A Vehicle-to-grid Framework Based on Electric Vehicle with Solar Panel

Yu Hao

College of Electronic and Information Engineering, Taiyuan University of Science and Technology, Taiyuan, China, 030024

Abstract: In this paper, we extend previous studies of vehicle-to-grid technology with electric vehicle equipped with solar panel. Instead of connecting a solar power system into the grid, we consider a distributed scenario in which every electric vehicle has the power of collecting solar power and bidirectional charging abilities. Through mathematical formulation and numerical simulations, we demonstrate that our framework has superior advantages of incentivizing electric vehicles to install solar panels and discharge to the grid.

1. Introduction
Fuel vehicles powered by petroleum products play an important role in modern society by providing us different transportation modes of traveling and commuting. While they bring us the convenience, these vehicles are also jeopardizing our environment and consuming the non-renewable natural resources. After entering the 21st century, people start to reflect on the use of these fuel vehicles, which bring energy crises and environmental issues. Countries across the world including Germany, France, the United States, Japan, and China are actively developing electric vehicles. Policy support and operational regulations are proposed to promote the adoption of electric vehicles.

In the development of electric vehicles, people are gradually realizing that electric vehicles are not an "independent" product. They must be connected to the power grid during charging. And if the vehicles support discharging, the feedback and economic benefits for the grid should be carefully considered, as well as the challenges they pose to the power grid. For example, the power grid needs to consider the power supply needed for a large number of distributed charging facilities, and the fluctuations caused to the power grid when a large number of electric vehicles are simultaneously charged.

In this paper, we firstly give a short review of related work about vehicle-to-grid technologies and grid with renewable energy. Then we extend previous studies of vehicle-to-grid technology with electric vehicle equipped with solar panel. We describe our framework in Section 3, the mathematical formulation in Section 4, and the numerical simulation in Section 5. We conclude this paper in Section 6.

2. Related Work
To solve the challenges brought to the grid by the large number of electric vehicles, previous studies have proposed the vehicle-to-grid technology [1-3]. Through the means of intelligent control, the purpose of the vehicle-to-grid technology is to use the electric power stored in the electric vehicles as a method of adjusting the user load and achieving a "peak clipping" phenomenon. There is basically no storage space in the grid.
In contrast, electric vehicles themselves have a larger storage space than their own load and can even discharge to balance fluctuations in demand when power resources are scarce. With renewable energy connected to power grid, electric vehicles would be a powerful tool for coordination in micro-grid with renewable energy [4-8].

The grid is characterized by high capital costs, but low production costs, which is exactly the opposite of the electric vehicles. They can be used as a perfect complement. In general, generators have a high usage rate, while in most cases personal vehicles are only used for 4% of the daily time, making them fully usable for the remaining 96% of the time. Although it is subject to the impact of frequent charging and discharging on the battery life of electric vehicles, once the electric vehicle participates in the regulation of the power grid, the cost per unit of electric energy will certainly increase. Thus the use of V2G is limited to the situation when the price of electricity is abnormally high, such as in some peak power markets.

Previous studies have analyzed the impact of hybrid plug-in vehicles on the power system in a specific area (e.g., Belgian Production Park) after accessing the grid. If the charging is not coordinated, the peak power of the grid will increase significantly, and the basic power level will increase a little. This is contrary to the assumptions of the vehicle-to-grid technology, and the grid needs to build new equipment to adapt to higher power levels. This will result in a significant increase in the cost of electricity use for electric or hybrid vehicles, which will have a negative impact on electricity prices. The management agency must provide a new coordination mechanism for this problem, apply smart meter technologies to coordinate charging, manage from the demand side, use floating electricity price to avoid centralized charging caused by a low electricity price, and minimize the charging impact.

3. An Overview of Our Framework
As shown in the last section, it has been proposed to solve the challenges caused by large-scale electric vehicles and renewable energy access to smart grids by using micro-grid systems, coordinating the various modules in the micro-grid, and interacting with the loads to complement each other. We propose a distributed scenario in which every electric vehicle has the power of collecting solar power and bidirectional charging abilities. A solar photovoltaic panel is installed on an electric vehicle to collect solar power. When the sunshine is sufficient during the daytime, the electric vehicle can obtain electric energy through the photovoltaic panel at the top and even return to the power grid when not in use, so that the promotion of electric vehicles can truly achieve environmental protection and energy saving, and reduce dependence on petroleum products.

We show our framework in Figure 1, which represents the connection relationship between the solar panel, the electric vehicle and the grid. The electric vehicle can choose to work when it is not charging or discharging. We assume that the electricity used by the vehicle would bring some earnings for its owner, e.g., running an electric taxi. When the vehicle runs out of electricity, it would find a charging pile and stay there for charging. We assume that the battery of the electric vehicle has a limitation. If enabled, the vehicle can also choose to discharge, especially when it could make some money by exploiting the different electricity prices caused by different levels of power load at different times. In our framework, we assume that the electric vehicle is equipped with a solar panel, which empower the vehicle with the ability of collecting solar power. We assume that the solar power is always being collected, regardless of the state of the vehicle. But the amount of solar power is affected by the time and the change of sunshine.
4. Mathematical Formulation
In this section, we give an analysis of our framework with a step-by-step process.

4.1. Baseline Model #1
We use baseline model #1 to denote the basic case that an electric vehicle can only choose to work or charge in a time slot, e.g., an hour. We assume that in the work state, the vehicle consumes 1 unit of electricity and earns at most 1 unit of money. The vehicle has a maximum E units of electricity as its capacity constraint. In each time slot, the vehicle can charge A units of electricity and normally we have $AE < \text{E}$. 

In time slot $t$, $t=1, 2, \ldots, 24$, we denote $m_t$ as the real money that the vehicle can earn in each time slot and we have $0 \leq m_t \leq 1$ always holds. If the electric vehicle operates as a taxi, the money it can earn varies in each time slot as the occupancy ratio is different. We denote the maximum electricity price is $P$ and the real-time price $p_t$ as a ratio of $P$, which may be affected by the overall load of the grid. Generally, the load is heavier, the price is higher.

Then we use binary variables $x_t$ and $y_t$, $t=1, 2, \ldots, 24$, to represent whether the vehicle would work or charge in time slot $t$. If $x_t = 1$, the vehicle would work, and if $y_t = 1$, the vehicle would charge. As we assume that the vehicle can either work or charge, but not simultaneously, we have constraints $x_t + y_t = 1$ for all time slots.

We track the electricity level of the vehicle as $e_t$, and manually add a start value $e_0 = 0$. Using the binary variables defined above, we have the recursion relation as follow: $e_t = e_{t-1} - A \times x_t + A \times y_t$. We can add the requirement that at no time could the vehicle has an electricity level below 0, which corresponds to $e_t \geq 0$. We also require that the vehicle should avoid the case of having a level above $E$, which corresponds to $e_t \leq E$.

Now we are ready to give the mathematical formulation as a 0-1 integer programming problem when the vehicle’s objective is to maximize its gain, which is the earning minus the payment for electricity charging:
4.2. Baseline Model #2

Now we extend Baseline Model #1 with the possibility of discharging. We denote B as the units of electricity the vehicle can discharge in a time slot. We use binary variables $z_t$, $t=1, 2, \ldots, 24$, to represent whether the vehicle would discharge in time slot $t$. Then we have constraints $x_t + y_t + z_t = 1$ for all time slots. We also have a updated recursion relation as follows: $e_t = e_{t-1} - 1 \times x_t + A \times y_t - B \times z_t$.

Now we are ready to give the new 0-1 integer programming problem as follows:

$$\max_{x_t, y_t, z_t} \sum_{n \in \{1, 2, \ldots, 24\}} (m_n \times x_t - A \times p_t \times y_t)$$

s.t. $e_t = e_{t-1} - 1 \times x_t + A \times y_t - B \times z_t \geq 0$

$e_t \leq E$

$x_t + y_t + z_t = 1$

$x_t \in \{0, 1\}, y_t \in \{0, 1\}, z_t \in \{0, 1\}$

4.3. Our Framework

For our framework, we take a further step that allows the electric vehicle to have its own solar power generation ability. The amount of power generated varies in different time slots. We denote the maximum unit of electricity generated by solar power as $S$, and the real-time solar power $s_t$ as a ratio of $S$.

Since the solar power generation only affects the update rule for $e_t$, we can easily update the 0-1 integer programming problem in this case:

$$\max_{x_t, y_t, z_t} \sum_{n \in \{1, 2, \ldots, 24\}} (m_n \times x_t - A \times p_t \times y_t + B \times p_t \times z_t)$$

s.t. $e_t = e_{t-1} - 1 \times x_t + A \times y_t - B \times z_t + s_t \geq 0$

$e_t \leq E$

$x_t + y_t + z_t = 1$

$x_t \in \{0, 1\}, y_t \in \{0, 1\}, z_t \in \{0, 1\}$

5. Numerical Simulation

In this section, we compare our framework with the two baseline models based on numerical simulations. The integer programming is solved by the intlinprog function in Matlab.
5.1. Parameter Settings
We set some parameters based on previous studies. The real-time money $m_i$ is based on the occupancy ratio of Beijing taxi drivers in 2015 [9, 10], and electricity price ratio $p_i / P$ and solar power ratio $s_i / S$ come from the Global Energy Forecasting Competition 2014 [11]. We plot these three ratios in Figure 2.

5.2. Results
Now we evaluate the effects of the following parameters on the vehicle’s gain:

1. The maximum electricity price $P$;
2. The charge electricity unit $A$;
3. The discharge electricity unit $B$;
4. The electricity capacity constraint $E$;
5. The maximum solar electricity unit $S$.

We firstly fix a baseline setting as $P=0.5$, $A=3$, $B=3$, $E=6$, $S=0.5$. Then we change each parameter and see how it affects the result.

5.2.1. The Influence of the Maximum Electricity Price
We plot the influence of the maximum electricity price in Figure 3. As we can see as the maximum electricity price increases, the performances of all three models become worse. However, after the price reaches 0.6, the situation becomes stable for both baseline model #2 and our framework. We explain this result as follows: even though the payment for charging increases, the earning from discharging also increases.
5.2.2. The Influence of the Charge Electricity Unit

We plot the influence of the charge electricity unit in Figure 4. As we can tell from the result, charging too fast and charging too slow both would harm the performances. While the influence of charging too slow is almost the same for both baseline models, the influence of charging too fast is more severe for the baseline model #1.

5.2.3. The Influence of the Discharge Electricity Unit

We plot the influence of the discharge electricity unit in Figure 5. While it has almost no influence on the baseline models, a larger or smaller discharge electricity unit would hurt the performance of our framework.
5.2.4. The Influence of the Electricity Capacity Constraint

We plot the influence of the electricity capacity constraint in Figure 6. Consistent with our intuition, a larger electricity capacity constraint always helps. However, as indicated in Figure 7, it would benefit our framework more than the baseline models.
5.2.5. The Influence of the Maximum Solar Electricity Unit
We plot the influence of the maximum solar electricity unit in Figure 8. The influence is not linear. When there is no solar power, our framework becomes the baseline model #2. However, when the solar power is small, our framework is worse than both the baseline models. When the solar power reaches a certain level, the advantage of our framework becomes obvious.

5.3. Discussion
While our numerical simulations are based on synthetic parameters, we can connect the results with the real situations. For example, as shown in Table 2 from [12], the maximum mileage is 316 km and the charging time is 7 h. We assume that the vehicle travels 45 km in an hour, then the electricity capacity constraint is approximately 7 and the charge unit is 1, as we charge for one hour, the vehicle can operate for one hour. With more data, we could set other parameters in a similar way.
6. Conclusion
In this paper, we present a practical vehicle-to-grid framework based on electric vehicles with solar panels and demonstrate its advantages above two baseline models. We also investigate the effects of different parameters on the performance of our framework, which gives the directions of efforts which is required before putting our framework into practice.

References
[1] Kempton W, Tomić J. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue[J]. Journal of power sources, 2005, 144(1): 268-279.
[2] Kempton W, Tomić J. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy[J]. Journal of power sources, 2005, 144(1): 280-294.
[3] Geth F, Willekens K, Clement K, et al. Impact-analysis of the charging of plug-in hybrid vehicles on the production park in Belgium[C]//MELECON 2010-2010 15th IEEE Mediterranean Electrotechnical Conference. IEEE, 2010: 425-430.
[4] Guang-Qing B, Xin X U, Xiao-Lan W, et al. Dispatch Strategy of Micro-grids Based on Coordination between the Electric Vehicle and Wind Power[J]. Control Engineering of China, 2016.
[5] Mao M, Sun S, Jianhui S U. Economic Analysis of a Microgrid with Wind/Photovoltaic/Storages and Electric Vehicles[J]. Automation of Electric Power Systems, 2011, 35(14):30-35.
[6] Yu W, Bide Z, Guosen Y, et al. Optimal configuration of micro-grid considering uncertainties of electric vehicles and PV/wind sources[J]. Electrical Measurement & Instrumentation, 2016.
[7] Da W, Li L, Bo Y, et al. Power Quality Analysis of Electric Vehicle Access to a Micro-grid with Wind/Photovoltaic/Storages[J]. Journal of Shenyang Institute of Engineering(Natural Science), 2017.
[8] Yong H E. Research on the Electric Vehicle Development Strategy in China Based on the Progressive History of Vehicle Energy Technology[J]. Science and Technology Management Research, 2014.