order optimization model does not depend on the number of PEVs. Rather it is the number of time steps in the prediction horizon, which is 144 in the example shown in (1).

The aggregator designed in the GM0085 project uses an aggregation step followed by a reduced order optimization model followed by a disaggregation step. The steps can be described as follows:

1. Aggregate PEV Constraints
2. Solve Reduced Order Optimization Model
3. Allocate energy to PEVs for the next time step

Steps 1 and 2 allocate the total PEV charge energy over the prediction horizon to meet some grid objective, such as shifting PEV charging to off peak times. Step 3 divides the total PEV charge energy for the next time step between the PEVs in a way to ensure that all PEV's charging needs are met. Figure 2.2 describes this process.

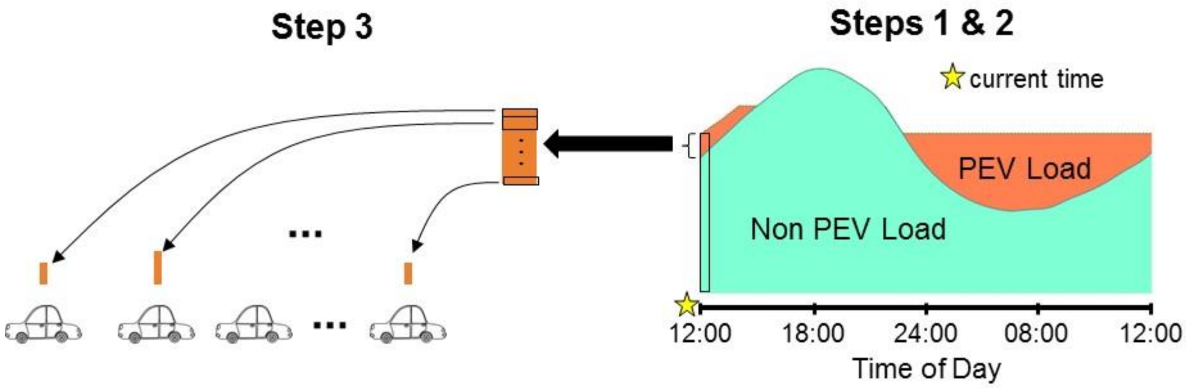


Figure 2.2: The control strategy allocates the total PEV load over the prediction horizon to minimize peak load (Steps 1 & 2). Step 3 divides the total PEV charge energy for the next time step between the PEVs in a way to ensure all PEV's charging needs are met.

The data flow diagram for the aggregator is displayed in Figure 2.3. The data flow diagram includes the external environmental information the aggregator needs (in light yellow boxes) as well as the three main analysis steps performed by the aggregator (in blue boxes). The external environmental information needed by the aggregator is:

- Load forecast of the non-PEV load for the prediction horizon
- PEV charging needs forecast for the prediction horizon
- Charging needs of PEVs that are currently charging

The creation of accurate non-PEV load forecasts and PEV charging needs forecasts is not the focus of the GM0085 project or this thesis. When developing, debugging, and testing the control strategy these forecasts were generated by adding randomness into available historical data. A paper describing the creation of PEV charging needs from historical PEV charging data is described in [17]. The three analysis steps performed by the aggregator will be described in Sections 2.1, 2.2, and 2.3.

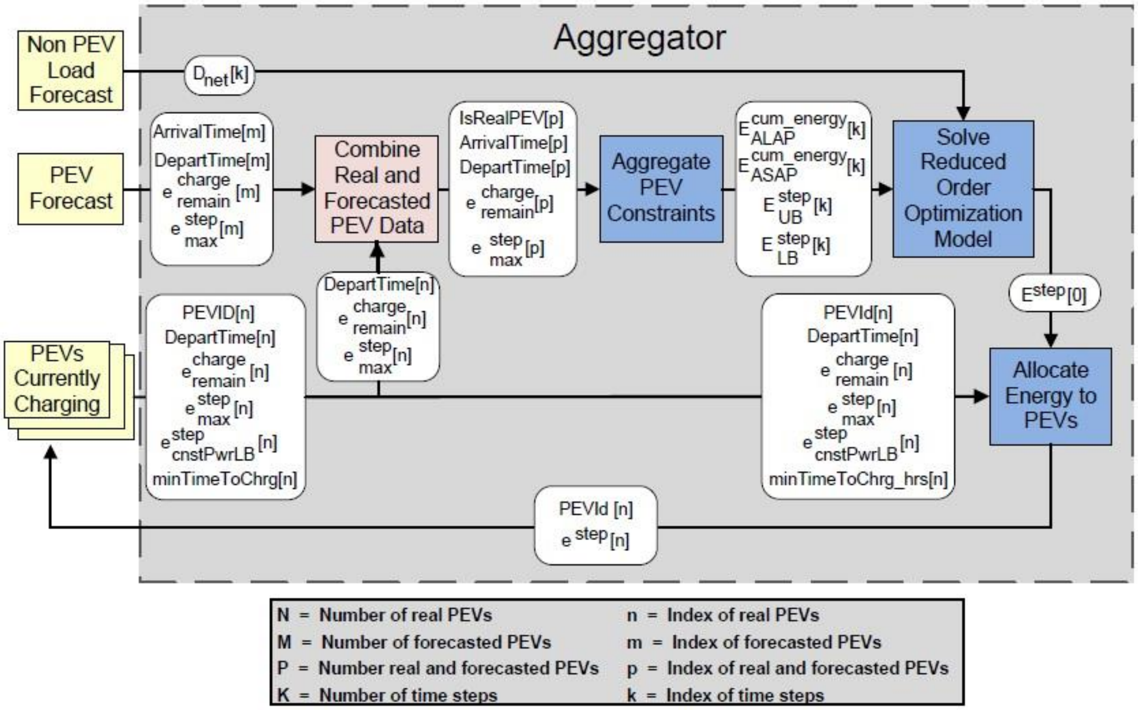


Figure 2.3: The aggregator data flow diagram. The three main analysis steps of the aggregator are displayed in the blue boxes. The external environmental information the aggregator needs is displayed in the light yellow boxes. The information passed between functional blocks is displayed in white boxes.

2.1 Aggregate PEV Constraints

Combining individual PEV charging constraints into a single aggregate set of charging constraints is the key insight that enables the calculation of energy set points for hundreds of thousands of PEVs on an ordinary PC in less than one minute. Aggregating PEV charging constraints transforms a potentially huge optimization problem into a reduced order optimization problem that is small and easy to solve quickly with minimal computational resources.

It is not possible for PEVs to charge faster than their max charge rate or to charge at times when they are not connected to a charger. In order to enforce these conditions, all valid PEV charging is bound by ‘as soon as possible’ (ASAP) charging and ‘as late as possible’

(ALAP) charging as shown in Figure 2.4. ASAP charging occurs when the PEV immediately starts charging as soon as it is connected to a charger and continues to charge until the PEV's charging needs are met. ALAP charging occurs when the PEV waits until the last minute to begin charging and the PEV's charge needs are met just before the PEV is scheduled to depart.

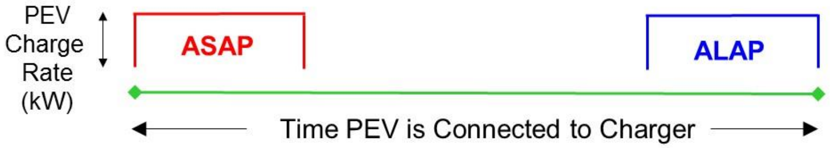


Figure 2.4: All PEV charging is bound by ASAP and ALAP charging. ASAP charging is when the PEV is charged as soon as possible. ALAP charging is when the PEV is charged as late as possible.

There are two types of aggregate PEV constraints used in the reduced order optimization model, cumulative energy constraints and step energy constraints.

Cumulative energy constraints are calculated for both ASAP charging and ALAP charging. ASAP charging corresponds to an upper bound and ALAP charging corresponds to a lower bound. These cumulative energy constraints ensure that the energy the aggregator allocates through time is sufficient to meet the charging needs of all PEVs. A point above the cumulative energy upper bound corresponds to a scenario where the aggregator is attempting to charge PEVs before they are connected to a charger or at a charge rate that is too large. A point below the cumulative energy lower bound corresponds to a scenario where the aggregator is attempting to charge PEVs after they have departed. The aggregator's cumulative energy being bound by the cumulative energy constraints is a necessary but not a sufficient condition to ensure all PEV's charging needs are met. To ensure all PEV's charging needs are met it is also necessary to prioritize which PEVs can charge based upon the remaining time each PEV can charge and the remaining energy required. This will be discussed further in Section 2.3.

The manner in which ASAP and ALAP cumulative energy constraints are calculated is identical. The only difference is whether ASAP charging or ALAP charging is used in the calculation. A cumulative energy constraint is the sum of the cumulative energies of all PEVs as shown in (2). Equation (3) describes how to calculate the cumulative energy for a single PEV.

$k\_start[n]$ → The time step k when PEV n started charging
$k\_end[n]$ → The time step k when PEV n finished charging
$e^{step}[n,z]$ → The energy set point for PEV n at time step z
$e^{cum}[n,k]$ → The cumulative energy for PEV n at time step k
$E^{cum}[k]$ → The cumulative energy of all PEVs at time step k

$$E^{cum}[k] = \sum_{n=1}^{N} e^{cum}[n,k] \tag{2}$$

$$e^{cum}[n,k] = \begin{cases} 0 & k < k\_start[n] \\ \displaystyle\sum_{z=k\_start[n]}^{k} e^{step}[n,z] & k\_start[n] \le k \le k\_end[n] \\ \displaystyle\sum_{z=k\_start[n]}^{k\_end[n]} e^{step}[n,z] & k > k\_end[n] \end{cases} \tag{3}$$

Figure 2.5 shows a graphical representation of the cumulative energy constraints for two hypothetical PEVs. Notice that the cumulative energy of PEV 1 and PEV 2 will always be bound by the ASAP and ALAP cumulative energy constraints when the charging is valid. Valid charging consists of two bounding criteria, first that PEVs are only allowed to charge when they are connected to a charger and second a PEV’s charge rate never exceeds its max charge rate.

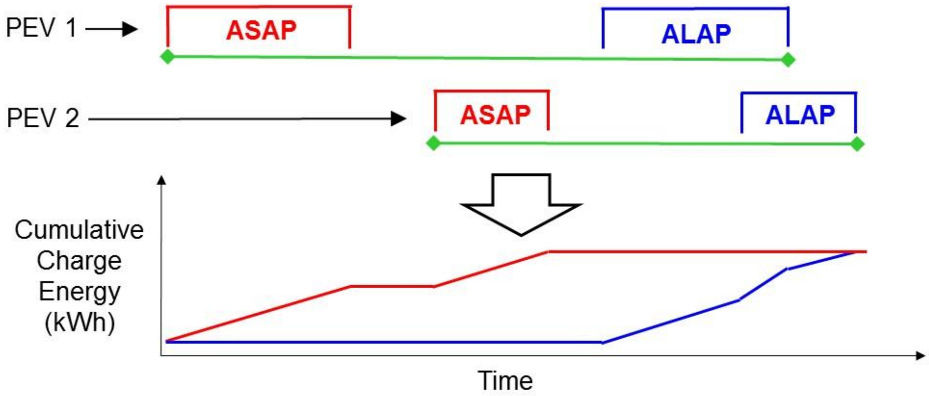


Figure 2.5: Graphical representation of the ASAP and ALAP cumulative energy constraints for two PEVs. All valid PEV charging for PEV 1 and PEV 2 is bound by the ASAP and ALAP cumulative energy constraints.

Unlike cumulative energy, which is the total energy drawn by all the PEVs from the beginning of their respective charges up to the present time step, step energy is the total energy drawn by all the PEVs during a given time step and is the decision variable of the optimization model. The step energy upper bound and lower bound constraints are intended to constrain the total energy the aggregator can allocate to the PEVs during individual time steps. The step energy lower bound is always zero since this control strategy was designed for grid to vehicle charging only. The scope of the GM0085 project was to only study grid to vehicle charging not vehicle to grid power flows. The step energy upper bound for a given time step is the maximum amount of energy that all PEVs can collectively draw during that time step (4). It is important to note that the max step energy for a given PEV is zero when the PEV's charging needs have been met or its battery is full, since the PEV does not require any more energy. As a result, the step energy upper bound at a given time step depends on the step energy values of the previous time steps. This creates the undesirable situation where one of the constraints of the reduced order optimization model (step energy upper bound) depends on the decision variable (step energy). This is the trade-off of the reduced order optimization model, which provides a huge reduction in the size of the optimization problem at the expense of making one of the constraints in the optimization model dependent on the decision variable.

$E_{UB}^{step}[k] \rightarrow$ The step energy upper bound at time step k
$e_{max}^{step}[n,k] \rightarrow$ The max energy PEV n can draw at time step k

$$E_{UB}^{step}[k] = \sum_{n=1}^{N} e_{max}^{step}[n,k] \tag{4}$$

In the GM0085 project the step energy upper bound was calculated under the assumption that PEVs would be able to draw max power from the grid the entire time they were connected to a charger as shown in Figure 2.6. This simplifying assumption makes sub-optimal PEV charging a possibility. As will be shown in simulation results later in this thesis, this control strategy works extremely well for residential charging. Even though the simplifying assumption works well for residential charging it may be problematic in other charging situations like commercial or workplace charging. This is an area where future work is needed both to investigate non-residential charging scenarios as well as to determine if there are better ways to estimate the step energy upper bound constraint.

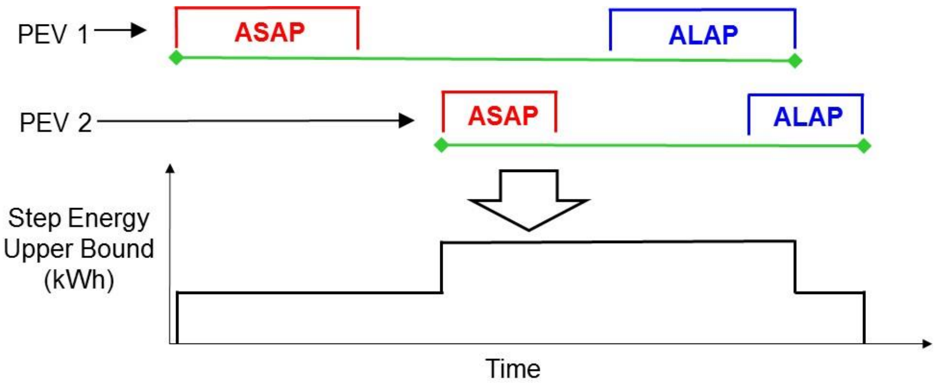


Figure 2.6: A graphical representation of the step energy upper bound for two hypothetical PEVs. The step energy upper bound was calculated under the simplifying assumption that PEVs would be able to draw max power from the grid the entire time they were connected to a charger (ALAP charging).

2.2 Solve Reduced Order Optimization Model

The reduced order optimization model is specified in (5). The optimization model decision variable, $E^{step}[\mathrm{k}]$, is the step energy for every time step in the prediction horizon. The objective function in equation (5a) allocates the step energy (PEV load) so that the total load (sum of PEV and non PEV load) has the smallest possible peak and is as flat as possible.

The optimization model also has three sets of constraints. The first set of constraints in equation (5b) ensures that the cumulative energy of the optimized solution is bound by the cumulative energy constraints. The second set of constraints in equation (5c) ensures that the step energy is bound by the step energy constraints. The final set of constraints in equation (5d) ensures that the total energy (sum of PEV and non PEV energy) does not exceed the max energy the feeder can supply in a single time step. Figure 2.7 shows a graphical example of the step energy and cumulative energy constraints.

$E_{ALAP}^{cum}[k]$ → The ALAP cumulative energy constraint
$E_{ASAP}^{cum}[k]$ → The ASAP cumulative energy constraint
$E_{LB}^{step}[k]$ → The step energy lower bound constraint
$E_{UB}^{step}[k]$ → The step energy upper bound constraint
$E^{step}[k]$ → The step energy (**Decision Variable**)
$D_{net}[k]$ → The load forecast of the non PEV load
$Feeder_{limit}^{step}$ → The max energy the feeder can supply
k → The index of the time step

$$min \sum_{k=1}^{K} (E^{step}[k] + D_{net}[k])^2 \qquad \text{(5a)}$$

$$s.t. \quad E_{ALAP}^{cum}[k] \leq \sum_{z=1}^{k} E^{step}[z] \leq E_{ASAP}^{cum}[k] \qquad \text{(5b)}$$

$$0 = E_{LB}^{step}[k] \leq E^{step}[k] \leq E_{UB}^{step}[k] \qquad \text{(5c)}$$

$$E^{step}[k] + D_{net}[k] \leq Feeder_{limit}^{step} \qquad \text{(5d)}$$

$$k = 1,2, \ldots, K$$

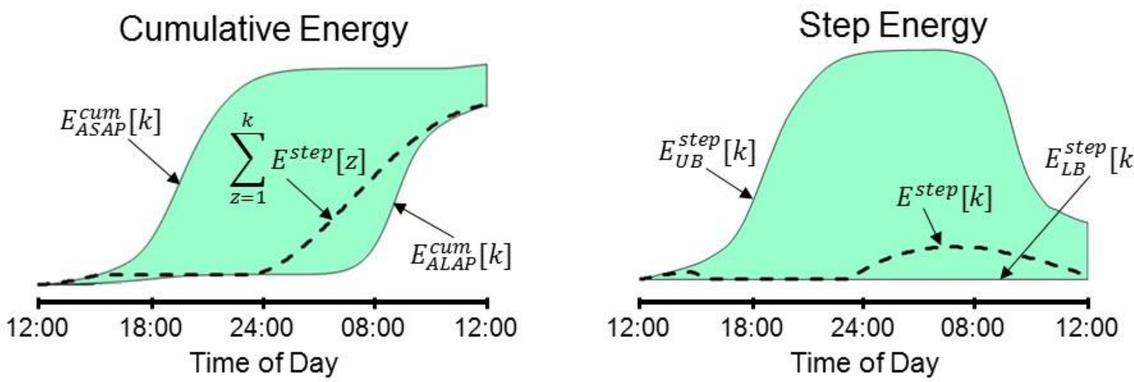


Figure 2.7: A hypothetical graphical representation of the cumulative energy constraints, the step energy constraints and an optimized $E^{step}[\mathrm{k}]$ for a 24 hour prediction horizon.

2.3 Allocate energy to PEVs

Allocating energy to individual PEVs is a disaggregation step that divides $E^{step}[0]$, the total PEV charge energy for the next time step, between the PEVs in a way to ensure all PEVs charging needs are met. A calculated value called the *charge priority* is used to determine which PEVs should charge. The *charge priority* is a PEVs *minimum remaining charge time* divided by its *remaining park time* as shown in (6). A PEVs *minimum remaining charge time* is the time required for a PEVs charging needs to be met when the PEV is charged at its max charge rate. A PEVs *remaining park time* is the time until the PEV departs.

$$charge\ priority[k] = \frac{minimum\ remaining\ charge\ time[k]}{remaining\ park\ time[k]} \qquad (6)$$

Charge priority is an indication of urgency to charge. For example a *charge priority* of 0.9 indicates that the PEV must charge at its max charge rate for 90% of the remaining park time to meet its charging needs, whereas a *charge priority* of 0.10 indicates that only 10% of the remaining park time is required to fully charge the PEV. Stated another way a *charge priority* of 0.9 indicates that the PEV must charge at 90% of its max charge rate for all of the remaining park time, and a *charge priority* of 0.10 indicates that the PEV must be charged at only 10% of the max charge rate for the remaining park time to fully charge the PEV.

After *charge priority* has been calculated for all PEVs, charge energy is allocated to each PEV in descending order of *charge priority*. Allocating energy in this way gives a PEV with higher *charge priority* charge energy before a PEV with lower *charge priority*. Once the total energy allocated to the PEVs is equal to $E^{step}[0]$, then all remaining PEVs are given an energy set point value of 0.

Allocating energy to the PEVs in descending order of *charge priority* is a necessary, but not a sufficient condition to ensure their charging needs are met. It is also necessary that the PEVs energy set points are large enough to meet their charging needs. The control strategy accomplishes this by allocating energy to each PEV in the range specified by (12).

$e^{step}[k]$ → The energy set point for the PEV at time step k
$e^{step}_{max}[k]$ → The max energy the PEV can draw at time step k
$MRCT[k]$ → The minimum remaining charge time at time step k

$$MRCT[k+1] = MRCT[k] - \frac{e^{step}[k]}{e^{step}_{max}[k]} * aggregator\ time\ step \qquad (7)$$

$$e^{step}_{LB}[k] = charge\ priority[k] * e^{step}_{max}[k] \qquad (8)$$

$$e^{step}[k] < e^{step}_{LB}[k] \quad \rightarrow \quad charge\ priority[k+1] > charge\ \text{priority[k]} \qquad (9)$$

$$e^{step}[k] = e^{step}_{LB}[k] \quad \rightarrow \quad charge\ priority[k+1] = charge\ \text{priority[k]} \qquad (10)$$

$$e^{step}[k] > e^{step}_{LB}[k] \quad \rightarrow \quad charge\ priority[k+1] < charge\ \text{priority[k]} \qquad (11)$$

$$charge\ priority[0] * e^{step}_{max}[0] < e^{step}[0] \leq e^{step}_{max}[0] \qquad (12)$$

The lower bound in (12), which is also given in (8) defines the energy set point that will cause the *charge priority* to remain constant. As shown in (9) and (11) whenever the energy set point is less than e^{step}_{LB} the *charge priority* will increase, and whenever the energy set point is greater than e^{step}_{LB} the *charge priority* will decrease. A consequence of this control strategy is that a PEVs *charge priority* decreases when it is charged and increases when it is not charged. The *minimum remaining charge time* as a function of the energy set point is given in (7).

This chapter has given an overview of the PEV charging control strategy developed in the GM0085 project. The next chapter will discuss an undesirable side effect of this control strategy.

Chapter 3: Undesirable Side Effect of PEV Charging Control Strategy

An overview of the PEV charging control strategy developed in the GM0085 project was given in Chapter 2. There is a side effect of this control strategy that was not discovered until the control strategy was completely implemented and tested. This side effect is called charge cycling. Charge cycling occurs when one PEV stops charging and another PEV starts charging in its place. Limited charge cycling can be a beneficial mechanism to start charging PEVs that need to start charging, but excessive charge cycling may lead to grid stability problems. The amount of charge cycling that is allowed is a decision that must consider these tradeoffs. Excessive charge cycling is a direct result of the methodology used to allocate energy to PEVs.

The methodology used to allocate energy to PEVs has several characteristics that first lead to a reduction in the natural diversity in the *charge priority* and then ultimately lead to charge cycling. These characteristics are:

- The PEVs are allocated energy in descending order of *charge priority*
- A PEVs *charge priority* decreases when it is charged
- A PEVs *charge priority* increases when it is not charged (energy set point is 0)

When a large number of PEVs begin charging there is initially a lot of natural diversity in the *charge priority* values. Over time, after PEVs have had time to charge, many PEVs tend to have about the same *charge priority* as shown in Figure 3.1. When PEVs are charging, those that are selected to charge are the PEVs that have the highest *charge priority*. When these PEVs are charged their *charge priority* decreases, whereas the *charge* *priority* increases for the PEVs that are not charging. As a result, over time the diversity in the *charge priority* values decreases.

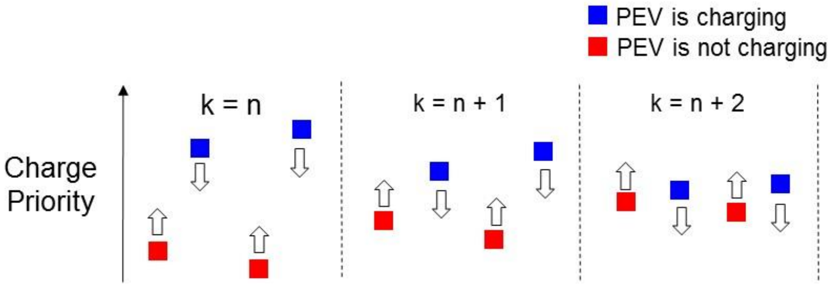
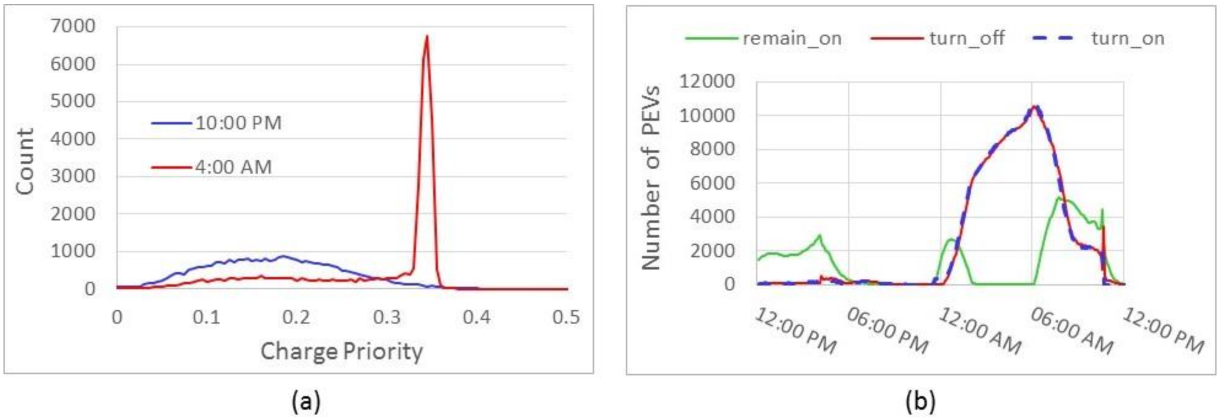


Figure 3.1: The *charge priority* for four hypothetical PEVs over three successive time steps. Notice that the diversity in the *charge priority* decreases over time. In other words the PEVs tend to have about the same *charge priority* as time advances.

Figure 3.2a shows a histogram of *charge priority* from a GM0085 simulation at two times, 10 PM and then six hours later at 4 AM. Notice that at 10 PM there is a large amount of diversity in *charge priorities* but at 4 AM there is a large number of PEVs that have about the same *charge priority*.



(a) (b)

Figure 3.2: **(a)** Histogram of *charge priorities* from a GM0085 simulation at 10 pm and then six hours later at 4 am. Notice the diversity in the *charge priority* at 10 pm and the number of PEVs whose *charge priority* is close to 0.35 by 4 am. **(b)** Results from a GM0085 simulation that shows the number of PEVs that remain on (green line), turn on (blue dashed line), and turn off (red line) between successive time steps. In this simulation there is excessive charge cycling during the early morning hours. For example, at 6 am there are over ten thousand PEVs that turn on, over ten thousand PEVs that turn off, and very few PEVs that remain on.

Once there are many PEVs with approximately the same *charge priority* then charge cycling begins. Charge cycling occurs when one PEV stops charging and another PEV starts charging in its place as shown in Figure 3.3. Charge cycling is a natural extension of the methodology used to allocate energy to PEVs.

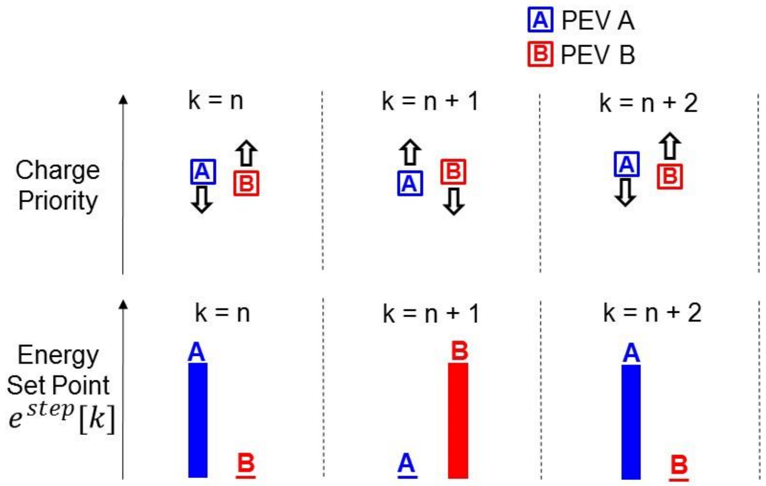


Figure 3.3: Charge cycling for two hypothetical PEVs over three consecutive time steps. In the first time step (k=n) PEV A is charging and PEV B is off because PEV A has a higher *charge priority* than PEV B. In the second time step (k=n+1) PEV B is charging and PEV A is off because PEV B has a higher *charge priority* than PEV A. In the third time step the charging of PEV A and PEV B cycles yet again.

Severe charge cycling occurs when there are many PEVs with about the same *charge priority* and not all the PEVs can charge at the same time. As a result, some of the PEVs are charging and some of the PEVs are not charging. In this situation, the PEVs with the highest *charge priority* are selected to charge. When these PEVs are charged their *charge priority* decreases. By contrast, the *charge priority* of the PEVs not selected to charge increases. By the beginning of the next time step, the PEVs that are charging have a *charge priority* that is less than the *charge priority* of the PEVs that are not charging. Since the PEVs with the highest *charge priority* are always selected to charge, the PEVs that are charging are all cycled off and the PEVs that are not charging are all cycled on. Figure 3.2b is a graph from a

GM0085 simulation that demonstrates this phenomenon. In the early morning hours, there are a large number of PEVs that turn on and an equally large number of PEVs that turn off each time step. There are also almost no PEVs that remain on during consecutive time steps. For example, at 6 am there are over ten thousand PEVs that turn on, over ten thousand PEVs that turn off, and only 11 PEVs that remain on.

Charge priority has another characteristic that can increase charge cycling as PEVs approach the end of their charge. As PEVs approach the end of their charge, there is a dramatic increase in the amount of change that can occur in the *charge priority* over a single time step (see Figure 3.4). This volatile characteristic of *charge priority* makes charge cycling very likely for PEVs as they approach the end of their charge.

Near Beginning of Charge

$$remaining\ park\ time[k] = 200\ minutes$$
$$\min remaining\ charge\ time[k] = 100\ minutes$$
$$aggregator\ time\ step\ = 10\ minutes$$
$$charge\ priority[k] = \frac{100\ minutes}{200\ minutes} = 0.50$$
$$charge\ priority[k+1] \in \left[\frac{100}{200-10}, \frac{100-10}{200-10}\right]$$
$$\in [0.526, 0.474]$$
$$\max increase\ in\ charge\ priority\ = 0.026$$
$$\max decrease\ in\ charge\ priority\ = 0.026$$

Near End of Charge

$$remaining\ park\ time[k] = 30\ minutes$$
$$\min remaining\ charge\ time[k] = 15\ minutes$$
$$aggregator\ time\ step\ = 10\ minutes$$
$$charge\ priority[k] = \frac{15\ minutes}{30\ minutes} = 0.50$$
$$charge\ priority[k+1] \in \left[\frac{15}{30-10}, \frac{15-10}{30-10}\right]$$
$$\in [0.75, 0.25]$$
$$\max increase\ in\ charge\ priority\ = 0.25$$
$$\max decrease\ in\ charge\ priority\ = 0.25$$

Figure 3.4: An example of the maximum possible change in charge priority when a PEV is near the beginning and end of its charge. At the beginning of the charge there is a little over 3 hours of park time remaining and the charge priority can only change by 0.026. By contrast, when there is only 30 minutes of park time remaining the charge priority can change by 0.25, which is nearly an order of magnitude increase in the amount of change that can occur in the charge priority over a single time step.

This chapter has described how charge cycling is a side effect of the PEV charging control strategy developed in the GM0085 project. The next chapter will discuss one way the control strategy can be modified to limit and control the charge cycling of PEVs.

Chapter 4: Modification of PEV Charging Control Strategy

Chapter 3 describes how the original methodology for allocating energy to PEVs can lead to excessive charge cycling. Charge cycling occurs when one PEV stops charging and another PEV starts charging in its place. There are several characteristics of the original methodology that contribute to excessive charge cycling. First, the original methodology allocates energy to PEVs in descending order of *charge priority* without regard to the current charge state of the PEVs. The PEVs that are charging are treated exactly the same as the PEVs that are not charging. Second, the *charge priority* metric has too much volatility as a PEV approaches the end of their park. Finally, the original methodology has no mechanism to monitor, limit, or control the amount of charge cycling.

The new methodology for allocating energy to PEVs described in this chapter addresses the issues inherent in the old methodology. First, the new methodology considers the current charging state of each PEV when deciding which PEVs should be charged the next time step. It does this using two state variables. Second, two new metrics that prioritize charging needs using a holistic approach replace the *charge priority* metric. This holistic approach uses the entire charge to prioritize charging needs and as a result is very stable at the beginning, middle, and end of the park. Finally, the new methodology defines three additional metrics that are used to monitor the amount of charge cycling and to decide when to stop charge cycling. Each of these additional metrics and state variables are described in Section 4.1.

The new methodology allocates energy to PEVs in four consecutive steps. These four steps are:

1. Set Up
2. Calculate Initial Delta Energy
3. Minimize Absolute Value of Delta Energy
4. Perform Controlled Charge Cycling

These four steps are each described in Sections 4.2, 4.3, 4.4, and 4.5 respectively.

4.1 New Metrics and State Variables

This section describes the additional metrics and state variables used in the new methodology for allocating energy to PEVs. The new metrics that replace charge priority, the new state variables that are used to quantify the current charging state of PEVs, and the new metrics used to quantify charge cycling are described in Section 4.1.1, Section 4.1.2, and Section 4.1.3 respectively.

4.1.1 New Metrics Replacing Charge Priority

In the new methodology, *charge priority* is replaced by two metrics. These metrics are named *charge progression* and *charge flexibility*.

Charge progression uses the entire charge as well as the entire park to prioritize charging needs. *Charge progression* is the *percent park time completed* minus the *percent charge time completed* (15). The *percent park time completed* is the time parked so far divided by *the total park time* (13). For example, if a PEV arrived at a location to charge at 1 pm, is scheduled to depart at 5 pm, and it is currently 2 pm then the *percent park time completed* is 25%.

$$percent\ park\ time\ competed = \frac{total\ park\ time\ - remaining\ park\ time}{total\ park\ time} \tag{13}$$

$$percent\ charge\ time\ competed = \frac{minimum\ time\ to\ complete\ entire\ charge\ -\ minimum\ remaining\ charge\ time}{minimum\ time\ to\ complete\ entire\ charge} \tag{14}$$

$$charge\ progression = percent\ park\ completed\ - percent\ charge\ completed \tag{15}$$

$$charge\ flexibility = \frac{remaining\ park\ time\ - minimum\ remaining\ charge\ time}{aggregator\ time\ step} \tag{16}$$

At first glance it may seem that the *percent charge time completed* should be defined in terms of charge energy and not in terms of charge time. This is not the case because the maximum rate at which energy can be delivered to the battery is not constant but depends on the state of charge of the PEV's battery. The *percent charge time completed* is defined in (14). In this equation the *minimum time to complete the entire charge* is the time required to completely charge the PEV from start to finish when charged at its max charge rate. The *minimum remaining charge time* is the time required to finish charging the PEV at its max charge rate from the current point in time. For example, if a PEV arrived at a charging station at 1pm and requires 2 hours to fully charge (when it is charged at its max charge rate), and three hours later at 4 pm this same PEV requires 0.5 hours to fully charge (when it is charged at its max charge rate), then at 4 pm the *percent charge time complete* is 75%.

Unlike *charge priority*, *charge progression* is a very stable metric at the beginning, middle and end of the park. *Charge progression* is a real number between -1 and 1. Conceptually, a negative *charge progression* indicates that the charge is closer to completion than the park or that the charge is ahead of schedule. A positive *charge progression* indicates that the park is closer to completion than the charge or that the charge is behind schedule. A *charge progression* of zero indicates that the charge is right on schedule.

Charge flexibility captures an aspect of *charge priority* that is not inherent in the *charge progression* metric. *Charge priority* indicates both the urgency to charge as well as the amount of flexibility available to charge at different rates or times. For example, the ability to shift PEV charge energy in time is a lot greater for a *charge priority* of 0.1 than for a *charge priority* of 0.99. When the *charge priority* is 0.99 there is almost no flexibility to shift PEV charge energy in time because the PEV must charge at its max charge rate for the remainder of the park time. *Charge flexibility* quantifies the ability of a PEV to shift charge energy in time while still having its charging needs met. *Charge flexibility* is the amount of time that a PEV does not need to draw power divided by the duration of the aggregator time step as show in (16). As the *charge flexibility* decreases the ability of a PEV to shift change energy in time also decreases.

4.1.2 New State Variables

The new methodology uses two state variables to monitor PEV charging state. These state variables are retained between successive time steps. The state variables are *must charge* and *is charging*. *Is charging* is a Boolean variable used to keep track of each PEVs current charging state. *Is charging* is true if a PEV is charging in the current time step and is false otherwise. *Must charge* is also a Boolean state value. When it has been determined that a PEV must charge for the remaining time it is parked to meet its charging needs, *must charge* is set to true and is false otherwise. *Must charge* is calculated using the *charge flexibility* metric.

4.1.3 New Metrics to Quantify Charge Cycling

The new methodology uses three variables to monitor the amount of charge cycling and to make the decision of when to stop charge cycling. These variables are named *off to on energy*, *on to off energy*, and *total on energy*. Each of these variables are a sum of PEV energy set points. *Off to on energy* is the sum of the energy set points in the next time step of all PEVs that are not charging in the current time step and will start charging in the next time step. *On to off energy* is the sum of the energy set points in the current time step of all PEVs that are charging in the current time step and will stop charging in the next time step. *Total on energy* is the sum of the energy set points of all PEVs that are charging in the current time step.

4.2 Set Up

The set up step consists of four distinct activities. These activities are summarized as follows:

1. Initialize *off to on energy* and *on to off energy* to zero
2. Calculate *charge progression* and *charge flexibility* for all PEVs
3. Calculate *total on energy*
4. Update the *must charge* state variable for all PEVs

The first activity is self-explanatory; the second activity is described in Section 4.1.1 and requires no further discussion. The third and fourth activities will be further discussed in this section.

Figure 4.1a is a flow diagram describing the calculation of the *total on energy*. In this flow diagram, N represents the total number of PEVs and n is an index used to iterate through all PEVs. *Total on energy* is the sum of the e^{step} energy set point values for all PEVs that are currently charging.

Figure 4.1b is a flow diagram describing the process of updating the *must charge* state variables for all PEVs. The *charge flexibility* metric is used to set the must charge state variable. *Must charge* is set to true when *charge flexibility* drops below a threshold value designated in the flow diagram as x. For the simulations in this thesis, x was given a value of 2.5. Once *must charge* is set to true for a given PEV it remains true for the duration of that PEVs charge. The function of the *must charge* state variable is to ensure that all PEVs charging needs are met.

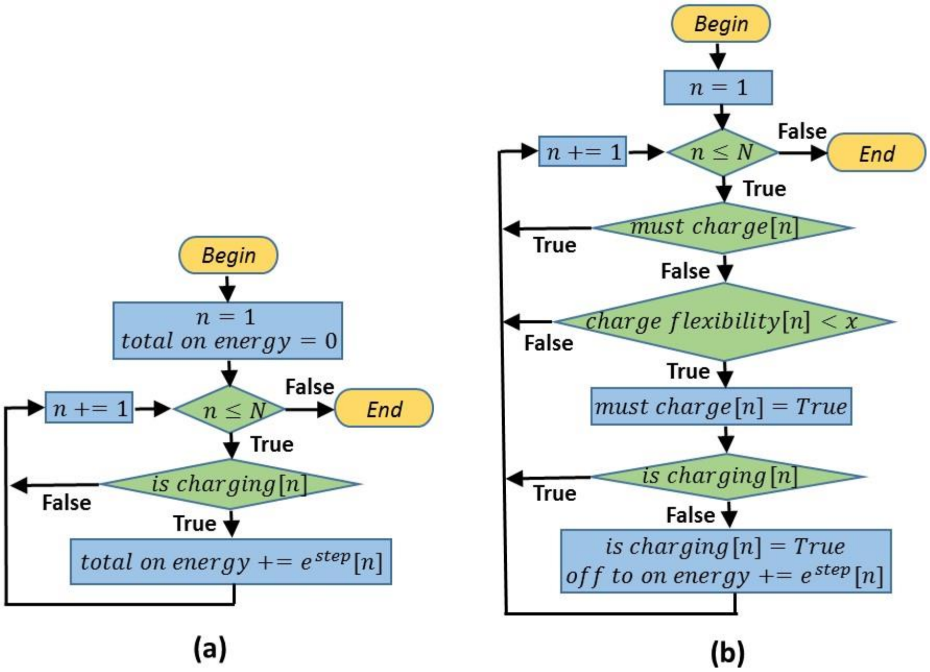


Figure 4.1: In these flow diagrams, N is the total number of PEVs and n is an index used to iterate through all PEVs. **(a)** Calculation of *total on energy*. **(b)** Updating the *must charge* state variable for all PEVs. *Must charge* is set to true when *charge flexibility* drops below the threshold value x. For the simulations in this thesis, x was given a value of 2.5.

4.3 Calculate Initial Delta Energy

Delta energy is the difference between the total PEV charge energy for the next time step, $E^{step}[0]$, and the sum of the energy set points, e^{step}, for all PEVs that will be charging during the next time step. *Delta energy* is a residual term that indicates whether PEVs should be turned on or turned off to meet the target energy from the aggregator. This adjustment of PEV dispatch to minimize the magnitude of the *delta energy* is performed during the entire process of allocating energy to PEVs. Figure 4.2 is a flow diagram describing the process of calculating the initial *delta energy*. Positive *delta energy* indicates that combined PEV charging energy is too low and should be increased, negative *delta energy* indicates that combined PEV charging energy is too high and should be decreased.

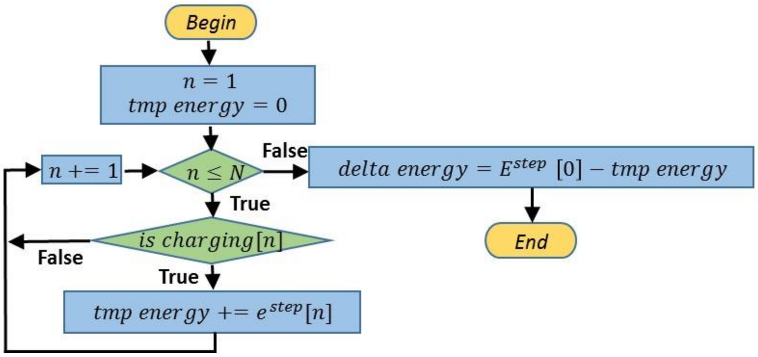
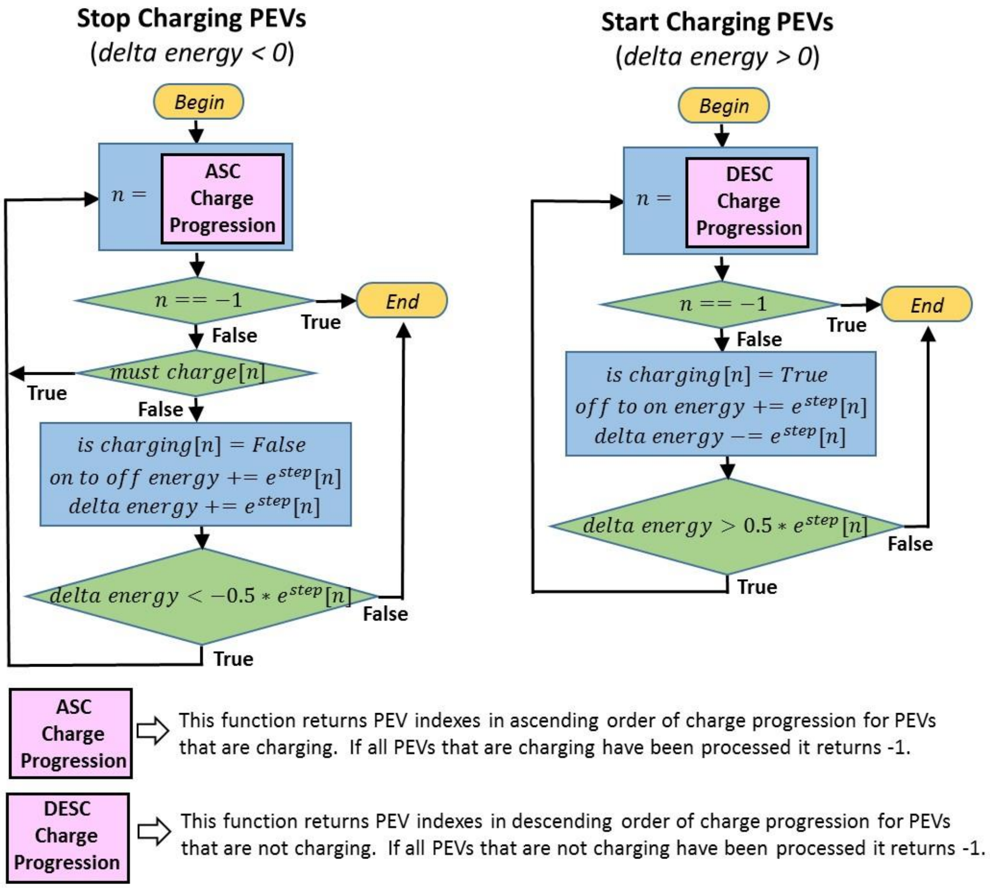


Figure 4.2: In this flow diagram, N is the total number of PEVs and n is an index used to iterate through all PEVs. Positive *delta energy* indicates that PEV charging should be increased, negative *delta energy* indicates that PEV charging should be decreased.

4.4 Minimize Absolute Value of Delta Energy

Delta energy is a residual term that indicates how close the combined PEV charging energy is to the target energy from the aggregator. *Delta energy* should be as close to zero as possible. Figure 4.3 shows two flow diagrams describing the process of minimizing the absolute value of *delta energy*. One flow diagram is used when *delta energy* is negative, the other when *delta energy* is positive. There are several important differences in these two flow diagrams, the most prominent difference is the functions used to select the PEVs to be turned on or turned off.



This function returns PEV indexes in ascending order of charge progression for PEVs that are charging. If all PEVs that are charging have been processed it returns -1.

This function returns PEV indexes in descending order of charge progression for PEVs that are not charging. If all PEVs that are not charging have been processed it returns -1.

Figure 4.3: In these flow diagrams, n is an index used to iterate through the PEVs. These flow diagrams demonstrate how to minimize the absolute value of *delta energy* when *delta energy* is both positive and negative.

When *delta energy* is negative, the function ASC Charge Progression is used to select the next PEV to be turned off. ASC Charge Progression returns a single PEV index each iteration. Each iteration this function selects the PEV that is currently charging that has the least need to continue charging. The PEV that has the least need to continue charging is the

PEV with the smallest *charge progression*. If all PEVs that are charging have been processed the function returns -1.

When *delta energy* is positive, the function DESC Charge Progression is used to select the next PEV to be turned on. DESC Charge Progression returns a single PEV index each iteration. At each iteration this function selects the PEV that is currently not charging that has the greatest need to start charging. The PEV that has the greatest need to start charging is the PEV with the largest *charge progression*. If all PEVs that are not charging have been processed the function returns -1.

4.5 Perform Controlled Charge Cycling

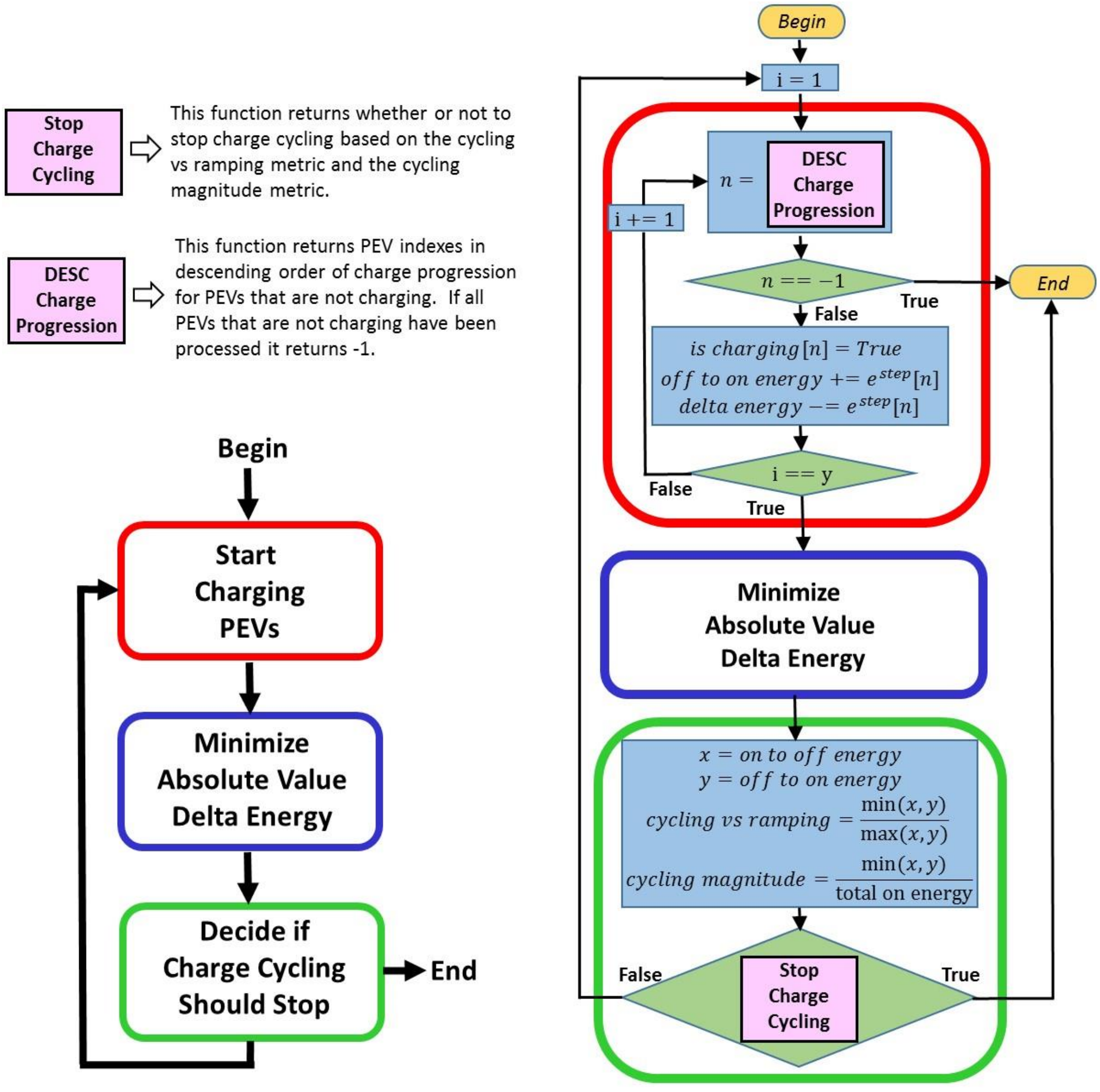
When charging many PEVs there is a tendency for the charging of some PEVs to fall behind schedule. A PEVs charge is behind schedule when its park is closer to completion than its charge. Limited charge cycling can be a very beneficial mechanism to start charging the PEVs that are furthest behind schedule and have the greatest need to begin charging. Controlled charge cycling encourages each PEVs charging to be completed at approximately the same rate as their parking. By contrast excessive charge cycling may pose stability challenges to the electric grid. The amount of charge cycling that is allowed is a decision that must take into account these tradeoffs. Understanding and quantifying these tradeoffs is not part of this thesis but is an important area of future work.

Controlled charge cycling is detailed in Figure 4.4. Figure 4.4b is a flow diagram that describes the process of controlled charge cycling and Figure 4.4a illustrates the three steps of controlled charge cycling which are:

1. Start charging PEVs

2. Minimize the absolute value of *delta energy*

3. Decide if charge cycling should stop



This function returns whether or not to stop charge cycling based on the cycling vs ramping metric and the cycling magnitude metric.

This function returns PEV indexes in descending order of charge progression for PEVs that are not charging. If all PEVs that are not charging have been processed it returns -1.

(a) **(b)**

Figure 4.4: **(a)** The three steps of controlled charge cycling. **(b)** Flow diagram describing controlled charge cycling.

The first step of controlled charge cycling uses the DESC Charge Progression function described in Section 4.4 to select the PEVs to start charging. The number of PEVs whose charging is started each controlled charge cycle iteration is designated as y in the flow diagram. When testing the modified control strategy in this thesis, y was given a value of 10.

The second step of controlled charge cycling is described in detail in Section 4.4. The process of minimizing the absolute value of *delta energy* in this step, will stop the charging of just enough PEVs to balance the displacement in *delta energy* caused by step 1. The combination of step 1 and step 2 facilitates charge cycling and maintains *delta energy* near zero.

The third step of controlled charge cycling decides whether or not charge cycling should be stopped. When making the decision to stop charge cycling it is essential to distinguish between charge cycling and the ramping of PEV charging. Rapidly ramping PEV charging is ok and should not be confused with excessive charge cycling. An example of ramping is when a large number of PEVs stop charging and very few PEVs start charging. By contrast, excessive charge cycling is when a large number of PEVs stop charging and large number of different PEVs start charging in their place.

The amount of charge cycling is quantified using two metrics named the *cycling vs ramping* metric and the *cycling magnitude* metric. These two metrics are calculated from the *off to on energy*, *on to off energy*, and *total on energy* metrics as shown in (17) and (18).

$$cycling\ vs\ ramping = \frac{\min(on\ to\ off\ energy,\ \ off\ to\ on\ energy)}{\max(on\ to\ off\ energy,\ \ off\ to\ on\ energy)} \quad (17)$$

$$cycling\ magnitude = \frac{\min(on\ to\ off\ energy,\ \ off\ to\ on\ energy)}{total\ on\ energy} \quad (18)$$

The value $\min(on\ to\ off\ energy, off\ to\ on\ energy)$ can be thought of loosely as the amount of charge cycling energy. Both the *cycling vs ramping* and *cycling magnitude* metric are a ratio of charge cycling energy and some other value.

The *cycling vs ramping* metric is a real number from 0 to 1 inclusive. A value of 0 indicates that the change in PEV charging is entirely due to ramping and not charge cycling. A value of 1 indicates that the change in PEV charging is entirely due to charge cycling and not ramping. When the *cycling vs ramping* metric is between 0 and 1 part of the change in PEV charging is due to charge cycling and part is due to ramping; as the value increases from 0 to 1 the part due to charge cycling increases and the part due to ramping decreases.

The *cycling magnitude* metric is also a real number from 0 to 1 inclusive. A value of 0 indicates that there is no charge cycling. A value of 1 is the case of maximum charge cycling where all PEVs that are on in the current time step are cycled off in the next time step. As the value increases from 0 to 1 the magnitude of charge cycling also increases.

The Stop Charge Cycling function in Figure 4.4b makes the decision of when to stop charge cycling using the *cycling vs ramping* metric and the *cycling magnitude* metric. When either the *cycling magnitude* metric is small or the *cycling vs ramping* metric is small the amount of charge cycling is limited. Figure 4.5a is a graphical representation of the *cycling vs ramping* metric and *cycling magnitude* metric as orthogonal dimensions. The shaded region in 4.5a corresponds to the metric combinations where charge cycling is limited and PEV charge cycling can be continued. In Figure 4.5b the space spanned by the *cycling vs ramping* metric and the *cycling magnitude metric* is divided into two sets by the charge cycling control boundary. The charge cycling control boundary maps every possible metric combination to one of two decisions. The decisions are either to continue charge cycling or to stop charge cycling.

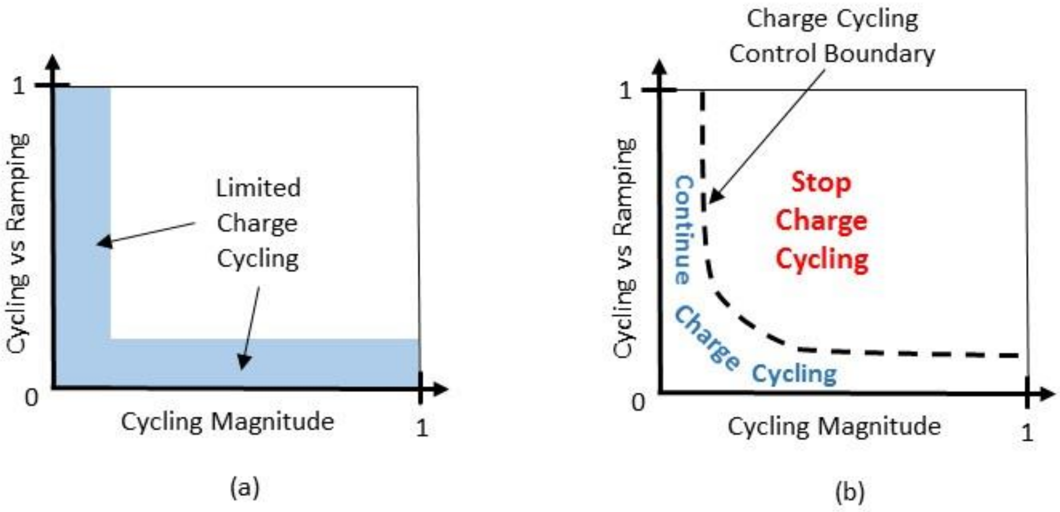


Figure 4.5: (a) When either the *cycling magnitude* metric is small or the *cycling vs ramping* metric is small the amount of charge cycling is limited. **(b)** The charge cycling control boundary maps every possible metric combination to one of two decisions: Continue Charge Cycling, Stop Charge Cycling.

The key design criteria for the methodology of allocating energy to PEVs described in this chapter was not only to be able to monitor and limit the amount of charge cycling, but to be able to control the amount of charge cycling as well. Controlling the amount of charge cycling is accomplished by shifting the charge cycling control boundary. When the charge cycling control boundary is shifted as shown in Figure 4.6 the amount of charge cycling increases. When the boundary is shifted in the opposite direction the amount of charge cycling decreases.

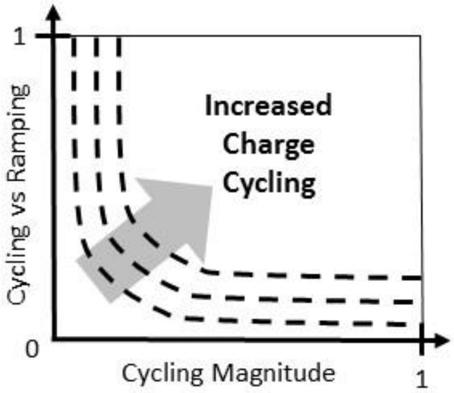


Figure 4.6: The amount of charge cycling can be controlled by shifting the charge cycling control boundary. When the boundary is shifted in the direction of the arrow the charge cycling increases.

This chapter discussed how the algorithm allocating energy to PEVs can be modified to monitor, limit, and control the amount of charge cycling. The next chapter will show results demonstrating the effectiveness of this new algorithm in limiting and controlling the amount of charge cycling.

Chapter 5: Results

Chapter 4 described a way to allocate energy to PEVs so that charge cycling can be monitored, limited, and controlled. This chapter compares simulation results from the original and modified control strategies. Section 5.1 describes the simulation environment used to test the control strategies, Section 5.2 presents the scenario description and results, and Section 5.3 compares the original and modified control strategies.

5.1 Simulation Environment

The aggregators in the original and modified control strategies do not work in isolation; rather they require forecast information and are frequently interacting with PEVs that are charging. The simulation environment used to test the aggregators has the following components:

- Models for PEV chargers
- Actual and forecasted non PEV feeder load profiles
- Actual and forecasted PEV charging behavior datasets

5.1.1 Models for PEV chargers

The models for PEV chargers accurately represent how PEVs behave as loads on the grid. High fidelity charging models were created for the 2015 Nissan Leaf, 2016 Chevy Volt, and the 2013 Ford Fusion in the GM0085 project. Lab testing results for each of these PEVs were used to both create and then validate the PEV charging models.

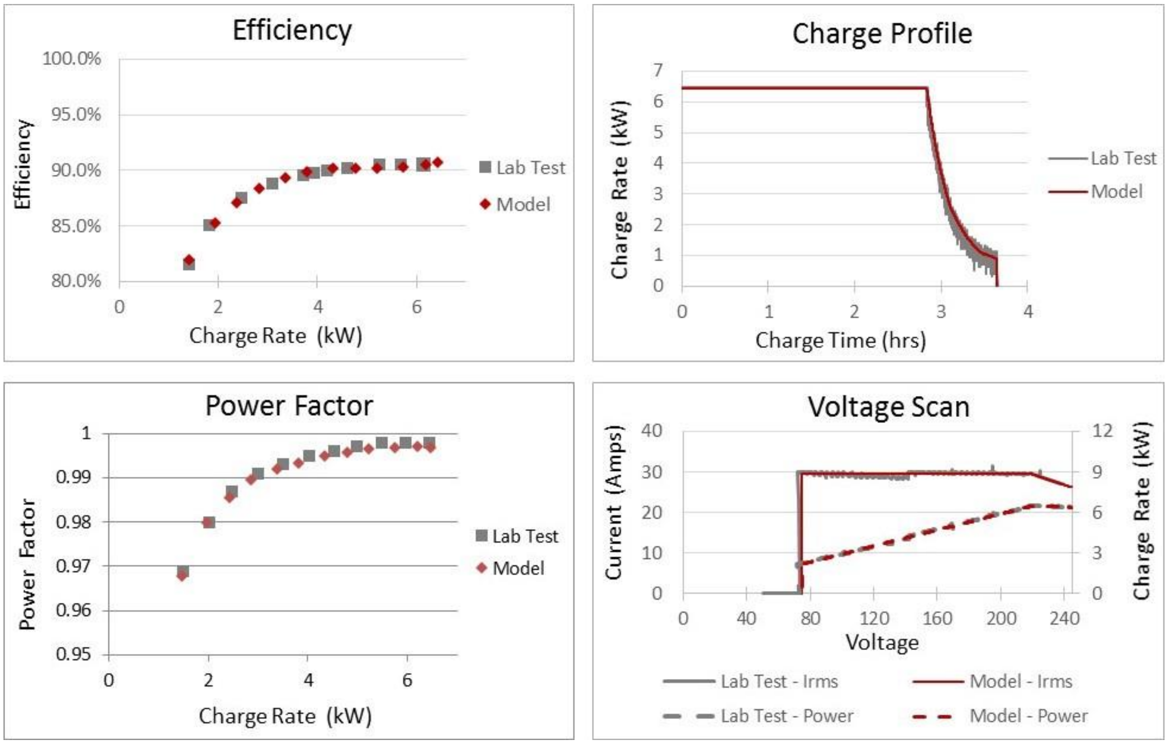


Figure 5.1: A comparison of lab test and model output results for a 2015 Nissan Leaf. The model output very accurately represents the charging behavior of the 2015 Nissan Leaf.

Figures 5.1 and 5.2 compare the output of the PEV charging model with the lab testing results for the 2015 Nissan Leaf. Figure 5.1 shows that the charging model output is a high fidelity representation of:

- Efficiency as a function of charge rate
- Power factor as a function of charge rate
- Max charge rate as a function of battery SOC
- Power and current limits as a function of voltage

Figure 5.2 demonstrates that the representation of the transitions from one charge rate to another charge rate of the charging model is sufficiently accurate for a 2015 Nissan Leaf.

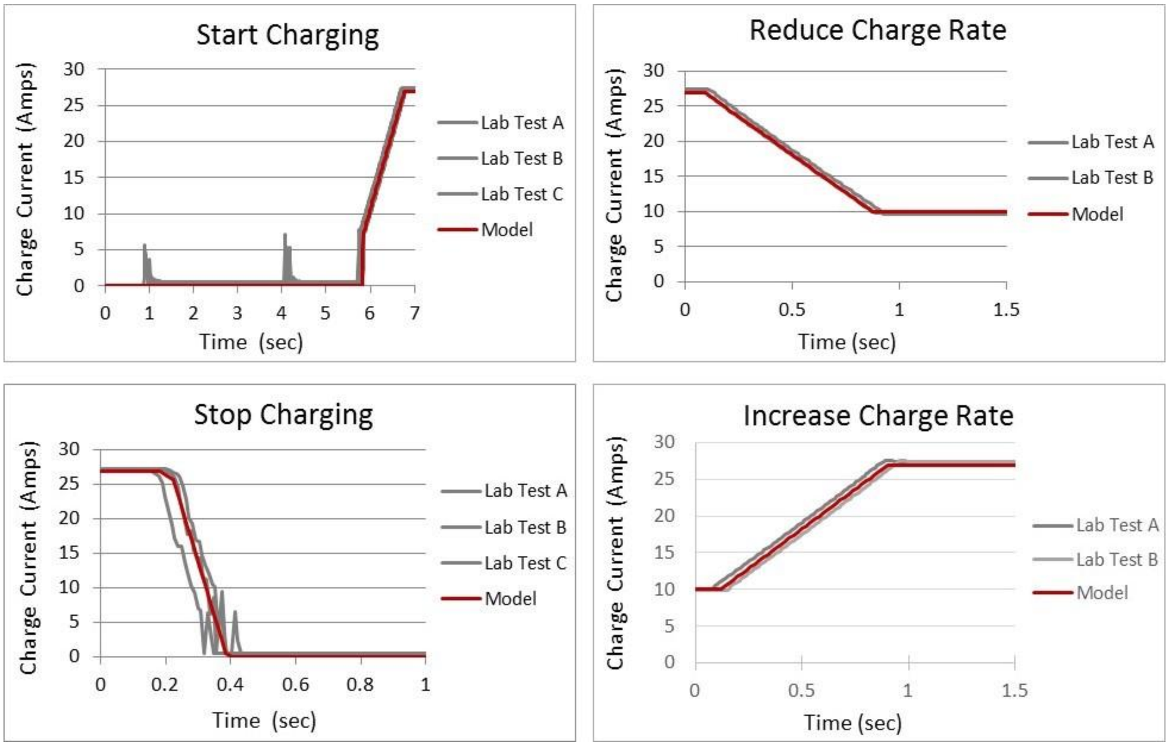


Figure 5.2: A comparison of lab test and model output results for a 2015 Nissan Leaf. The model output very accurately represents the transitions from one charge rate to another charge rate.

5.1.2 Actual and Forecasted non PEV Feeder Load Profiles

The non-PEV feeder load profile used in the simulation environment is derived from the typical PG&E residential load profile downloaded from the PG&E website [18]. The typical residential load profile is an hourly load profile for each calendar year over a several year period and represents the typical or average load of a single residence in the PG&E service area. The non-PEV feeder load profile is calculated by multiplying the number of residences on the feeder by the typical residential load profile. The typical PG&E residential profiles were used to derive both the actual and forecasted non PEV feeder load profiles. The actual profile used the PG&E data from July, 27th 2016 and the forecasted profile used the previous day, July 26th 2016. Both of these days are peak load days in the typical PG&E residential profile for 2016 (see Figure 5.3).

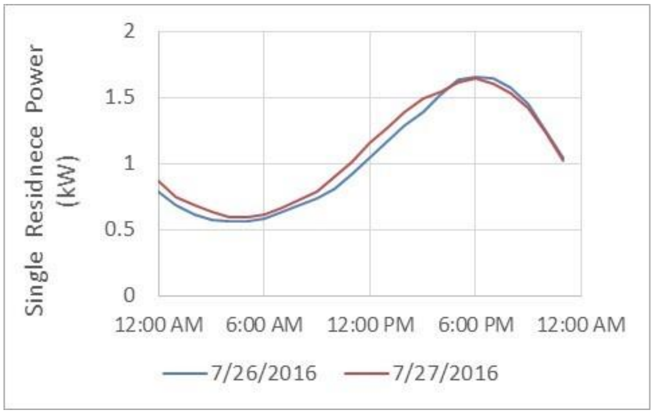


Figure 5.3: The typical or average load of a single residence in the PG&E area. The data on 7/27/2016 is used to calculate the actual feeder load profile; the data on the previous day, 7/26/2016 is used to calculate the forecasted feeder load profile.

5.1.3 Actual and Forecasted PEV Charging Behavior Datasets

PEV charging behavior describes where and at what time PEV owners choose to charge their PEVs. PEV charging behavior data consists of the following:

- Time PEV connected to charger
- Time PEV disconnected from charger
- Battery SOC when PEV started charging
- Requested charge energy
- PEV charge location

PEV charging behavior data used in the simulation environment is derived from actual charging behavior data in The EV Project from the PG&E service territory for 2013 Nissan Leafs. The methodology used to derive PEV charging behavior data from the historical charging data is described in [17]. The forecasted charging behavior dataset was derived by adding small errors to the PEV arrival times, departure times, and requested charge energy in the actual charging behavior dataset. The actual charging behavior dataset is used to initialize the models for PEV charging systems described in Section 5.1.1. The forecasted charging behavior dataset is used by the aggregator to determine when PEVs should be charged during the prediction time horizon.

5.2 Scenario Description and Results

The same scenario was used for both the original control strategy and the modified control strategy. The scenario consisted of a residential feeder with 100,000 residential homes in the PG&E area where 50% of the homes have a PEV. The 2016 Nissan Leaf charging model was used for all PEVs.

Figure 5.4a shows the feeder load profiles when there are no PEVs charging, when the PEV charging is not controlled, and when the PEV charging is controlled using the original control strategy. When charging is not controlled, each PEV begins charging as soon as it is connected to a charger and continues to charge as fast as possible until its charge is complete. When PEV charging is not controlled, the PEV charging occurs at the same time as the peak of the non-PEV load. This increases both the peak and ramping in the feeder load when compared to the feeder load with no PEV charging. By contrast, controlled charging shifts the PEV charging to off peak hours which flattens the feeder load profile and causes only a very small increase in peak load. Controlled charging in large part mitigates the need for capacity upgrades to residential feeders as PEV penetration increases.

Figure 5.4b shows that the feeder load profiles of the original and the modified control strategies are nearly identical. This is due to the fact that the reduced order optimization model used in the original and modified control strategies are identical and the total PEV charging energy is determined by the reduced order optimization model. The only difference between the original and modified control strategies is how the total PEV charging energy is allocated to the individual PEVs.

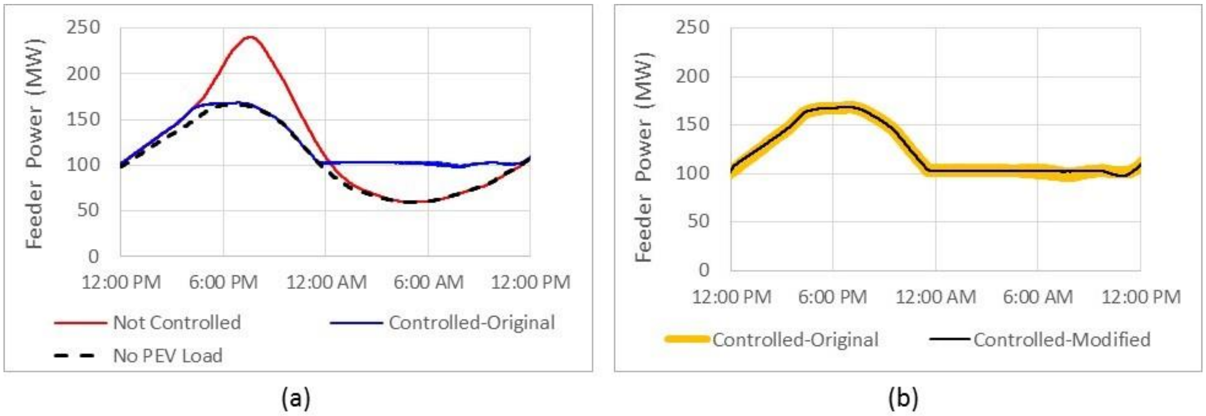


Figure 5.4: (a) The feeder load profiles when there are no PEVs charging (black dashed line), when the PEV charging is not controlled (red line), and when the PEV charging is controlled using the original control strategy (blue line). **(b)** The feeder load profiles for the original and modified control strategies are nearly identical.

Figure 5.5 shows the number of PEVs that are connected to a charger somewhere on the feeder as a function of the time of day. Of the 50,000 PEVs that are parked at their respective home overnight, only a little over 35,000 PEVs are connected to a charger. This is typical of the residential charging behavior of PEVs in the EV Project. Not every PEV charges every night, typically only 70 to 80 percent of PEVs charge on a given night.

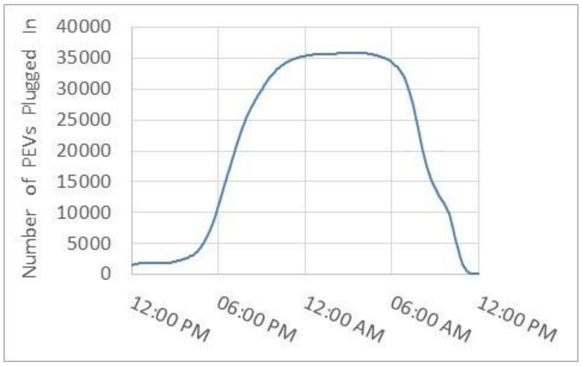


Figure 5.5: The number of PEVs that are connected to a charger on the residential feeder.

5.3 Comparison of Original Control Strategy with Modified Control Strategy

Once the modified control strategy was implemented, it was tested using three different charge cycling control boundaries. The three charge cycling control boundaries are displayed in Figure 5.6. See Section 4.5 for a detailed description of charge cycling control boundaries. M1 is the most restrictive boundary, limiting charge cycling more than either M2 or M3. M3 is the least restrictive boundary.

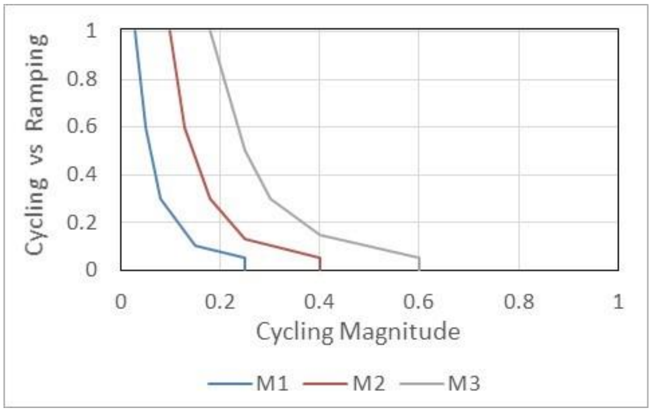


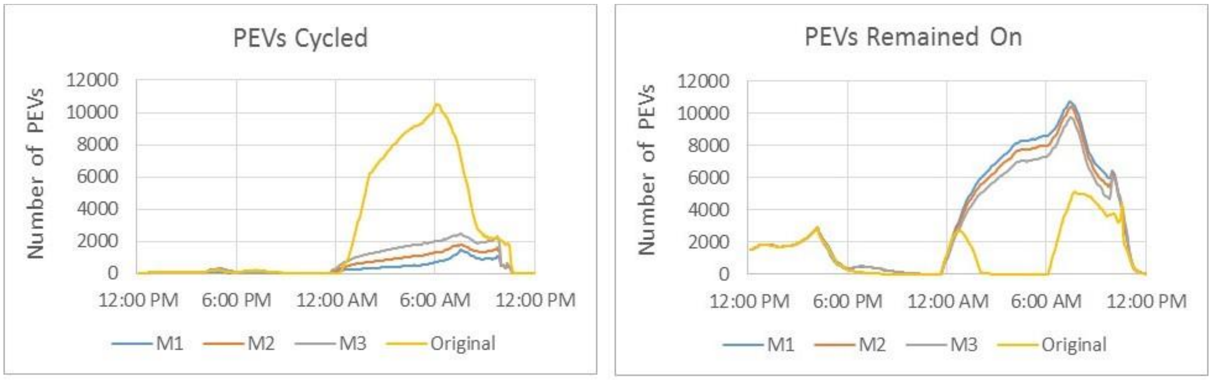
Figure 5.6: Three Charge Cycling Control Boundaries named M1, M2, and M3. M1 limits charge cycling the most, M3 limits charge cycling the least, M2 is between M1 and M3.

Outputs from the three scenarios using the modified control strategy were compared with each other and with outputs from the original control strategy. In the following discussion, these four scenarios will be referred to as M1, M2, M3 and Original. The amount of charge cycling in the four scenarios was compared using the number of PEVs cycled and the number of PEVs that remained on. The number of PEVs cycled is defined in equation (19).

$$\begin{gathered} x = Number\ of\ PEVs\ that\ turned\ on\ between\ successive\ time\ steps \\ y = Number\ of\ PEVs\ that\ turned\ off\ between\ successive\ time\ steps \\ Number\ of\ PEVs\ cycled = \min(x, y) \end{gathered} \tag{19}$$

As the names imply, the number of PEVs cycled can be thought of loosely as the number of PEVs that were charge cycled between successive time steps; the number of PEVs that remained on is the number of PEVs that remained on between successive time steps.

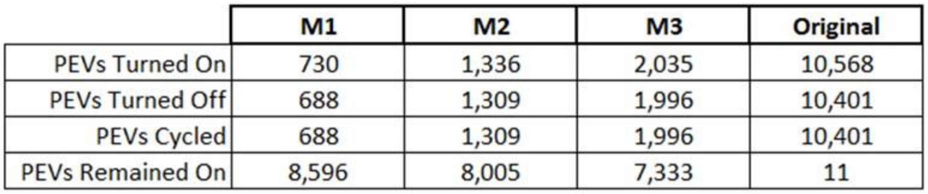
The first thing to notice in Figure 5.7 and Table 5.1 is that the modified control strategy limits charge cycling when compared to the original control strategy. Fewer PEVs are cycled, and more PEVs remain on between successive time steps when the modified control strategy is used with M3. For example, at 6 am less than 2000 PEVs are cycled when the modified control strategy is used, but more than 10,000 PEVs are cycled when the original control strategy is used. Moreover, at 6 am more than 7,000 PEVs remain on when the modified control strategy is used, but only 11 PEVs remain on when the original control strategy is used.



(a) (b)

Figure 5.7: **(a)** The number of PEVs that were cycled between successive time steps. **(b)** The number of PEVs that remained on between successive time steps.

The second thing to notice in Figure 5.7 and Table 5.1 is that the amount of charge cycling can be controlled when the modified control strategy is used. M1, which is the scenario with the most restrictive charge cycling control boundary, has the fewest PEVs that are cycled and the most PEVs that remain on. M3, which is the scenario with the least restrictive charge cycling control boundary, has the most PEVs that are cycled and the fewest PEVs that remain on. For example, at 6 am the number of PEVs that are cycled in scenarios M1, M2, and M3 is 688, 1309, and 1996 respectively. The number of PEVs that remained on at 6 am in scenarios M1, M2, and M3 is 8596, 8005, and 7333 respectively. Understanding the tradeoffs between the benefits charge cycling offers to PEV charging and the adverse effects that charge cycling might have on grid stability has not been investigated in this thesis and is an important area of future work.



	M1	M2	M3	Original
PEVs Turned On	730	1,336	2,035	10,568
PEVs Turned Off	688	1,309	1,996	10,401
PEVs Cycled	688	1,309	1,996	10,401
PEVs Remained On	8,596	8,005	7,333	11

Table 5.1: The number of PEVs turned on, number of PEVs turned off, number of PEVs cycled, and number of PEVs that remained on for the four scenarios M1, M2, M3, and Original. These values were taken at 6 am.

When the original control strategy was designed the most important design criteria was scalability and computational efficiency. It was very important to be able to calculate the energy set points for a very large number of PEVs, in a very small amount of time on an ordinary PC.

Figure 5.5 in Section 5.2 displays the number of PEVs that are actively charged throughout the simulation day. The number of PEVs that are actively charged is the same for all four of the scenarios evaluated in this study. In the early morning hours there are over 35,000 PEVs that are actively charged. Figure 5.8 displays the time required to execute the control strategy for all four scenarios. An overview of the control strategy is given in Chapter 2 and consists of the following steps:

1. Aggregate the PEV constraints
2. Solve the reduced order optimization model
3. Allocate energy to PEVs

There is no meaningful difference in computational performance between the original and modified control strategies. Both control strategies were able to consistently manage the charging of over 35,000 PEVs in about 1.07 seconds.

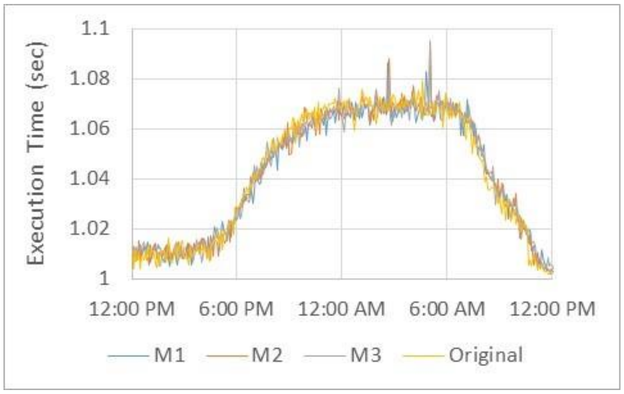


Figure 5.8: The time required to execute the control strategies for the four scenarios. All control strategies were able to consistently manage the charging of over 35,000 PEVs in about 1.07 seconds.

All these scenarios were run on a laptop with the following specifications:

- Dell latitude E6440
- Intel Core i7-4600M CPU @ 2.90 GHz x 4
- 4 GB of ram

Chapter 6: Summary, Conclusions and Future Work

6.1 Summary

This thesis builds on and improves a Plugin Electric Vehicle (PEV) charging control strategy developed in a Grid Modernization Laboratory Consortium (GMLC) project. This charging control strategy was developed with an emphasis on shifting residential PEV charging load from peak to off-peak hours. When the control strategy was designed the most important design criteria was scalability and computational efficiency. It was very important to be able to control the charging of a very large number of PEVs, in a very small amount of time using an ordinary PC.

The control strategy developed in the GMLC project was successfully implemented and tested as part of the project. After the control strategy was demonstrated and the focus of the GMLC project had been shifted, the author recognized the need for further refinement of the control strategy. The original control strategy is not able to limit or control the amount of PEV charge cycling. PEV charge cycling occurs when one PEV stops charging and another PEV starts charging in its place. Limited charge cycling can be a beneficial mechanism to start charging PEVs that need to start charging, but excessive charge cycling may lead to grid stability problems. The amount of charge cycling that is allowed is a decision that must consider these tradeoffs. This thesis modifies the original control strategy to be able to limit, and control the amount of PEV charge cycling.

6.2 Conclusions

This thesis modifies the original control strategy and proposes a methodology to monitor, limit, and control charge cycling. The effectiveness of this methodology is discussed in Section 5.2 which describes the performance of both the original and modified control strategies. Both strategies are able to shift the PEV charging to off peak hours flattening the feeder load profile and causing only a very small increase in peak load. Both strategies are scalable and computationally efficient; they are both able to consistently manage the charging of over 35,000 PEVs in about 1.07 seconds on an ordinary laptop. Unlike the original control strategy, the modified control strategy is able to monitor, limit and control the amount of charge cycling. For this reason, it is recommended that the modified control strategy be used in all future implementations.

6.3 Future Work

There are two bodies of work connected to this thesis that merit further investigation. The first is to develop a methodology that can be used to estimate the step energy upper bound that will achieve the best results for various charging scenarios. The step energy upper bound is described in Section 2.1 and is the maximum amount of energy that all PEVs can collectively draw. The second is to develop criteria that can be used to determine the optimal charge cycling control boundary. The charge cycling control boundary is described in Section 4.5 and is the mechanism used in the modified control strategy to control the amount of charge cycling. Each of these bodies of work are described below.

6.3.1 Develop Methodology to Estimate Step Energy Upper Bound

The step energy upper bound constrains the total energy the control strategy can allocate to PEVs during individual time steps. The step energy upper bound for a given time step is the maximum amount of energy that all PEVs can collectively draw during that time step. When a PEVs charging needs have been met or its battery is full, the max step energy for that PEV is zero. For this reason the max step energy for a given PEV depends on how the PEV was charged previously. In other words the step energy upper bound constraint of the reduced order optimization model depends on the model's decision variable (step energy). For this reason, the step energy upper bound cannot be calculated directly prior to solving the optimization model, rather it must be estimated.

In this thesis the step energy upper bound was estimated under the assumption that PEVs would be able to draw max power from the grid the entire time they were connected to a charger. This assumption is only correct if the PEVs wait until the last possible moment to charge. As was shown in Section 5.2 when the step energy upper bound is calculated in this way the control strategy works very well for residential charging. Even though it works well for residential charging it may be problematic in other charging situations like commercial or workplace charging. In addition, an increasing number of commercial buildings have building energy management systems (BEMS) that may be used to integrate PEV charging into the building load. If PEV charging is integrated directly into the BEMS, this control strategy may not be needed. This is an area where future work is needed both to investigate the utility of non-residential charging scenarios as well as to determine if there are better ways to estimate the step energy upper bound constraint.

6.3.2 Develop Criteria to Determine Optimal Charge Cycling Control Boundary

The focus of this thesis has been to develop a methodology that can be used to monitor, limit, and control the amount of charge cycling. Understanding the tradeoffs between the benefits charge cycling offers to PEV charging and the adverse effects that charge cycling might have on grid stability has not been investigated in this thesis and is an important area of future work. Once these tradeoffs are understood, it might be possible to develop criteria that define the optimal charge cycling control boundary for various PEV charging and grid conditions. If such criteria are derived, an algorithm could be developed that makes the charge cycling control boundary adaptive to both PEV charging conditions as well as grid conditions.

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Appendix A – Glossary of Terms

ALAP Charging – As long as possible charging occurs when a PEV waits until the last minute to begin charging and the PEV's charging needs are met just before the PEV is scheduled to depart.

ASAP Charging – As soon as possible charging occurs when a PEV immediately starts charging as soon as it is connected to a charger and continues to charge until the PEV's charging needs are met.

ASC Charge Progression – A function that selects the PEV that is currently charging that has the least need to continue charging.

Charge Cycling – When on PEV stops charging and another PEV starts charging in its place.

Charge Cycling Control Boundary – A boundary that maps every combination of cycling vs ramping and cycling magnitude metric to one of two decisions. The decisions are either to continue charge cycling or to stop charge cycling.

Charge Flexibility – The amount of time that a PEV does not need to draw power divided by the duration of the aggregator time step.

Charge Priority – A PEVs minimum remaining charge time divided by its remaining park time.

Charge Progression – Percent park time completed minus the percent charge time completed.

Cumulative Energy – The total energy drawn by a group of PEVs from the beginning of their respective charges up to the present time.

Cycling Magnitude – A metric that compares the amount of charge cycling energy to the total PEV charging energy.

Cycling vs Ramping – A metric that quantifies how much of the change in the PEV charging energy is due to charge cycling and how much is due to ramping.

Delta Energy – A residual term that is the difference between the total PEV charge energy for the next time step and the sum of the charge energy for all PEVs that will be charging the next time step.

DESC Charge Progression – A function that selects the PEV that is currently not charging that has the greatest need to start charging.

$D^{net}[k]$ – The load forecast of the non PEV load.

$e^{step}[n,k]$ – The energy set point for PEV n at time step k.

$e^{cum}[n,k]$ – The cumulative energy for PEV n at time step k.

$e_{max}^{step}[n,k]$ – The max energy PEV n can draw at time step k.

$E^{step}[k]$ – The step energy of all PEVs at time step k. The decision variable of the optimization model.

$E_{UB}^{step}[k]$ – The step energy upper bound at time step k.

$E_{LB}^{step}[k]$ – The step energy lower bound at time step k.

$E^{cum}[k]$ – The cumulative energy of all PEVs at time step k.

$E_{ALAP}^{cum}\ [k]$ – The As Long As Possible (ALAP) cumulative energy constraint at time step k.

$E_{ASAP}^{cum}\ [k]$ – The As Soon As Possible (ASAP) cumulative energy constraint at time step k.

Energy Set Point – The energy allocated to a given PEV to be drawn during the next time step.

EVSE – Electric Vehicle Supply Equipment

$Feeder_{limit}^{step}$ – The max energy the feeder can supply during a single time step.

Is Charging – Boolean state variable used to track a PEV's current charging state.

Must Charge – Boolean state variable used to track if a PEV must charge for the remainder of its park.

Off to On Energy – Total PEV charging energy in the next time step of all PEVs not charging in the current time step that will start charging in the next time step.

On to Off Energy – Total PEV charge energy in the current time step of all PEVs charging in the current time step that will stop charging in the next time step.

PEV – Plug-in electric vehicle.

Step Energy – The total energy drawn by all the PEVs during a given time step.

Stop Charge Cycling – A function that decides whether or not to stop charge cycling based on the cycling vs ramping and the cycling magnitude metric.

Total On Energy – The total PEV charge energy of all PEVs charging in the current time step.