論文の内容の要旨

論文題目　Vehicle-to-Grid Frequency Regulation for Smart Grid
（スマートグリッドにおけるV2G周波数制御）

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With highly successful commercialization of the hybrid electric vehicle (HEV), the electrification of vehicles is being accelerated. Especially, to avoid the burden of rapid charging to the power grid and the vehicle battery, slow charging through the conventional electric outlet is mainly employed for recent electric vehicles. This kind of electric vehicle is referred to as plug-in electric vehicle (PEV). The PEV concept has been originally developed from the facts that the vehicles are parked more than 90% of the time and the average driving distance is usually less than 40 miles a day. In addition, the mature technology of Lithium-ion battery has brought the battery into affordable size for the midsize vehicles.

As the rapid propagation of PEV is foreseen, the researchers have started to investigate the impact of PEVs from the electric grid side. Since the electric grid needs to be balanced between supply and load, the grid operator constantly strives to follow the load change by adjusting the output of generator. If the grid operator fails to follow the load fluctuation, the grid frequency deviates from the standard value, say 60 Hz, and may incur the black out as it gets severer. However, due to the inherent structure of the generator, it is difficult to change the output of the generator rapidly, and thus some frequency error exists always. On the other hand, the batteries can reach its rate power almost immediately and can mitigate the frequency error by adjusting its charging rate in accordance with the grid operator's call. Moreover, by adding a feature of backward electricity flow to the vehicle inverter, the PEV batteries can be fully utilized for the frequency regulation. This concept is referred to as vehicle-to-grid, or V2G frequency regulation, and has been investigated mainly from the aspect of economic feasibility thus far. The only technical approach used to be about the physical interfacing between the grid and vehicles. In particular, electric infrastructure regarding the backward electricity flow has been the main issue. However, the typical power capacity of a vehicle battery ranges around 1-20 kW, and thus is nothing more than a small noise in a power grid as a single battery. In addition, the transactions are carried out in MW basis in most power markets. Consequently, an intermediate system, called an aggregator, is essential to aggregate the small-scale powers of individual vehicles for providing a V2G service on the appropriate scale.

As depicted in Fig. 1, the V2G aggregator will receive the regulation signal from a grid operator in MW scale. Then, it would call the pertaining vehicles to charge or discharge so that the total amount matches the original signal. At this point, the aggregator should choose the vehicles and the amount in which the vehicles must charge or discharge. Since the battery conditions such as available power and energy may vary for each vehicle, the aggregator should consider these in distributing the original signal. Likewise, the remained time to the next driving would work as a constraint in determining the optimal charging schedule.

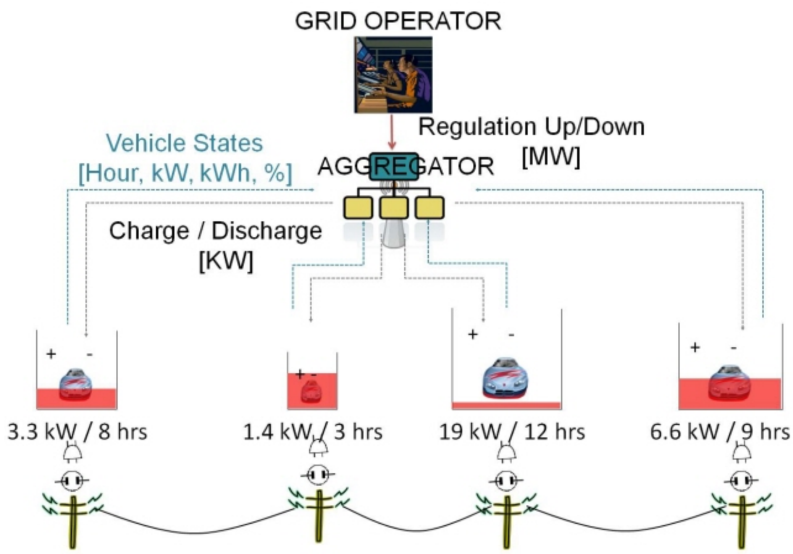

Fig. 1. Hierarchical structure of the V2G frequency regulation

Developing the distribution algorithm of the V2G aggregator is one of the main research topics in this dissertation. Chapter 2 discusses about the control strategy of each vehicle for the frequency regulation. A performance measure is built incorporating two typical price factors, regulation market clearing price (RMCP) and locational marginal price (LMP), each of which reflects the revenue paid to the vehicle owner for providing the power capacity and the expense paid by the vehicle owner for charging the battery from the grid, respectively. In addition, an energy constraint arising from the limit of energy capacity of the battery is devised and reflected to the RMCP. Then the optimal charging schedule is obtained using dynamic programming. With dynamic programming, no active discharge is considered, and thus the vehicles plugged in at high state-of-charge, say fully charged, remain disabled for regulation down (absorbing the energy). To overcome the problem, the impact of the energy deviation caused by the regulation signal is incorporated in the following section. That is, the aggregator distributes the regulation signal selectively. For instance, a highly charged battery would be called more frequently for discharge. Through this, the initially charged battery can be brought back to the mid-range state-of-charge hence mitigating the energy constraint. Then, the battery can be used for the regulation down as well and charged back as the time to the next driving approaches. With this strategy, however, the problem becomes much more complicated due to the increased variables, and thus the dynamic programming cannot be used as in before. To incorporate the multiple constraints in real time, the problems are broken into many pieces for each control time, and the variables for each divided problems are related as constraints in time series. Ultimately, the equations yield quadratic form and are solved using a well-developed quadratic programming solver.

In chapter 3, the V2G economics regarding the battery degradation is discussed with real battery data. Although the technical approaches of the V2G have been based on the precedent studies that claim the economic feasibility of the V2G frequency regulation, the battery degradation has usually been ignored, and thus the effective economic feasibility has always been controversies. To overcome this problem, we performed the economic assessment regarding the battery degradation. Firstly, a general assessment is made utilizing the pervasive requirement goals used by most battery manufactures and automakers. Since the requirements are created by the consortium of the three major U. S. automakers in conjunction with the Department of Energy, most battery manufactures take those requirements into consideration in the actual development. Typically, the criterions are considered as minimum goals since it does not specify any specific kind of the batteries or manufactures. Consequently, if the usage of the battery during a V2G service can be analyzed in terms of the prescribed test profile in the requirement specification, the total energy transferred until the battery's end-of-life (EOL) can be calculated. The expected income for providing a battery to the V2G regulation is then estimated by analyzing the regulation signal in conjunction with the estimated energy flow until the EOL of the battery. During the analysis, actual regulation price from PJM, one of the major grid operator in U. S., is incorporated, and the estimated incomes are compared with current and prospective battery prices.

In order to verify the proposed assessment method and investigate the degradation rate with respect to the cycling depth, several experiments are made in the following section. The experiments are conducted using the commercialized battery cell from SK Innovation, one of the major battery manufacturers in South Korea. Through the experiments, it turned out that the actual battery lasts much longer than the criterions specified in the aforementioned requirements. Consequently, the actual V2G income would be increased than the general assessment result, hence enhancing the prospect of the realization of the V2G regulation.

Another experiment is performed to investigate the degradation rate in terms of the cycling depth. Three test profiles with different cycling depth are assigned and the estimated EOLs along with the expected V2G incomes are compared. From the result, it appears that a battery can transfer more energy with shallower cycling. Thus, the aggregator should try to maintain the swing range of the state-of-charge of each vehicle battery as narrow as possible to slow down the degradation of the battery, hence maximizing the effective profit.

Meanwhile, market participation of the V2G aggregator is also an important research interest. In a competitive electricity market, regulation providers should be aware of the power capacity that they can provide prior to the actual service delivery. Thus, it is important to identify the overall plug-in patterns of vehicles. The energy management system (EMS) in a grid operator dispatches regulation signal based on economical strategies built on prior information given by the regulation providers. Specifically, the information includes generation cost, ramp rate, and most of all, the rated power capacity of each generator. In the existing power market, frequency regulation is provided by generators, and the achievable power capacity (APC) can be easily acquired from their rated power capacity. Regarding the V2G frequency regulation, however, the exact APC cannot be obtained due to the plug-in uncertainties incurred by the human behavior of pertaining vehicle owners. In chapter 4, the methodological approach is proposed to obtain the probability distribution of the APC. The vehicles are clustered into multiple groups depending on their plug-in probability and power capacity. Each group represents the vehicles with a similar plug-in probability and power capacity. For each group, APC is derived in the form of the binomial distribution. Then the APCs from each group are approximated to the normal distributions and summed up yielding the total APC of entire vehicles. Based on the developed probability distribution of the APC, profit functions are built considering several possible penalty cases. The optimal contract power capacity can be then chosen to maximize the corresponding profit functions. For a specific case, a closed form solution is derived as well.

In chapter 5, the impact of V2G frequency regulation is quantitatively investigated. So far, big portion of the frequency regulation has been performed by combined cycle generators for their load following ability. However, the ramp rate restricts the load following ability up to just a few percent of the rated power of the generators hence requiring excessive facility capacity for the frequency regulation. The amount of introducible renewable energy, say wind power, has been usually restricted by this factor due to its intermittent output characteristic. With V2G frequency regulation, however, the load following capacity can be procured through the battery power, and thus more renewable power can be employed without extra investment for the generators. In order to provide a quantitative measure for the required amount of regulation capacity, we propose a new reliability index called failure rate for frequency regulation (FRFR) that addresses the failure probability of frequency regulation. During the calculation, grid parameters are incorporated in either of deterministic or probabilistic form. The probability of carrying out successful frequency regulation is estimated from the physical constraints and the equilibrium condition between load and generation. The suggested reliability index (failure rate) is then obtained by reversing the estimated success probability. During the formulation, V2G power is incorporated as well to assess the impact quantitatively. Using the derived reliability criterion, the impact of incorporated wind power can be estimated in a quantitative manner hence providing a measure for the required amount of the V2G power.

Finally, the conclusion and future works are given in chapter 6.