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Vehicle to Grid Implementation and Battery Management Optimization

A Thesis submitted in partial satisfaction of the requirements for the degree of

Master of Science

in

Electrical Engineering

by

Yuchen Zhao

September 2017

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I would like to first thank my great parents, Mr. Shengli Zhao and Ms. Hongping Mo. They have given me the opportunity to study at UCR with their endless support, encouragement and love. I truly dedicate all this work to both of you.

Also, I would like to thank my advisor Dr. Matthew Barth, as well as Dr. Sadrul Ula and Mike Todd for their guidance and all help throughout my thesis. I would also like to thank my committee members for their time, advice, and suggestions during the construction of this work.

I would like to thank my lab mates, Daniel Sandez and Henry Gomez for always giving their suggestions and help when I really need it.
The need for energy independence and rising environmental pollution concerns are factors that drive the growing popularity of electric vehicles (EV), including electric and plug-in hybrid cars. Studies indicate that for 90% of the Americans who use their cars to get to work every day, on average, passenger vehicles are driven 1 to 2 hours a day, the remaining 22 to 23 hours they are parked, most often either at home or at work. The average distance driven each day is around 30 miles. However, a typical electrical vehicle has range of about 100 miles, thus, there would be around 70 miles’ battery capacity left in the vehicle. Thus, we can make use of the remaining battery capacity in EV as a potential energy supply. To perform adequately at highway speeds, electric vehicles require an output peak of 100 kW when they are accelerating. Therefore, the vehicle electronics are already sized for power output at levels above standard AC vehicle connection, giving electric vehicles the potential and ability to provide energy to outside when parked for most of time. In addition, the EVs typically have common battery standards, which provide storage capability that can be effectively harnessed. It happens
when the vehicles are integrated to the energy grid and can provide substantial power available to and from the grid with the existing vehicle systems. The entire communication technology of using the EVs as a distributed energy resource to receive and sent back power is known as the Vehicle-to-Grid or V2G technology.

The University of California, Riverside has started a Vehicle to Grid project as a part of Sustainable Integrated Grid Initiative (SIGI) system in 2014\(^1\). This project uses light duty electric vehicles and a large trolley electric bus as supplementary energy storage source to provide energy to building, thereby reducing the electric bill cost. In addition, it’s necessary to consider batteries life cycle and EVs’ driving schedule. Thus, EVs are not ready to supply power all the time and the charging and discharging events would reduce the batteries capacity. Therefore, this thesis introduces an Adaptive Peak Control (APC) algorithm to control the electric system so that batteries would discharge occasionally according to the building load trends while simultaneously protecting batteries in the same time.

This thesis introduces a Vehicle to Grid research system which mainly focuses on: (1) the testing of electric vehicle battery performance during charging and discharging events, (2) the construction and implementation of the connection between an electric trolley and the energy grid; and (3) battery charging and discharging management optimization considering price policy and battery life cycle behavior. It is important to note that allowing EVs to charge and discharge without any control may cause the increase of peak load and electric bill cost, or may cause the insufficient discharges that

\(^{1}\) http://www.cert.ucr.edu/newgrid/SIGIBrochure.pdf
are unable to lower the peak load. Within smart controls, the EV energy source can lower the bill cost by discharging during on-peak price period and charging during off-peak price period to store energy. In this thesis, we utilize Adaptive Peak Control (APC) algorithm as a real-time control method that manages discharging operation of an electric trolley and helps the building better manage its energy. Simulation results are illustrated (using MATLAB), showing the advantage of this algorithm. The proposed method is compared with a constant threshold model predictive control (CT-MPC) method, which is also used for battery management.
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1. INTRODUCTION

1.1. Vehicle to Grid Technology

Vehicle to Grid (V2G) system consists of plug-in electric vehicles, such as electric cars (BEV) and plug-in hybrids (PHEV), that can communicate with the power grid to provide demand response services by their returning energy to the grid or by throttling their charging rate.\textsuperscript{2,3} Electric vehicles, whether powered by batteries, fuel cells, or gasoline hybrids, have within them the energy source and power electronics capable of producing the 60 Hz AC electricity typically used to power buildings. When connections are added to allow this electricity to flow from cars to power lines, we call it “vehicle to grid” power, or V2G. As in Fig. 1.1, V2G has a bidirectional model of a converter that also incorporates a power factor correction to insure the power that will be taken from electric vehicle will be in-phase with the grid. The DC/DC Converter controls the charging and discharging of the battery.

Generally, electric vehicles are parked for many hours after we get to work or go home. Therefore, we can make use of the unused time of electric vehicles as a backup renewable energy source to power the building, and send back to the grid or provide emergency power load by charging the battery during low demand times and discharge the battery when power is required. To transfer the power, each vehicle must meet three


requirements: (1) they need to be connected to the grid and have electrical bi-directional energy flow, (2) they must be equipped with logical control communication with the grid operator; and (3) they must have an equipped on-board control system on the with the electric vehicles itself. This is illustrated in detail in below in Chapter 3.

Among the three types of electric vehicles, pure battery electric vehicles are used more widely for V2G research. Many research institutions and auto companies, such as the University of Delaware\(^4\), Lawrence Berkeley National Laboratory\(^5\), Nissan and Enel\(^6\) are using battery electric vehicles for V2G research.

The University of Delaware started their V2G research the year 2000, focusing on three key aspects of the V2G electrical system: storage size, availability, and economic potential. Overall, they conclude that all three types of electric drive vehicles studied represent a significant source of energy power for the electric grid. The largest value is in ancillary services such as spinning reserves and regulation. Lawrence Berkeley National

Laboratory created V2G-Sim\(^7\), which is a simulation platform that couples vehicle powertrain, charging, and driver usage pattern sub-modules to address vehicle-grid integration concerns in a systematic way\(^8\).

The rapid development of battery technology, especially the increase of the battery capacity, provides more opportunities for V2G research. Electric vehicles store energy electrochemically in their batteries, using typically lithium-ion, and lithium-metal-polymer chemistries due to longer cycle life and higher energy density. A typical lithium-ion battery has the capability to source 1 to 60kwh with the output of 0.2 to 6kw\(^9\). As for a parking lot or a residential village, we can gather more vehicles as fleets, which increases the capacity and the flexibility to support the grid.\(^{10}\) Therefore, with the help of V2G, the efficiency, stability and reliability of the grid can be significantly improved\(^{11}\).

1.2. Battery Management Optimization

The College of Engineering Center for Environmental Research and Technology (CE-CERT) in the University of California, Riverside is utilizing two Nissan Leaf light duty electric vehicles and a trolley electric bus to build up a V2G system, which also consists of a photovoltaic solar system delivering power to facility buildings in order to

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\(^7\) http://v2gsim.lbl.gov/overview  
\(^8\) http://v2gsim.lbl.gov/  
\(^9\) The V2G Concept: A New Model for Power?, University of Delaware.  
\(^{10}\) Jasna Tomic, Willett Kempton, “Using fleets of electric-drive vehicles for grid support”, Received 15 January 2007  
reduce the monthly electric bill cost\(^\text{12}\). The monthly electric bill is based on the rate schedule time-of-use (TOU) for large general and industrial service in the city of Riverside. Each month, this rate schedule has both demand charges (kW) and energy consumption charge (kWh) for three different rate periods: on-peak, mid-pick, and off-peak. Therefore, the monthly electric bill cost is partially determined by building monthly peak load (kW). When the photovoltaics has low power output (e.g., during cloudy days or maintenance) and the building power load is high, the utility costs could be high since there is little power output from solar panels. During that time, we can use the remaining battery capacity in electric vehicles when they are parked, and we can control the battery discharging at the on-peak rate period to lower the peak load and charging at the off-peak rate period to store energy. In a real-time system, we can only predict when will the peak load happens, and the daily peak load varies significantly during a month. If the batteries were not utilized during the monthly peak load periods, the demand charges can be significant. To avoid utility demand changes, an Adaptive Peak Control (APC) real-time battery control algorithm was designed and implement to optimize the charging and discharging management that can efficiently lower the monthly electric bill, while protecting the battery cycle life.

1.3. V2G System Connection Implementation

CE-CERT utilizes a stationary battery energy storage system (BESS) at CE-CERT that has been used to store energy from grid and deliver energy to grid. Part of this

\(^{12}\) http://www.cert.ucr.edu/newgrid/updates/2016_SIGI_Summary.pdf
storage is in a mobile trailer, where the DC power from stationary battery storage flows to an AC power grid connector through a DC/DC switch and a DC/AC inverter. In addition, a battery management system (BMS) collects the battery performance information and controls the charging and discharging operation between grid and batteries. To accomplish the Vehicle to Grid connection and communication, we connected the trolley electric bus to the AC connector through the same inverter and allowed the BMS on the trolley controls the power transmission. Therefore, there are two sets of power systems connected to the inverter, where only one power system is used at a time, shown as Fig. 1.2. Due to the difference of the voltage range between the two power storage systems, it was necessary to install a protected double pole switch between the inverter and two systems. In addition, it was necessary to apply a new DC connector that can sustain high DC voltage and current to connect the trolley battery and double pole switch. After the installation and testing of new components, we are able to achieve the bidirectional energy flows between the electric trolley and the power grid and achieve a viable V2G implementation.

Fig. 1.2. The Connection of Two Power System
1.4. Organization

In this project, we utilized to use V2G technology as a backup power source to provide electric energy to buildings during high demand periods, thereby lowering building’s monthly highest peak load which reduces the monthly electric bill consequently. In this battery management optimization process, there are two important and difficult issues. One is how to predict when the peak load moment will occur since the peak time won’t last long and is easy to miss. The second issue is how to determine the discharging power rate since if we lower the first peak too much it’s easy to cause the “second” peak and lower the efficiency of the system.

To solve these issues, an algorithm was developed that can adapt to the real-time building load and “find” the highest monthly peak load even with low accuracy peak prediction.

This thesis is organized as follows. Chapter 2 introduces the background acknowledgement of V2G development and implementation information of electric vehicles. Chapter 3 illustrates the detailed modeling of the V2G system and optimization algorithm. Chapter 4 discusses and shows the results of the simulation and MATLAB figures. Finally, Chapter 5 concludes and presents future work.
2. BACKGROUND INFORMATION ON V2G PROJECT

2.1. Overview of CE-CERT PEV Utilization

With the foundational support from the SCAQMD, the College of Engineering Center for Environmental Research and Technology (CE-CERT) at University of California, Riverside has recently developed a smart grid testbed called the Sustainable Integrated Grid Initiative (SIGI) consisting of four MW of photovoltaics, two MWh of battery storage, a variety of vehicle charging stations and three facility buildings, which include one administrative building (1084) and two research building (1086 and 1200). CE-CERT is implementing and testing V2G communication protocols and demonstrating V2G charging and discharging events, monitoring the detailed efficiencies and operational constraints.

Now the photovoltaics and battery storage are providing power to three administrative buildings to reduce the cost from power grid. Then we want to make use of Nissan Leaf electric vehicles and a trolley bus. This is illustrated in Fig. 2.1. and Fig. 2.2. where it can be seen that CE-CERT is just a part of the overall SIGI smart grid, cooperated with the stationary battery system in Bourns College of Engineering and solar panels on campus. CE-CERT is helping UCR build a smart grid that not only can meet the power needs for itself as far as possible to cut the electric bill or even make revenue, but also can respond to the electric load demand from the grid and power dispatching to avoid power shortage in emergencies.

\[\text{13 http://www.cert.ucr.edu/newgrid/SIGIBrochure.pdf}\]
Fig. 2.1. Integrating Photovoltaics, Energy Storage, and a Local Utility for Electric Transportation

In this research, we test the battery charging and discharging performance, and utilize trolley electric bus to achieve V2G implementation. By using simulation results on MATLAB, it can be demonstrated that this project will help CE-CERT provide methods and strategies to incorporate renewable energy and electric vehicles to mitigate the negative impacts of PEV charging and discharging events as well as reduce the building peak load.
2.2. Related Work of V2G Battery Management

Vehicle to Grid technology has been used for many years to deliver electric power to buildings or as the emergency power supply. There are many papers focus on the V2G application for residential villages, commercial facilities and parking lot. Lucia Igualada et al\textsuperscript{14} proposed an optimization model to manage a residential microgrid including a charging spot with a V2G system and renewable energy sources. To find the optimal management of residential microgrid with the inclusion of a realistic use of local V2G capability, they also consider the arrival and departure times for the EV and its battery capacity, however, they use daily price policies. For the optimal management of different

types of microgrids, they split the energy component behavior while the algorithm introduced in this thesis integrates the photovoltaics and the building energy consumption.

The biggest challenge with the electric vehicle has been the battery that stores the energy needed to drive the vehicle, with the challenge of both cost and cycle life. In the recent literature, there are many scheduling schemes for EV charging and discharging have been proposed such as Shrestha and Ang\textsuperscript{15}, Mets et al\textsuperscript{16}, Huston et al\textsuperscript{17}, and Saber and Venayagamoorthy\textsuperscript{18}. However, they all have limitation and are quite different from this CE-CERT study. Shrestha and Mets only focus on the battery charging without the V2G function. Also, Huston’s and Saber’s methods are essentially centralized algorithms and focus on the parking lot with large populations with random and continuous arrivals while we only have a trolley to manage in this project. In addition, although Hung’s\textsuperscript{19} algorithm considers smart charging and discharging to optimize the energy consumption profile, it is for multiple PHEV’s in a building’s garage. There are some other strategies used in V2G such as using Time of Use (TOU) price policy, which is different from the Peak Demand price policy that we use.

2.3. Nissan Leaf Implementation

In this project, we use two 2014 Nissan Leaf electric vehicles as a part of the V2G program. The Nissan Leaf can be charged by the AC Level-2 chargers, which takes about two hours to get fully charged and DC Level-3 fast charger, which takes about half an hour to get fully charged\textsuperscript{20}. Table 1 is the official battery specifications of the Nissan Leaf.

To verify the specifications and research the practical performance of the laminated lithium-ion battery when charging and discharging, several experiments were conducted consisting of road driving tests and charging tests. While testing, I connected the Consult\textsuperscript{®} III monitor software\textsuperscript{21} to the electric vehicle in order to obtain real time information about the vehicle, including voltage, current, power, and temperature.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>laminated lithium-ion battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>403.2V</td>
</tr>
<tr>
<td>Normal Voltage</td>
<td>360V</td>
</tr>
<tr>
<td>Total Capacity</td>
<td>24kWh</td>
</tr>
<tr>
<td>Available</td>
<td>16kWh</td>
</tr>
<tr>
<td>DoD</td>
<td>67%</td>
</tr>
<tr>
<td>Power Output</td>
<td>&gt;90kW</td>
</tr>
<tr>
<td>Numbers of Modules</td>
<td>48*4</td>
</tr>
</tbody>
</table>

Table 1 Nissan Leaf Battery Specifications

\textsuperscript{20} After tested, due to the battery charging limitation, the battery can only be charged up to around 90%, so we call this as “fully charged”.

\textsuperscript{21} http://nissanconsult.service-solutions.com/overview.htm
For the road testing, I took several round trips on several sections on Interstate 60 Freeway. The Fig 2.3 Shows the Battery Level (in percentage) status during the road test. From the time point 500 to 2200, the vehicle was mostly running in a steady speed, and the battery power dropped almost linearly, so when discharging the battery, if we keep using steady power, the SOC of the battery would change linearly. The speed was not closely controlled well due to the traffic at the beginning and ending of the trip, so the battery tended to lost energy faster.

![Fig. 2.3. Battery Level Status](image)

In the Fig 2.4, when the battery current is negative, the battery is discharging the energy to the vehicle. When the battery current is positive, the vehicle is charging the battery as the vehicle is braking. During this 53.4 mile road test, the battery voltage range is 395.19 V to 322.48 V, and the battery current range is 120.467 A to -270.77 A. The total power consumption was 14.845 kWh, the battery level dropped from 92.2% to 8.2%, and the max battery temperature was 28°C. Total power consumption is close to the
16kWh available from official specifications, and all other road tests show similar results. We can take these number as a reference of a normal work situation. If the temperature is too high, or if the voltage is too low, we need to stop charging or discharging.

Fig. 2.4. Road Test Battery Current, Voltage, Temperature and Cell Voltage Status

In the charging tests, Fig. 2.5, we can see when we use DC Level-3 charger, due to the high current levels, which can be as high as 120.3 A at the beginning and decreases exponentially to zero as the battery state-of-charge level increases at a normal pace. Meanwhile, the voltage will increase rapidly, from 360.72V to 395.88V, and will hold level until the charging period ends. This means there is a fast charging period when the battery level is low, and the charging power increases will be increasing to around 48 kW at the time point 500. After that, the power will decrease till the time point 2000, when the charging ends. The total energy received from the battery level, when in the range of
21.6% to 89.3% is 14.884 kWh, which matches the energy consumption from the road test; the maximum battery temperature is 35°C, which is higher than the discharging temperature.

![Graph showing battery level, current, and voltage over time.](image)

**Fig. 2.5.** DC Charging Test Battery Current and Voltage

The Nissan Leaf already has the protocol to discharge the battery, so if we replace the chargers at CE-CERT with the Princeton Power System CA-30 V2X charger\(^\text{22}\), we can accomplish vehicle to grid communication.

---

2.4. Trolley Electric Bus Implementation

Apart from the Nissan Leaf, the RTA operated trolley is another essential part of the SIGI V2G network. This trolley bus itself uses CALB 180Ah CA Series Lithium Iron Phosphate Batteries. The trolley is connected so that it can take the place of the stationary battery storage in a trailer, and will enabled to provide power to facility buildings with an on-board control algorithm. As we can see in Fig. 2.6, the trolley already has DC/AC converter between AC charger to battery, and battery to motor. However, this system can’t do discharge, so we need a separate line from battery to another inverter by a DC connector that can do both charging and discharging, which is showed in imaginary lines.

![Fig. 2.6. Graphical Representation of Trolley Side](image)
Fig. 2.7 shows the components and connections inside the trailer. The DC power from the batteries is transformed to AC power by the inverter. The Battery Management System (BMS) collects battery information including voltage, current, temperature. The OPTO-22\(^{23}\) system determines the output for the battery. The battery power goes to a 480V AC connector outside the trailer, which then connects to the building power network.

As for Vehicle to Grid, we use the battery energy on the trolley bus to provide the energy to the grid. Therefore, we added trolley battery connection to the power grid through an inverter. Fig. 2.8 shows the new construction considering the battery supply on the trolley.

\(^{23}\)https://en.wikipedia.org/wiki/Opto_22
During the switch, the sudden change in range of DC voltage would cause voltaic arc, which is dangerous and harmful to both the human body, and electrical components. Thus, there are two auxiliary aspects we need to consider:

1. **Pre-Charge Circuit:** When initially connecting a battery to a load with capacitive input, there is an inrush of current as the load capacitance is charged up to the battery voltage. With large batteries and powerful loads, the inrush current can easily peak 1000 A. A pre-charge circuit limits that inrush current, without limiting the operating current. In the most basic form, the pre-charge circuit is operated as follows:

   - **Off:** When the system is off, all relays or contactors are off.
   - **Pre-charge:** When the system is first turned on, K1 and K3 are turned on, to pre-charge the load, until the inrush current has subsided.
   - **On:** After pre-charge, contactor K2 is turned on. Relay K1 may be turned off to save coil power.
(2) **Contactor**: In a well-designed system, under normal operation, the contactors are not required to interrupt the operating current, because the system will reduce the load.
current to 0 before the contactors are opened. Therefore, only the carrying current rating needs to be sufficient for the average load current. The contactors must be rated for the maximum battery voltage, as that voltage will be across the contacts when they are opened. The contactors must be rated for DC operation. AC rated contactors rely on current waveform going through 0 A at every crossing from + to -, to interrupt arcing across the opening contacts. However, this does not happen to batteries, instead, a DC contactor incorporates other ways of quenching the arc that forms at the turn off. One method is a magnet that creates field across the path of arc, bending it and breaking it. In that case, the contacts of the contactors are polarized (one terminal is labeled ‘+’), connecting the contactors so that normally (while discharging) the current flows into the ‘+’ terminal.

Based on the voltage and current requirement of both batteries on the trailer and the trolley, we decided to use EV 202 Series DPST –NO Contactor, which can hold up to 400 Vdc and 350 A and to use Anderson Power® DIN 43589-1 Euro Battery Connector, which can hold up to 340 A.

In addition, we also replace OPTO-22 by CampactRIO since it can achieve communication and data transmission between BMS and the server database.
Fig. 2.11. Plug-in Connector (Left) and Contactor (Right)
3. OPTIMIZATION OF VEHICLE BATTERY MANAGEMENT

3.1. Modeling of V2G System

3.1.1 Modeling of Battery

A 155.52 kWh battery set was installed on the trolley for V2G with 80% depth-of-discharge (DOD). To protect and prolong the lifetime of the Li-ion battery in the trolley, the SOC is normally maintained between 30% to 90%. In case of the emergency need of battery energy, such as the receiving demand required from the grid or the photovoltaic is too low while the building load is too high, the SOC can go down to 20%. The SOC status can be expressed as:

\[ \text{SOC}_t = \frac{BC_t}{BC} \]

where \( \text{SOC}_t \) means the SOC value at time \( t \), \( BC_t \) means the battery capacity at time \( t \), and \( BC \) means the total battery capacity. The charging and discharging power rate can be defined as:

\[ R_{(i)} = \begin{cases} -r_{d(i)}, & \text{Discharging} \\ r_{c(i)}, & \text{Charging} \end{cases} \]

\[ 0 < |R_{(i)}| < R_{\text{max}} \]

3.1.2 Modeling of Building Demand

Among the three facility buildings at CE-CERT, I utilized the 1200 Research Building for research since it has the highest energy use amplitude and largest scale, which is a would be beneficial to my test and perform analysis. As we prefer not to turn off the photovoltaics and take the electric bus as a backup only when special cases occur,
I prefer to combine both photovoltaics delivery and building consumption as the total power load. The data can be observed and downloaded from the SIGI website as shown in Fig. 3.1. There are four data recorded per second and the meter records data in every 15 minutes, matching the recorded data with measured data from meter. From this I calculated the average of the four data per second as the mean value for every second and store only one record every 900 means to analysis and plot. The total power demand can be defined as:

\[ p_{t}^{net} = p_{t}^{b} - p_{t}^{pv} \]

where \( p_{t}^{b} \) means the power load of 1200 building, \( p_{t}^{pv} \) means power delivery of photovoltaics, and \( p_{t}^{net} \) means the total power demand of net. When \( p_{t}^{net} > 0 \), the building load is larger than the photovoltaics delivery, so the power from solar panels is not enough to meet the building need and we may need to use trolley battery power to reduce the net peak load. Otherwise, the photovoltaics delivered power is enough for building usage and we don’t have to use the trolley bus as power supply, as shown in Fig. 3.2.
Fig. 3.1. SIGI Website Database Interface

Fig. 3.2. Total Net Usage Recorded on 5.14.2017
3.1.3 Modeling of Electric Bill Cost

According to the City of Riverside Public Utilities Department, the monthly electric bill cost includes a Demand Charge, a monthly one-time charge based on the peak load, and an Energy Charge, an accumulating charge based on the total energy usage. In this project, we only consider the Demand Charge since the total energy usage won’t change a lot due to the charging and discharging cycle. The Demand Charge includes all kW of on-peak cost $C_{dp}$, mid-peak cost $C_{dm}$, and off-peak cost $C_{do}$. The time divisions are different between summer and winter season, the tables are built as Tables 2 and 3.

<table>
<thead>
<tr>
<th>Rate Period</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-peak</td>
<td>12:00 p.m. to 6:00 p.m.</td>
</tr>
<tr>
<td>Mid-peak</td>
<td>8:00 a.m. to 12:00 p.m.</td>
</tr>
<tr>
<td>Off-peak</td>
<td>All other hours</td>
</tr>
</tbody>
</table>

Table 2 Summer Time\(^{24}\) Schedule

<table>
<thead>
<tr>
<th>Rate Period</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-peak</td>
<td>5:00 p.m. to 9:00 p.m.</td>
</tr>
<tr>
<td>Mid-peak</td>
<td>8:00 a.m. to 5:00 p.m.</td>
</tr>
<tr>
<td>Off-peak</td>
<td>All other hours</td>
</tr>
</tbody>
</table>

Table 3 Winter Time\(^{25}\) Schedule

\(^{24}\) Based on the TOU rate schedule, summer time are the month of May, June, July, August, September.

\(^{25}\) Based on the TOU rate schedule, winter time are the month of January, February, March, April, October, December, November.
3.1.4 Modeling of Prediction

According to the building’s electric bill policy, if we can have a good prediction of the peak demand for each month, we can effectively control the power load to reduce the monthly peak load with the V2G system. As the 1200 building is a laboratory building with many experiments, events, and facilities, so in addition to the HVAC system, the workload every day is another crucial factor to be considered. We can also use historical data as reference. We can collect the peak load of last week, last month, last year, and select the relative data. Therefore, the predicted monthly peak load can be defined as:

\[ P_{m}^{pre} = \sum \alpha_i \ast f(p_i) + \beta \ast P_{m-1}^{pre} \]

\[ \sum \alpha_i + \beta = 1 \]

where \( P_{m}^{pre} \) corresponds to the predicted peak load in month \( m \), \( f(p_i) \) means the function of how each factor like HVAC, experiment workload schedule, temperature etc. will influence the peak load in month \( m \), \( \alpha_i \) and \( \beta \) are the parameter of each factor that sum up to 1.

3.2. Optimization Algorithm of V2G System

As the backup power supplier, the primary goal of the battery on our electric bus is to reduce the monthly peak load as much as possible when the photovoltaics power is not enough for building demand. However, as a trolley bus, it should be ready for the schedule with full battery capacity and reduce times of charging and discharging events.
Therefore, the purpose of this optimization algorithm is to lower peak load while keeping a high battery capacity and less charging cycles. Based on the price model mentioned before, the subject can be defined as follow:

\[
\text{Cost} = \min_{P_p(i), P_m(i), P_o(i)} \left\{ \max_i [P_p(i)] * C_{do} + \max_i [P_m(i)] * C_{dm} + \max_i [P_o(i)] * C_{df} \right\}
\]

\[
P_p(i) = \max\{p_{p(i)}^{net} + R(i), 0\}
\]

\[
P_m(i) = \max\{p_{m(i)}^{net} + R(i), 0\}
\]

\[
P_o(i) = \max\{p_{o(i)}^{net} + R(i), 0\}
\]

where \(P_p(i)\) is real-time peak load during On-peak period on date \(i\), \(P_m(i)\) is real-time peak load during Mid-peak period on date \(i\), and \(P_o(i)\) is real-time peak load during Off-peak period on date \(i\).

In the above equation, \(\max_i [P_p(i)]\) is not same as the \(P_p(i) = \max\{p_{p(i)}^{net} + R(i), 0\}\), because \(\max_i [P_p(i)]\) represents the peak value during a month (which means the index \(i\) could be different), same with the mid-peak value and off-peak value. In addition, the index \(i\) of \(\max_i [P_p(i)]\), \(\max_i [P_m(i)]\), and \(\max_i [P_o(i)]\) could be different because the peak value could happen in different days.

As mentioned above, the charging and discharging rate \(R(i)\) is:

\[
R(i) = \begin{cases} 
-r_d(i), & \text{Discharging} \\
 r_c(i), & \text{Charging}
\end{cases}
\]

When net power \(p_{p(i)}^{net}\) is negative, the batteries on the trolley will be charged, so the \(R(i)\) is positive. When net power \(p_{p(i)}^{net}\) is positive, the batteries on the trolley will be discharged under control, so the \(R(i)\) is negative. Therefore, we could narrow down the
total peak power demand to zero by optimizing the charging and discharging schedule with well-designed algorithm.

In our project, the subject function can be simplified when considering the schedule of the trolley bus. We applied the school bus time schedule on the trolley bus for our experiment since it’s often in idle and use the summer time for experiments. The bus would be occupied normally from 6:30 a.m. to 9:30 a.m. and it takes more than two hours to fully charge the battery, so basically the trolley battery will not help much at mid-peak period. In addition, batteries are set to charging mode during the off-peak period. Therefore, the optimization only focuses on the on-peak period, so the subject can be simplified as:

Subject: \( \text{Cost} = \min_{P_{p(i)}} \{ \max_i [P_{p(i)}] \cdot C_{do} \} \)

Object: \( SOC_{min} < SOC_t < SOC_{max} \)

\( SOC_{min} < SOC_t < SOC_{max} \)

\( 0 < |R_{(i)}| < R_{max} \)

To minimize the total cost, we need to estimate the possible monthly load peak and discharge the battery when the real-time load is close to or beyond the predicted peak. Fig. 3.3 shows the overall battery control logic diagram.
Fig. 3.3. Battery Management Algorithm Diagram

If there’s no special demand request from the grid, which they usually signal in advance, then the system uses a Time of Use (TOU) Mode, where the battery would charge or discharge depending on the load. If there’s a demand request from the grid, the battery would discharge as much as possible to get the largest revenue, which is called the Greedy Mode. As for the Greedy Mode, if the SOC is above 20% and meet the minimum capacity demands for schedule, then the battery just discharges at the highest rate.
As for the TOU Mode, the detailed control principles are as follows:

i. Determine the battery SOC status: if $SOC_t < SOC_{min}$, battery will charge and recheck the mode. If $SOC_{min} < SOC_t$, go to step ii.

ii. Determine the net power status: If $p_{t}^{\text{net}} < 0$, battery would charge and recheck the mode. If $p_{t}^{\text{net}} > 0$, go to step iii.

iii. Determine the rate period: If it’s off-peak period, battery would charge and recheck the mode. If it’s on-peak period, go to step iv.

iv. Apply the Adaptive Peak Control (APC) algorithm:

$$p_{t}^{\text{net}} = \max \{p_{t}^{\text{net}} \times \gamma, P_{m}^{\text{pre}}\}$$

$$\gamma = f(SOC_t)$$

$$0 \leq \gamma \leq 1$$

where $\gamma$ is the sensitivity that determines the battery discharging rate. Larger battery capacity and higher battery SOC status allows higher discharging rate in a certain time. On the first day of each month, we have a “guess” for the monthly peak load and set the threshold based on $P_{m}^{\text{pre}}$. When real-time load is beyond the threshold, the batteries will be discharged to lower the temporary peak load. However, it is necessary to control the discharging rate to avoid the “second peak”. If the load was reduced too much, another new higher load could occur as a new peak load, which would cause more discharging times.

Therefore, by applying APC algorithm, the peak threshold is adaptive to the real-time load and self-correcting. Even if we don’t have an accurate “guess”, the threshold will increase automatically and the battery only discharge when the real peak load comes.
4. EXPERIMENTS AND RESULTS

4.1 Peak-Day Algorithm Applying Test

I used the May data in 2017 as sample to simulate and analyze the real-time operation. To show the advantage of this APC algorithm, I will compare the result by using constant threshold model predictive control (CT-MPC) mode\(^{26}\) that is used in other battery management system.

The detailed simulation steps are as follows:

i. Recording the workday peak load and find the highest peak date. From Fig. 4.1, we can see the peak load varies a lot during the workdays, and the difference between the highest peak (79.7 kW) and the lowest is large. Therefore, the accuracy of prediction could be low.

![Fig. 4.1. Load Figure of Workday Peak and Highest Date](image)

\(^{26}\) Yun Xue, Michael Todd, Sadruil Ula, Matthew J. Barth, and Alfredo A. Martinez-Morales, “A Comparison Between Two MPC Algorithms for Demand Charge Reduction in a Real-World Microgrid System”, University of California - Riverside, CA 92557
ii. Applying the APC algorithm to the daily load pattern with different predicted peak load and sensitivity parameter.

**Case 1: “Good Guess” Scenario**

When $P_m^{pre} = 70$, $\gamma = 0.94$. From Fig. 4.2, we can see, after applying the APC algorithm, we set the peak threshold to 70 kW, the final peak load is 74.9, so the peak was reduced by 4.8 kW. The total energy consumption from the trolley bus is 74.1 kWh, which is smaller than the 70% DOD capacity (93 kWh). In addition, the battery just needed two discharging events and didn’t have to charge thus protecting and prolonging the battery life.

![Fig. 4.2. Daily Load Pattern after Applied APC Algorithm with a “Good Guess”](image)
Case 2: “Bad Guess” Scenario

When $P_m^{pre} = 50$, $\gamma = 0.94$, from Fig. 4.3 we can see, even we have a bad prediction about the peak load, the final peak load still is 74.9. the total energy consumption from the trolley bus is 109.25 kWh, and there are three discharging events. This means it can adapt to the real load performance and reset automatically to discharge at the necessary time.

![Image](image.png)

**Fig. 4.3.** Daily Load Pattern after Applied APC Algorithm with a “Bad Guess”

iii. Comparing the APC results with the CT-MPC algorithm result.

Case 3: “Good Guess” with comparison scenario

By using CT-MPC methods, once the load is above the constant threshold, batteries should start discharging and consume much more total capacity.

If $P_m^{pre} = 70$, the total consumption is 322.7 kWh, which is much more
than the total battery capacity. The battery needs to be charged during the black period shown in Fig. 4.4, which may cause more battery cycle events and risk a new peak load.

**Case 4:** “Bad Guess” with comparison scenario

When the prediction is bad ($P_{m}^{pre} = 50$) in Fig. 4.5, the trolley battery would be occupied almost all the time, which is impossible considering the battery capacity. It could miss the highest peak time and cause a new peak load.

![Fig. 4.4. Comparison between APC (Red) and CT-MPC (Yellow) Method](image)

**4.2 Monthly Algorithm Applying Test**

Next I tested the APC algorithm by applying it for a month with random rearrangement of daily load figure.
In general, it is hard to know on which day the highest peak load would occur, so I randomly rearrange\textsuperscript{27} the workdays in May and repeat the rearrangement to see how the monthly load feature would influence the result (e.g., peak load, battery discharging times, total power consumption). Fig. 4.6 shows the load figure during May after applying APC algorithm, and there are only three discharging events with a predicted peak load of 70 kWh. I repeated the rearrangement randomly 50 times\textsuperscript{28} and summed up the total discharging times during a month for each arrangement. From Fig. 4.7 we can see, there were no more than 8 discharging times no matter which day the highest peak load occurs.

\textsuperscript{27} The date in May is in random order rather than the nature order. For example, the first day might not be May 1\textsuperscript{st}, the last day might not be May 30\textsuperscript{th}, and May 3\textsuperscript{rd} might not follow May 2\textsuperscript{nd}.

\textsuperscript{28} During the test, $P_m^{pre} = 70$ and $\gamma = 0.94$, results may vary based on the different parameter values.
The average discharging times is 5.88, which proves this algorithm is reliable and efficient.

Fig. 4.6. Monthly Peak Figure after Applied APC Algorithm When $P_{m}^{pre} = 70, \gamma = 0.94$

Fig. 4.7. Discharging Times for 50 Random Rearrangement
5. CONCLUSIONS AND FUTURE WORK

In this project, the Vehicle to Grid (V2G) system was introduced with battery management optimization algorithm and vehicle connection and reconstruction implementation. As a part of SIGI smart grid, a V2G system was developed consisting of light duty electric vehicles (Nissan Leaf) and an electric trolley bus. To build this system, we took a long time and did a lot of experiments to determine the battery performance features and added protection equipment. When the photovoltaics output is low due to the weather or maintenance, as the backup power supply, the battery on the trolley bus should transmit power to the facility building to lower the monthly peak load. However, the trolley can’t be ready to discharge at anytime considering its work schedule and battery life. Instead, we created a new real-time optimization algorithm to control the battery discharging when it might be the highest monthly peak load based on the prediction. In addition, this algorithm can efficiently control the discharging rate to avoid the creation of a new peak, which will increase the discharging times.

The V2G concept has been improved over recent years. In the real world, each building has different load features, different demand schedules, and each electric vehicle has different available times. As for future work, it’s possible to improve the prediction model and apply more advanced prediction models\textsuperscript{29,30} to different building situations if we can have more detailed data information like workload and HVAC system. Finally,

\textsuperscript{29} Hae Young Noh and Ram Rajagopal, “Data-Driven Forecasting Algorithms for Building Energy Consumption” Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA

\textsuperscript{30} A. J. Hoffman, “Peak demand control in commercial buildings with target peak adjustment based on load forecasting”, Potchefstroom University for CHE
after the connector and contactor has been installed on the trolley and trailer system, we can apply APC in real cases to test and modify this algorithm.
6. REFERENCE


[6] Lawrence Berkeley National Laboratory V2G-Sim System:
http://v2gsim.lbl.gov/overview


[16] Yun Xue, Michael Todd, Sadrul Ula, Matthew J. Barth, and Alfredo A. Martinez-Morales, “A Comparison Between Two MPC Algorithms for Demand Charge Reduction in a Real-World Microgrid System”, University of California - Riverside, CA 92557

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[18] A.J. Hoffman, “Peak demand control in commercial buildings with target peak adjustment based on load forecasting”, Potchefstroom University for CHE


[20] The University of California, Riverside SIGI Project:
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