

# Optimal Frequency Regulation V2G Control with DOD of EV Battery

Seungmin Jung, Minhan Yoon, Jaewan Suh

**Abstract:** As the proportion of electric vehicles increases, interest in Vehicle to Grid (V2G) service is increasing. Many studies are underway to use V2G for peak shaving and frequency regulation in power system. However, V2G can shorten battery cycle life for electric vehicle (EV) which is the most variable part in EV. Hence battery cycle life should be considered in V2G service. As well as the number of discharges, depth of discharge (DOD) also highly affects battery cycle life. High depth of discharge reduces the cycle life of the EV battery exponentially. However, conventional droop control, which has been used for frequency regulation, controls the active power linearly without regard to the DOD. This paper proposes an optimal frequency regulation V2G control which considers the DOD of EV. Proposed method uniformly distributes the discharge for V2G. Therefore battery cycle life is preserved and inconvenience of EV owner from discharge is reduced. The case study result demonstrates the advantages of the proposed method over the conventional droop method. Battery cycle life of entire EV is preserved and energy consumption under V2G is uniformly distributed.

**Keywords :** Cycle life of battery, Droop control, Electric vehicle, Frequency regulation, Vehicle to Grid

## I. INTRODUCTION

Worldwide sales of electric vehicles in 2017 increased by 54% from 2016 to over 1 million units[1]. It is expected to operate 18.7 million vehicles, which is 7% of all US vehicles by 2030, and 9.6 million chargers will be needed[2]. Large penetration of EV in power system can cause many problems such as imbalance between electric demand and supply[3, 4]. And power quality and voltage quality problems can arise due to EV chargers in distribution system[5-8]. As the penetration rate of electric vehicles and charging stations increases, interest in V2G is also increasing to solve the challenges due to large EV penetration. V2G means a service that supplies electric power to the power system through charging and discharging of EV[9]. Through V2G, EV can be transformed into controllable resources in power system from operational challenges.

Until recently research has been mainly focused on peak shaving with V2G[10-12]. In peak shaving operation, EVs are charged during off-peak hours and discharged during peak hours to use as reserve. Through peak shaving, power system operation costs and necessity of new power plants can be reduced. However, there are several challenges to realize the

V2G service for peak shaving. First challenge is the difficulty of predicting operation pattern of EV. In order to use EV in peak shaving, it is necessary to predict the charging pattern, the expected departure time, and the minimum SOC of EV required at the start[13, 14]. Second problem is the influence on cycle life of EV battery. Battery is one of the most valuable components of EV and it has relatively short life span compared to other component. Peak shaving from EV needs a lot of energy from the battery which means that the depth of discharge (DOD) gets large. DOD highly affects to battery cycle life and the larger the DOD every cycle means the smaller the available life cycle will be[15, 16]. Recent days, many researches are underway to use V2G for frequency regulation[17, 18]. When V2G is applied to frequency regulation, prediction is easier than peak shaving and the amount of energy for V2G is reduced. Since the unit price of frequency regulation reserve is relatively high, power system operation costs can be significantly reduced by V2G. To save the battery life cycle in V2G operation, DOD should be considered for V2G efficiency because DOD highly affects battery life cycle. In this paper, optimal frequency regulation V2G control, which considers the DOD of each EV in V2G service, is proposed. The conventional droop control did not consider the DOD of each EV but the proposed control can save battery cycle life by considering DOD when allocating the discharge. Realistic data from PJM and tesla are used for case study. Case study with MATLAB shows the effectiveness of propose control.

## II. DOD AND CYCLE LIFE OF BATTERY

Battery cycle life is number of charge and discharge cycles until battery reaches its End of Life (EOL) which is typically defined as 20% reduction in rated capacity of battery. Cycle life highly depends on the DOD and number of cycles. Charging and discharging in high DOD results stress to battery cell and reduce the cycle life of battery[15]. In 50% DOD case, the expected number of equivalent full cycles is 2.7 times longer than expected number of equivalent full cycles of 80% DOD case. It is general for all cell chemistries such as lead acid or lithium-ion battery, more or less. Relation between DOD and cycle life of Li-ion battery is expressed as[15].

$$\text{Cycle life} = 1591.1 \cdot \text{DOD}^{-2.089} \quad (1)$$

However, it is unreasonable to directly compare the life cycles of different DODs, it is necessary to use the equivalent full cycle life which is calculated by multiplying cycle life by DOD.

**Revised Manuscript Received on July 22, 2019.**

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Equivalent full cycle life =  $1591.1 \cdot DOD^{-1.089}$  (2)

Fig.1 shows the relationship between the DOD and equivalent full cycle life. As shown in Fig.1, the DOD and equivalent full cycle life have an inverse proportion. Hence operating the EV battery with low DOD is very crucial to protect the cycle life of battery.

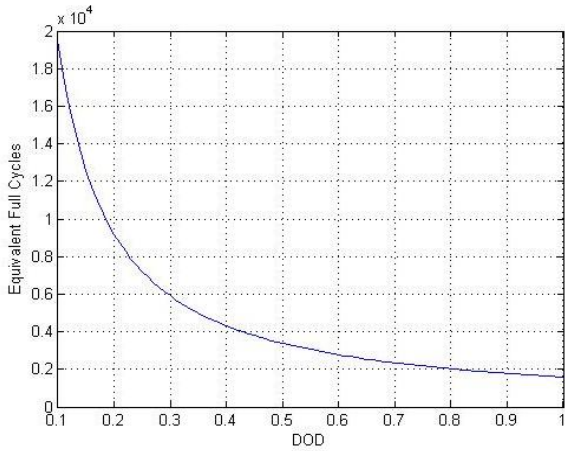


Fig. 1. DOD and equivalent full cycle of life

### III. FREQUENCY REGULATING V2G CONTROL WITH DOD

Power system frequency is held by frequency regulation reserve which adjust the output quickly[19]. Normally, operating hour of frequency regulation reserve is not long. Therefore, DOD can be kept low in V2G operation and battery cycle life can be protected. In addition, predicting the schedule of EV is easier because frequency regulation is a short time unit operation. In those reason, frequency regulation reserve is suitable for V2G application taking account of battery cycle life. The droop control has been used most widely for power system frequency regulation[20].

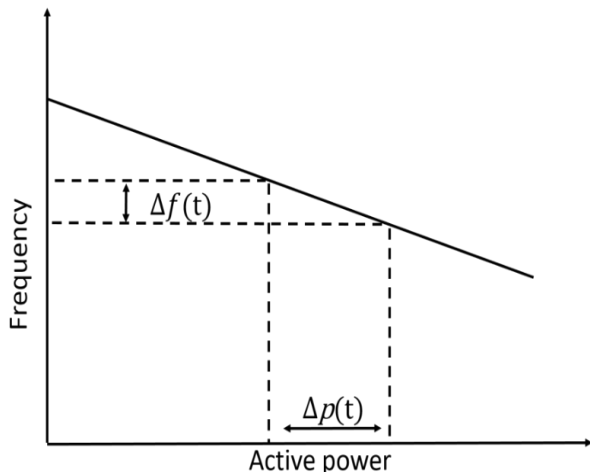


Fig. 2. Droop control in frequency regulation

Droop control has the advantage of being reliable and not requiring additional communication devices. Frequency deviation is used for signal for droop control as shown in the following equation

$$P - P_0 = -k(f - f_0) \quad (3)$$

where  $P_0$  and  $f_0$  are base active power and base frequency of the power system.  $k$  is droop control constant for frequency regulation. Fig.2 shows the droop characteristics between frequency and active power. Since the cycle life of the battery

decreases exponentially with increasing DOD, uniform distribution of the DOD is very important. However, conventional droop control does not consider DOD of EV battery because it is proportional control over frequency deviation. Thus, in this study, conventional droop control is implemented to distribute the frequency regulation reserve considering the DOD of the entire EVs battery. In proposed control, droop control constant  $k_i$  is calculated as follow

$$k_i(t) = -\frac{1}{DOD_{total}(t)} k_0 \quad (4)$$

where  $k_0$  is initial droop constant of  $i$ th EV,  $DOD_i$  is DOD of  $i$ th EV, and  $DOD_{total}$  is sum of the DOD inverse as shown below

$$DOD_{total}(t) = \sum_{m=1}^n \frac{1}{DOD_m(t)} \quad (5)$$

From (3) and (4) implemented droop control which considers the DOD is expressed as follow

$$P_i(t) = k_i(t) \Delta f(t) \quad (6)$$

where  $P_i$  is charging/discharging power of  $i$ th EV and  $\Delta f$  is frequency deviation. The implemented droop control allocates the frequency regulation reserve in real time, taking into account the DOD of each EV and the overall EV. EV batteries with a relatively low DOD are preferentially used for frequency regulation. And EV batteries with high DOD will be relatively excluded in V2G frequency regulation.

### IV. CASE STUDY

In this case study, V2G operation of EV for a day is simulated by MATLAB. Historical operation data of PJM on 01. Feb. 2018 is used for 24 hours simulation. Number of EV which participates in V2G service are assumed as 10. Tesla model S 90D and Tesla single charger model data are used for case study. Table I shows the parameters and values for case study. Frequency regulation signal of PJM on 01. Feb. 2018 is shown in Fig.3. From those regulation signals, frequency fluctuation on 01. Feb. 2018 is estimated and used for V2G control signal in case study. As shown in Fig.3, frequency regulation reserves are not fully operated for most of time in real power system operation. Fig.4 shows the result of case study which compares between conventional droop control and proposed control for 24 hours. Initial DODs at 0 hour are randomly chosen and EVs were assumed to be parked for 24 hours. Energy consumption during frequency regulation in EV batteries is calculated by Fig.3 and (6).

Table- I: Parameters and values for case study

Parameter	Value
Number of EVs	10
Battery capacity	90kWh
Power of charger	10kW

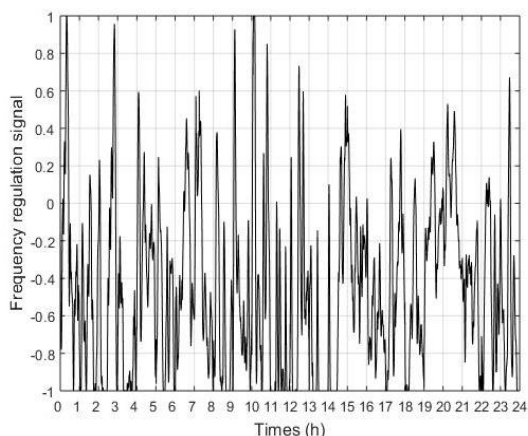


Fig. 3. Frequency regulation signal for 24 hours

### V. RESULT AND DISCUSSION

By applying the proposed control in V2G, discharges for frequency regulation in EVs are uniformly distributed. From DOD in Fig.4 and (2), total consumed cycle life of EV battery can be calculated.

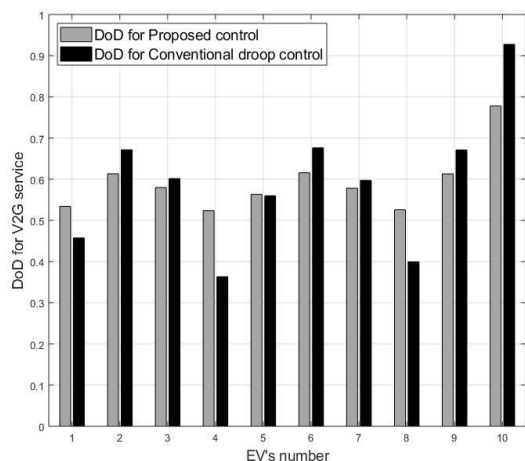


Fig. 4. Comparison between conventional droop and proposed control

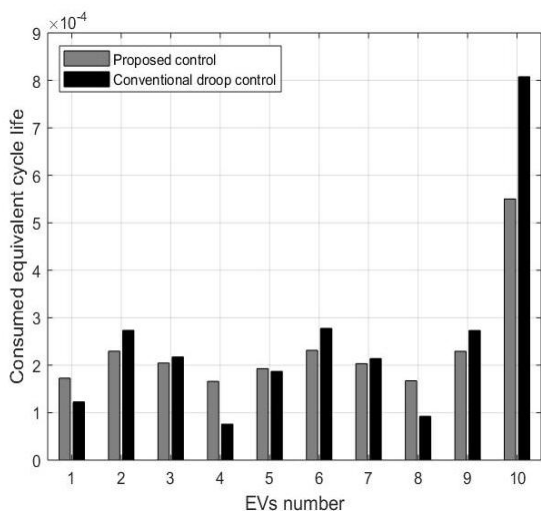


Fig. 5. Consumed equivalent cycle life of EV batteries due to V2G

Table II shows the comparison of the consumed equivalent

cycle life of the conventional droop control and the proposed droop control. About 7.7% of consumed equivalent cycle life for entire EVs which participate in V2G is reduced by applying the proposed droop control for 24 hours V2G operation. And proposed control prevented battery cycle life consumption by V2G operation from being concentrated on some EVs.

Table- II: Consumed equivalent cycle life in case study

EV number	Initial DOD	Consumed equivalent cycle life of battery for frequency regulation	
		Conventional droop control	Implemented droop control
1	0.40497	0.00017271	0.00012266
2	0.31890	0.00022940	0.00027340
3	0.44903	0.00020451	0.00021732
4	0.31091	0.00016595	0.00007583
5	0.20730	0.00019260	0.00018701
6	0.32378	0.00023137	0.00027757
7	0.24463	0.00020315	0.00021401
8	0.04688	0.00016723	0.00009236
9	0.31866	0.00022930	0.00027320
10	0.47513	0.00055003	0.00080768
Total		0.00234625	0.00254105

### VI. CONCLUSION

The biggest challenges to realizing V2G service are damage to battery life cycle, owner's inconvenience and EV schedule prediction. If we use V2G for frequency regulation, it is relatively free from these challenges. However droop control, which normally used for frequency regulation, is not suitable for V2G frequency regulation. DOD and battery cycle life must be considered in the frequency regulation through EV to realize the V2G service. In this paper, we proposed implemented droop control for V2G in frequency regulation. DODs of each EV battery are reflected in droop constant in real time to control the discharge of the battery in proposed method. Proposed control allocates the discharge to prevent from concentrating only on some of the EV batteries. As the discharges are uniformly distributed, cycle life of the EV batteries participating in V2G are saved and inconvenient of the EV owner is minimized. MATLAB case study shows the effectiveness of proposed control. Compared to conventional droop control, proposed control saves the battery cycle life of the overall EV by 7.7%. In order to maximize the usability, V2G has to be used both peak shaving and frequency regulation[21]. DOD based V2G control for dual-use will be treated in future work.

### ACKNOWLEDGMENT

This work was supported by National Research Foundation Grant (NRF-2019R1C1C1007566) funded by the Korean government.



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