Economic Dispatch of a Smart Grid with Vehicle-to-Grid Integration

Charles Uko
Department of Electrical Engineering
University of South Carolina.
Columbia, USA.
Email: cuko@email.sc.edu

Ona Egbue, PhD
Department of Informatics and Engineering Systems
University of South Carolina Upstate.
Spartanburg, USA.
Email: egbueo@uscupstate.edu

D. Subbaram Naidu, PhD, Fellow IEEE
Department of Electrical Engineering
University of Minnesota Duluth.
Duluth, USA.
Email: dsnaidu@d.umn.edu

***Abstract*— Plug-in electric vehicles (PEVs) have gained a lot of popularity due to their environmental-friendly operation when compared to conventional fuel vehicles. Through collective control by an aggregator, PEVs batteries can also provide ancillary services such as load leveling and frequency regulation to improve the quality of power provided in the power grid. This study presents the modeling, simulation, and analysis of a vehicle-to-grid (V2G) system connected to a smart power grid. The model considers different penetration levels of PEVs in a system and investigates the economic and technical effects of using PEVs to support the grid. The model was tested using an IEEE 24 bus network to verify the effects that PEVs penetration has on generation cost in power systems. Results show that although the use of PEVs did not result in a significant reduction in the cost of power generation, the optimal scheduling of PEVs was effective in flattening the load profile through valley filling and peak load reduction.**

Keywords— Vehicle-to-grid, Optimization, Economic Dispatch, Clean energy, Plug-in Electric Vehicle.

I. INTRODUCTION

According to the Energy Policy Act of 2005, Economic Dispatch is defined as "The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities." [1]. Optimal economic dispatch has several benefits to the power grid, such as improving the system reliability and meeting the system demand at the lowest possible cost [2,3,4].

The increasing demand for a cleaner transportation system will likely result in large scale charging demand by plug-in electric vehicles (PEV). If this increased demand is not properly managed, it can lead to overloading of transmission lines and distribution transformers. Hence it is important to consider PEV loads while implementing economic dispatch. Zhao et al. [5] proposed a method to reduce the harmful effects of PEV overload on the grid by replacing full-charged batteries for PEVs, thus shifting peak load to periods with less demand. Ahmad et al. [6] proposed a new framework to identify the fleet size capability of a power network in both uncontrolled and vehicle-to-grid (V2G) modes of operation. The results of their study showed that the participation of PEVs in a V2G market significantly enhanced the ability of the existing power grid infrastructure to handle increased PEV load.

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In this paper, a mathematical model is proposed to reduce the cost of power generation in a smart grid using coordinated charging and discharging of PEV batteries.

This approach considers the arrival and distribution of PEVs at different buses in the distribution system. Power flow within the system is also modeled to study how the location of a PEV in the system affects its charging decision. Further analysis is also conducted to evaluate the effect that increasing the number of available PEVs have on the economic dispatch problem in the system.

II. PLUG-IN ELECTRIC VEHICLES

A. Vehicle distribution and properties

Physical properties of the vehicles include the battery capacity and the consumption rate. For these properties, information was obtained from www.fueleconomy.gov, the official US government source for fuel economy information [7]. Ten types of vehicle models used in the study are generated based on the sales distribution of PEVs in the market obtained from [8].

B. Driver travel pattern

Information from the National Household Travel Survey (NHTS) [9] was used to model travel behavior. Attributes such as the travel speed, the average commute distance to several destinations, and the dwell time at each destination were inferred from data obtained from the NHTS survey. Figures 1 and 2 below show the departure and arrival of vehicles based on travel data obtained from NHTS.

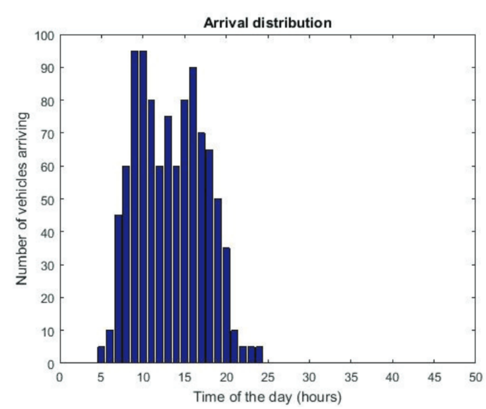

Fig 1. Arrival distribution based on NHTS data

For the simulation in this study, a total of 400 driver profiles were generated. Each profile has its distinctive properties, such as arrival time to the charging station, departure time, the initial state of charge on arrival, and the desired state of charge at departure. The different penetration levels for different scenarios in the study are implemented by applying a penetration factor to the set of 400 distinct driver profiles.

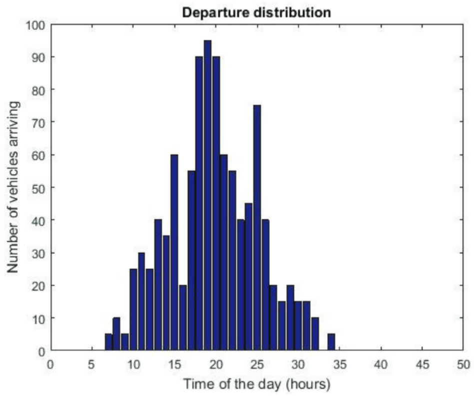

Fig 2. Departure distribution based on NHTS data

III. MODIFIED IEEE 24 BUS SYSTEM

Illustration of the modified IEEE 24 bus system, including the generators, dynamic non-PEV load and charging stations used in the optimization and simulation, is shown in Figure 3 below [10]. The information for the dynamic non-PEV load is based on PJM hourly load profile [11].

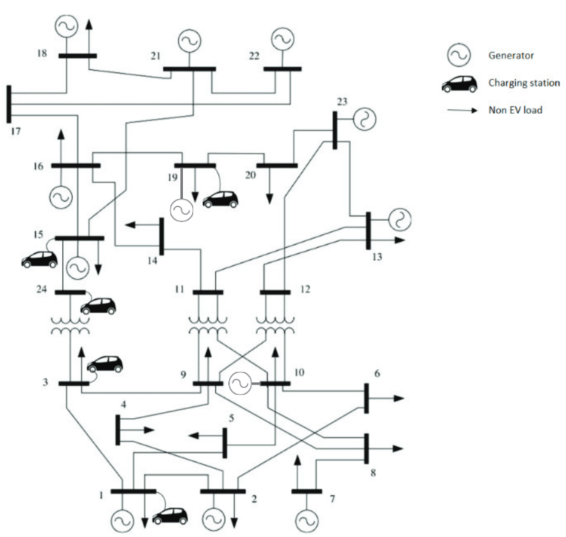

Fig 3. Modified IEEE 24 bus system

The economic dispatch model has been developed to include 12 different generators obtained from [12] and five parking stations. This takes into account the fuel costs of the generators in the system. Table I below shows the information for generating sets used in the study. This includes the operating power limits and the cost coefficients of the respective generating units.

The optimal power flow between the lines in this study focuses on the direct current (DC) optimal power flow. It is worth noting that losses on the lines have been neglected as it is outside the scope of this study. The ramp rates and the unit commitment information for the generating sets have also been neglected in the formulation of this economic dispatch problem.

TABLE I. INFORMATION FOR 12 GENERATING SETS

Generator No	Location (bus)	P_{max} (MW)	P_{max} (MW)	A ($/MW²h)	b ($/MWh)	c ($/h)
1	18	4	1	0.0148	12.1	82
2	21	4	1	0.0289	12.6	49
3	1	1.52	0.30	0.0135	13.2	100
4	2	1.52	0.30	0.0127	13.9	105
5	19	1.55	0.54	0.0261	13.5	72
6	16	1.55	0.54	0.0212	15.4	29
7	23	3.10	1.09	0.0382	14	32
8	10	3.50	1.40	0.0393	13.5	40
9	7	3.50	0.75	0.0396	15	25
10	13	5.91	2.07	0.051	14.3	15
11	15	0.60	0.12	0.051	14.3	15
12	22	3.0	0	0.051	14.3	15

IV. OBJECTIVE FUNCTION AND CONSTRAINTS

The objective is to minimize the total cost needed for energy generation. Generally, the fuel costs of thermal generators in an economic dispatch problem are described as a quadratic function, as seen below [13].

$$f_{ed} = \sum_{i=1}^{N} aiPi^2 + biPi + ci \tag{1}$$

Where N is the number of generating units; ai, bi, and ci are the cost coefficients of the i^{th} generating unit obtained from [14], and Pi is the active output power of the generating unit. The economic dispatch problem has a quadratic nature which can be computationally challenging to solve, hence the objective function was linearized to reduce computation time. The linearization was implemented using the piece-wise linearization method, where the economic dispatch function was divided into 100 equal affine functions. The steps for the linearization of the economic dispatch problem in GAMS were adopted from [12].

The objective function is subject to the constraints shown in equations 2-11 below. Equations 2-7 account for the individual vehicle charging behaviors while constraints 7 to 10 account for the generator limits and the optimal flow of power between nodes in the system.

Vehicles only charge or discharge when they are at the charging station.

$$C_{chg}^{i,t} + C_{dch}^{i,t} = 0 \text{ , } \forall \ arr_{time}^{i} \leq \text{t} \leq dep_{time}^{i} \tag{2}$$

Where arr_{time}^{i} and dep_{time}^{i} are the arrival and departure times of PEV i respectively.

Charging and discharging cannot take place at the same time.

$$I_{chg}^{i,t} + I_{dch}^{i,t} \leq 1 \qquad \forall \text{ i, t} \tag{3}$$

Where $I_{chg}^{i,t}$ and $I_{dch}^{i,t}$ are binary variables indicating charging and discharging respectively.

The maximum level of the state of charge (SOC) is limited to 90% of the battery capacity. This reduces battery degradation due to overcharging.

$$soc^{i,t} \leq 0.9 * Bat_{cap}^{i} \qquad \forall \text{ i, t} \tag{4}$$

Where Bat^{i}_{cap} is the battery capacity for the specific vehicle.

Vehicles only discharge if the SOC is above the minimum required SOC.

$$I^{i,t}_{dch} = 0 \text{ , } \forall \text{ i,t } \mid Msoc^{i} \geq soc^{i,t} \quad (5)$$

Where $Msoc^{i}$ is the minimum desired SOC

The SOC can increase, decrease or remain the same after every period

$$soc^{i,t} = soc^{i,(t-1)} + (C^{i,t}_{chg} * \eta_{chg}) + (C^{i,t}_{dch} * \eta_{dch}) \quad (6)$$

Where η_{chg} and η_{dch} are the charging and discharging efficiencies respectively.

The total power charged during each period is given by

$$P^{t}_{total} = \sum_{i=1}^{I} C^{i,t}_{chg} \quad (7)$$

The total power discharged during each period is given by

$$Pd^{t}_{total} = \sum_{i=1}^{I} C^{i,t}_{dch} \quad (8)$$

Constraint to set the lower operating limits of the generators

$$P^{min}_{g} \leq P_{g,t} \quad (9)$$

Where P^{min}_{g} is the minimum operating limit of the generator.

Constraint to set the upper operating limits of the generators

$$P_{g,t} \leq P^{max}_{g} \quad (10)$$

Where P^{max}_{g} is the upper operating limit of the generator.

Active power flow between buses b and n for every line Ω

$$P_{nb} = \frac{\delta_n - \delta_b}{x_{nb}} \qquad \text{n,b} \in \Omega \quad (11)$$

Where P_{nb} is the active power and x_{nb} is the reactance between the nodes n and b.

Load flow balance between buses, the power generated, PEV and non-PEV loads

$$\sum_{b} P_{g,t} - Load_{b,t} - TotalEVDemand_{b,t} + TotalEVSupply_{b,t} = \sum_{nb} P_{nb} \quad (12)$$

The objective function and the constraints were formulated as a mixed-integer programming (MIP) problem and solved using CPLEX [15].

V. RESULTS

The following figures show the results for simulation with 2000 vehicles in the system. As shown in Figure 4 below, generators significantly increased their outputs between hours 17 and 22, which are considered as peak hours of the day based on the load profile obtained from PJM. Similarly, generation was reduced during valley periods such as the period between hours 25 and hours 30, which is the early hour of the next day. The generators with lower fuel coefficients such as generator 1 carried out more generation, and the generators that were more expensive to operate only started operation when the demand exceeded power generated by the cheaper options as seen in the periods between hours 17 and 22. The most expensive generators, which are 10, 11 and 12, can be seen operating at their minimum point to reduce the operation cost of the system.

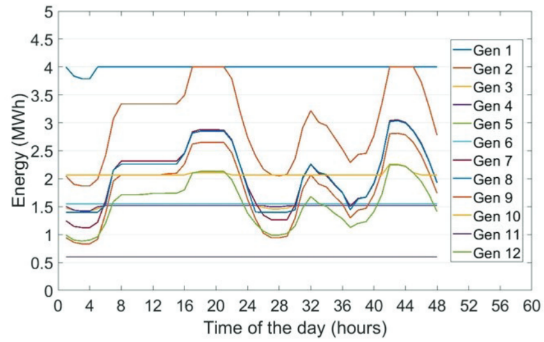

Fig 4. Energy supplied by generators per period

Figure 5 below shows the charging and discharging behavior of the vehicles in the system. It is shown that lesser charging took place between hours 13 and 21 where the non-PEV load demand is high. Discharging also took place to support the system during periods of peak non-PEV load demand. This results in load profile flattening which is a desirable condition for the power grid.

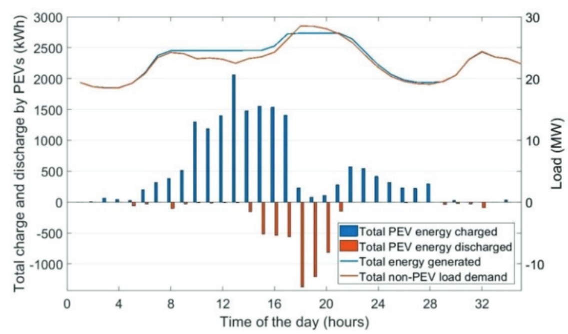

Fig 5. Profile of generation and PEV charging and discharging for 2000 vehicles

Figure 6 below shows the energy demand by PEVs at different buses. As seen, the demand at the buses differs even for a similar set of PEVs at each bus. This is due to the power flow between the different buses in the power system. To maintain optimal power flow while also minimizing the generation cost, the charging decisions of vehicles depend on the proximity of the generation station to the bus and also the amount of non-PEV load demand.

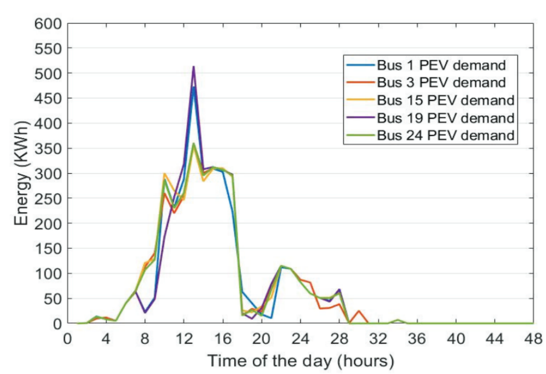

Fig 6. Total PEV demand at buses with PEV load

Figure 7 shows the energy discharged by the PEVs at different buses. The same reason for the disparity in charging behavior applies to discharge behaviors. Depending on the availability of generation at the bus or a neighboring bus, the discharging of PEV differs.

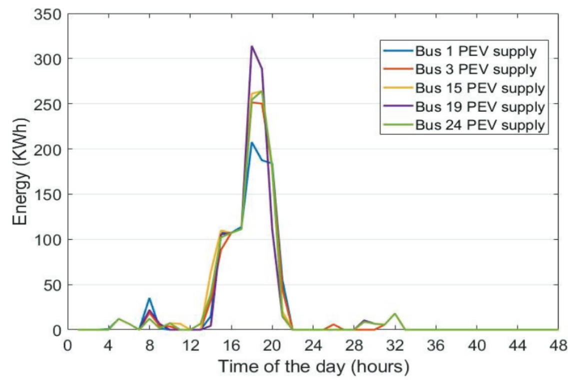

Fig 7. Total PEV supply at buses with PEV load

Figure 8 below shows the distribution locational marginal pricing (DLMP) for the different buses in the system. The concept of distribution system locational marginal pricing is applied to reflect the congestion costs in distributing energy within the system. It can be observed that bus 3 has a DLMP relatively higher than the other buses. Looking at the bus system, it can be seen that at bus 3, there is a charging station and no nearby generating plant so as expected, it will cost more to deliver power to bus 3.

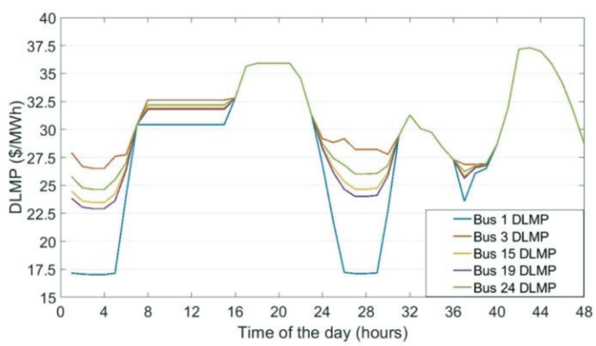

Fig 8. Distribution Locational Marginal Pricing (DLMP) at buses with PEV load

Further analysis was conducted to observe the effect of increasing the number of PEVs in the system and the results are displayed in Table II below. It is worth noting that the cost of generation without any PEV in the system is $22,738.50.

TABLE II. RESULTS FOR DIFFERENT PENETRATION LEVELS OF V2G

	Cost of generation ($) Without V2G	Cost of generation ($) With V2G
2000 vehicles	$23075.47	$23057.51
4000 vehicles	$23426.07	$23403.81
10000 vehicles	$24590.95	$24561.86
20000 vehicles	$27543.83	$27347.31

From the results in Table II above, it can be seen that the cost of generation for scenarios with or without V2G does not differ much for different penetration levels of PEVs in the system. This is because although the PEVs discharge energy back into the grid to optimize the cost of generation, they still need to draw back energy from the grid to meet the PEV owner's desired state of charge at departure. Though the presence of PEVs in the grid does not result in a significant reduction in the cost of generation, the PEVs provide a more substantial effect by carrying out valley filling and peak shaving services. Figure 9 below shows the significant flattening of the energy profile when the penetration level of the PEVs is at 20,000 vehicles. In this scenario, a flat power profile is maintained for most of the day between hours 7 and hours 24 when there is a significant amount of PEVs in the system to carry out frequency regulation.

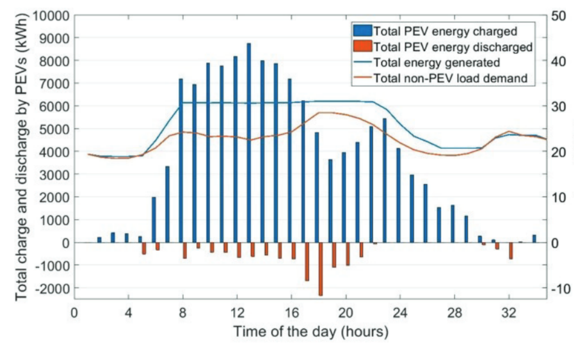

Fig 9. Profile of generation and PEV charging and discharging for 20000 vehicles

VI. CONCLUSION

In this study, the effect of PEV penetration level in a distribution grid system was analyzed while the economic dispatch problem was solved within given system constraints. Results from different scenarios show PEV batteries did not provide a significant reduction in cost but were more effective in balancing the system frequency through peak-shaving and valley-filling strategies. The use of PEV batteries as storage will be more effective in demand-side management where customers can store energy in their PEV batteries during periods where the cost of electricity is low and discharge the energy for use or sell back to the grid during periods with high electricity cost. Also, the ability of PEV batteries to respond quickly to frequency balancing has great potential in the grid of the future. With an increase in the number of intermittent distributed energy resources such as wind and solar energy which are susceptible to frequency imbalance, PEVs batteries can be used for frequency control. Future work will include unit commitment to the economic dispatch problem and determine the cost of using PEV batteries to reduce the generation cost of thermal generators.

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