Coordinated Vehicle-to-Grid Scheduling to Minimize Grid Load Variance

Mohd Syahmi Hashim
Institute of Power Engineering
Department of Electrical Power Engineering
Universiti Tenaga Nasional
Kajang, Malaysia
mohdsyahmihashim@gmail.com

Jia Ying Yong
Institute of Power Engineering
Department of Electrical Power Engineering
Universiti Tenaga Nasional
Kajang, Malaysia
jiaying@uniten.edu.my

Vigna K. Ramachandaramurthy
Institute of Power Engineering
Department of Electrical Power Engineering
Universiti Tenaga Nasional
Kajang, Malaysia
vigna@uniten.edu.my

Kang Miao Tan
Institute of Power Engineering
Department of Electrical Power Engineering
Universiti Tenaga Nasional
Kajang, Malaysia
tan.kangmiao.1988@ieee.org

Mohd. Tariq
Department of Electrical Engineering
Z.H.C.E.T
Aligarh Muslim University
Aligarh, India
Tariq.iitkgp@gmail.com

***Abstract*—This paper presents the Vehicle-to-Grid scheduling algorithm to minimize the grid load variance by utilizing the grid-connected electric vehicle battery. The algorithm performs in two modes, which are load leveling and peak load shaving. In the load leveling mode, the grid-connected electric vehicle is charged from the power grid and hence, increase the grid loading. Meanwhile, the grid loading is reduced in peak load shaving mode since electric vehicle discharges energy from the battery to support the power grid. Various constraints have been considered to ensure the practicality of this study. The Vehicle-to-Grid study was implemented in a commercial-residential area with electric vehicle mobility of 1300. Both uncoordinated charging and coordinated Vehicle-to-Grid scheduling were performed and compared. The results showed that the uncoordinated charging of electric vehicle will induce a new peak in the power grid load profile. On the other hand, the results showed that the proposed coordinated Vehicle-to-Grid scheduling algorithm successfully minimized the grid load variance while satisfying all the constraints and power grid requirements.**

Keywords—Bidirectional power flow, electric vehicles, energy management, optimization, vehicle-to-grid.

I. INTRODUCTION

The penetration rate of Electric Vehicle (EV) has been increasing exponentially as EV is a potential solution to cater for climate change problem. With the capability of producing zero exhaust gas and generating minimal noise, EV becomes an alternative option to replace the traditional internal combustion engine vehicle in the transportation sector [1]. However, EV battery needs to receive regular charging from the power grid. Therefore, EV is considered as an additional load to the power grid and may pose possible threats to the power grid reliability by overloading the grid equipment, disturbing the grid voltage stability and injecting harmonics into the power grid [2]. The aforementioned negative impacts of EV charging will happen and become significant if the penetration level of EV keeps increasing and not managed properly. To overcome this issue, EV charging shall be carefully managed by implementing appropriate scheduling strategies. EV can also provide benefits to the power grid through Vehicle-to-grid (V2G) application by discharging battery energy into the power grid [3]-[4]. In other words, EV can use the battery energy to support the power grid. Some external parties called aggregators can be utilized to control the charging/discharging of the EV battery to provide ancillary services to the grid, such as load leveling and peak load shaving, thus minimizing the grid load variance [5].

In the body of knowledge, several studies had focused on the scheduling optimization in the load leveling mode. In [6] and [7], load leveling optimization algorithms that considered EV owners' driving behavior were developed. Meanwhile, a coordinated charging algorithm was designed in [8] and was used for congestion management. The optimized EV charging scheduling could also be used to maximize the renewable energy generation/capacity, which was presented in [9]. In [10], the authors performed the coordinated charging in a chosen commercial parking place with the consideration of EV arrival and departure times. Studies in [11]-[14] highlighted the V2G scheduling by performing both charging and discharging of EV. In [15], peak load shaving was implemented by optimizing both EV discharging time and power.

Based on previous studies, there were several considerations that had been made in the V2G optimization, such as EV driving pattern, EV charging level and penetration level. However, most of the studies lacked the consideration of practical constraints in the algorithm. To overcome this research gap, various practical constraints have been considered in the V2G scheduling algorithm in this paper. Furthermore, only several studies considered the combination of commercial and residential loads in the research scope. The implementation of V2G in an area with residential and commercial loads can ensure continuous availability of EV for V2G service throughout the day.

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This paper presents a V2G optimization algorithm that minimizes the grid load variance by utilizing grid-connected EV to perform load leveling and peak load shaving. By considering factors such as EV connection probability and power grid requirements, the proposed algorithm will find the optimal outcome to minimize the grid load variance. The algorithm also considers practical constraints, such as State-of-Charge (SOC) of each EV battery and power supply-demand balance. The main contributions of this paper are: (i) a V2G optimization algorithm to flatten the grid load profile was successfully designed, (ii) the V2G algorithm with the consideration of various practical constraints was developed and (iii) comparative analysis between uncoordinated EV charging with coordinated V2G scheduling was implemented and verified.

The rest of the paper is organized in several sections. The setting of the scenario is introduced in Section II. In Section III, the objective function and constraints of the proposed V2G algorithm are formulated. In Section IV, the results are presented and discussed. Section V concludes the paper.

II. SCENARIO SETTING

In this paper, the V2G technology is carried out in a combination of shopping malls and residential homes. The area is chosen because of its continual EV mobility throughout the day. The commercial area consists of 450 unit of shops and offices while the residential area consists of 400 unit of houses and condominiums. Each unit has different maximum demand with commercial unit having maximum demand of 15 kW while residential unit having maximum demand of 10 kW. In order to successfully implement the V2G technology in that area, some assumptions need to be made which are listed as follow:

- The initial SOC level of EV batteries is set randomly from 10% to 100%.
- The grid supply is available throughout the day without interruption.
- EV mobility is set to 1300 which includes the proposed and neighbouring area.

Fig. 1 shows the power grid load profile of the proposed area. The residential profile has two peaks, where the first peak (between 07:00 to 09:00) indicates that the residents are preparing themselves to start the day and go to work while the second peak (between 17:00 to 19:00) indicates people travelling back home from workplace. Meanwhile, the commercial profile has roughly the same amount of peak loading from 10:00 to 17:00 because most people are already at the workplace. It can be seen that the residential profile during these period is very low compared to the commercial profile. The total load curve follows the pattern of residential profile due to the significant peaks in the morning and evening.

Fig. 2 depicts the connection probability of EV in the proposed area. It shows the percentage of EV connected to grid at a certain time. It is assumed that there are five units of charger available for each shop/office unit, while only one charger unit is available for each house/condominium. Based on this setting of charger quantity, the EV connection profile is more influenced by the commercial sector due to higher number of charger unit available than the residential sector.

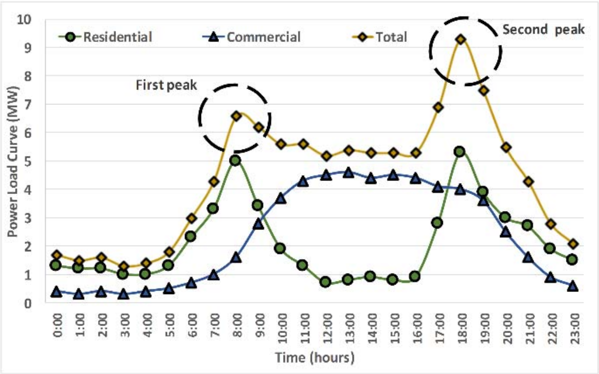

Fig. 1. Power grid load profile.

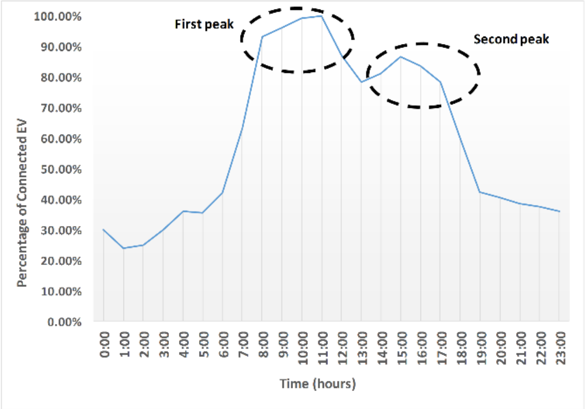

Fig. 2. Profile of EV connection probability.

The first peak indicates that workers plug in their EVs after arriving at workplace/shopping malls (08:00 to 11:00) while the second peak is when the workers plug in their cars after having a lunch break (14:00 to 16:00). The residential homes have lower percentage of connected EV due to limited charger at each house/condominium.

III. DESIGN OF V2G OPTIMIZATION ALGORITHM FOR LOAD VARIANCE MINIMIZATION

A. Objective Function

The objective function of this paper is to minimize the power grid load variance by utilizing V2G technology. Equation (1) is used to find the optimum value of charging and discharging for each EV. First, the algorithm will determine if the grid loading is greater or smaller than the target loading. If the grid loading is smaller than the minimum (min) target loading, the algorithm will perform load leveling and it will charge the battery of the grid-connected EV. Meanwhile, the peak load shaving procedure will take place if the grid loading is higher than the maximum (max) target loading. The grid-connected EV will use the energy in the EV battery to support the grid. If the grid loading is between or the same as grid target loadings, the grid-connected EV will not perform any charging or discharging.

$$min\Delta P = P_{load}(t) - P_{EV}(t) \tag{1}$$

$$P_{EV}(t) = \sum_{i=1}^{I} C_i N_{EV} \times P_{EV,Charging}(t) \tag{2}$$

$$: \quad P_{load} < P_{min}$$

$$P_{EV}(t) = \sum_{i=1}^{I} C_i N_{EV} \times P_{EV,dis\ Charging}(t) \quad : \quad P_{load} > P_{max} \tag{3}$$

$$P_{EV}(t) = 0 \ : \ P_{min} \le P_{load} \le P_{max} \tag{4}$$

where P_{EV} = charging/discharging power, C_i = connection probability, N_{EV} = number of connected EV, i = index number of EV, P_{load} = power of grid load, P_{min} = minimum target loading and P_{max} = maximum target loading.

B. Constraint

The constraints of V2G optimization scheduling can be split into EV-related constraint and power grid constraint. The power grid constraint is important as to maintain system stability by matching the supply with the demand. The supply-side consists of generated power from generation plant and EV discharging power while the demand side consists of power grid load demand and EV charging demand. The power grid constraint can be split into two modes as follow:

1) *Load leveling*

$$P_{grid}(t) = P_{load}(t) + P_{EV,Charging}(t) \tag{5}$$

2) *Peak load shaving*

$$P_{grid}(t) + P_{EV,Discharging}(t) = P_{load}(t) \tag{6}$$

where P_{grid} = power supply from the grid.

The EV-related constraints are listed as follow:

1) *EV power exchange rate:* the current rate and the power rate of the EV battery is restricted to 10 A and 3.3 kW, respectively for load leveling while -10 A and -3.3 kW for peak load shaving, respectively.

$$P_{EV,charging} \le 3.3\ kW \tag{7}$$

$$P_{EV,discharging} \ge -3.3\ kW \tag{8}$$

2) *EV grid connection probability:* for practical purpose, EV can be connected to and disconnected from the grid at any given time.

$$C_i = 1, \text{EV is connected to the grid} \tag{9}$$

$$C_i = 0, \text{EV is not-connected to the grid} \tag{10}$$

3) *EV battery SOC:* in order to protect the battery health and to have enough energy for EV propulsion, the SOC of EV battery must be held within a certain range. In this paper, the maximum SOC is set to 90% while the minimum SOC is set to 50%. EV is allowed to charge if the SOC of the EV battery is below the maximum value while the EV is allowed to discharge if the SOC of the EV battery is higher than the minimum value.

$$SOC_i < 50\%, \text{load leveling} \tag{11}$$

$$50\% \le SOC_i \le 90\%, \text{load leveling and peak load shaving} \tag{12}$$

$$SOC_i > 90\%, \text{peak load shaving} \tag{13}$$

where SOC = State-of-Charge of EV battery.

C. Flow Chart of Optimization

Fig. 3 shows the flowchart of the V2G optimization algorithm. It starts by initializing some variables, such as SOC of EV battery and the connection probability of EV. Next, the algorithm will check the power grid loading to see whether to operate in load leveling mode, peak load shaving mode or no action mode. By using the time iteration loop, the algorithm will be executed for every hour until the stopping criteria is reached.

Fig. 4 depicts the operation of load leveling while Fig. 5 presents the operation of peak load shaving. These operations consist of all the constraints that are discussed earlier. The difference between the load leveling operation and peak load shaving operation lies in the SOC constraint, charging constraint and power balance constraint. The power grid and EV constraints are defined differently according to peak load shaving and load leveling scenarios. In load leveling mode, the constraint function is to protect the EV battery, while the main purpose is for propulsion in peak load shaving mode. The charging constraint is different in term of current direction. If the EV is charging, the current is positive. On the other hand, if the EV is discharging, the current is negative. The power balance constraint is to match the supply with demand. In load leveling mode, the supply has to match with both the grid load and EV charging load. While in peak load

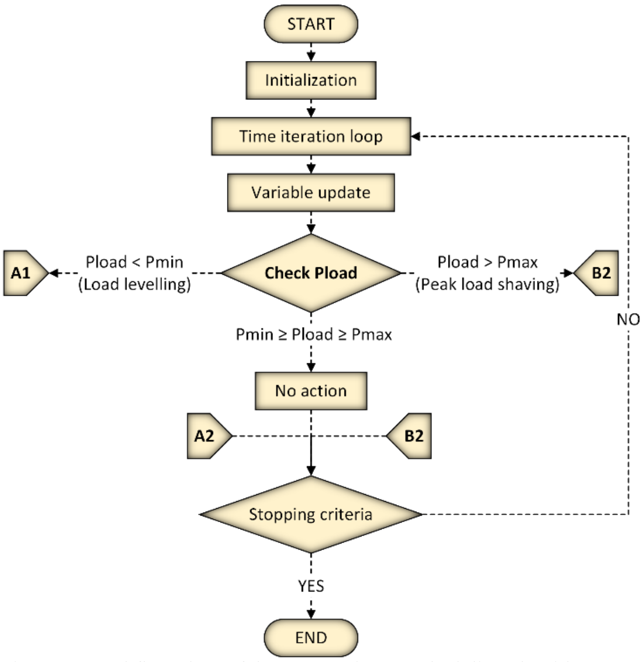

Fig. 3. General flow chart of the proposed V2G scheduling algorithm.

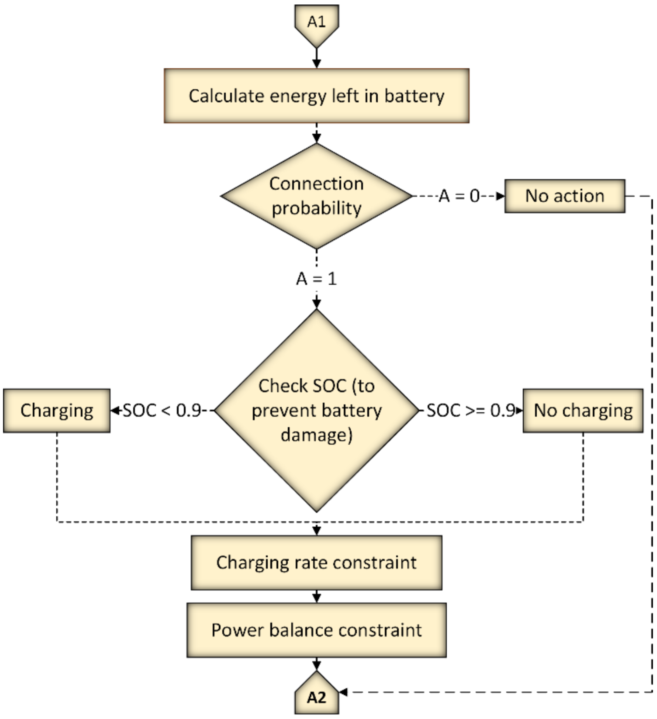

Fig. 4. Sub-algorithm A in general flow chart.

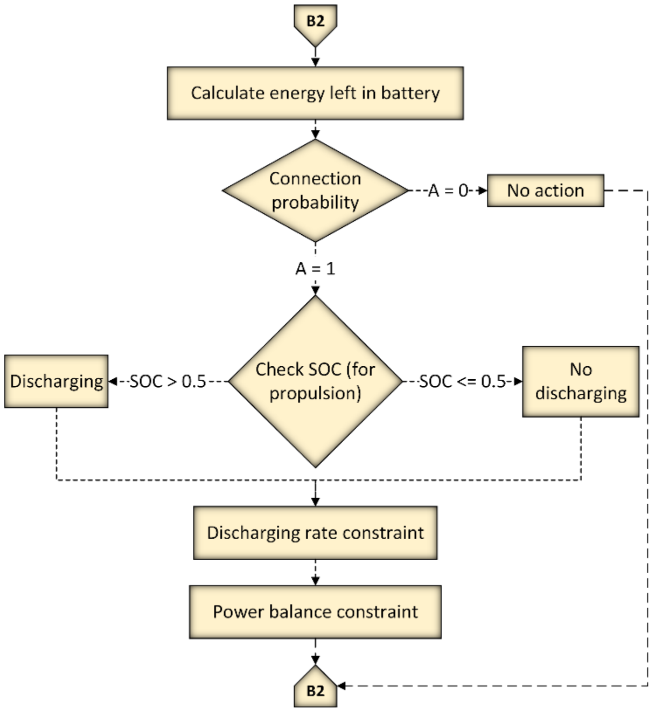

Fig. 5. Sub-algorithm B in general flow chart.

shaving mode, the supply and EV discharging power has to match with the grid load. These constraints play major role to differentiate the difference between these two operations.

IV. RESULTS AND DISCUSSION

A. *Power Load Profile*

This section examined the performance of V2G optimization algorithm to perform coordinated EV scheduling. The results were compared with uncoordinated EV charging scenario. In coordinated V2G, the algorithm will perform in two modes, which are load leveling and peak load shaving. Both of these modes have the same objective that is to minimize load variance in power grid by utilizing the grid-connected EV. Meanwhile, uncoordinated charging will solely charge the EV once the EV is connected without considering the target loading constraints.

Fig. 6 shows the result of optimization algorithm for both uncoordinated charging and coordinated V2G scheduling. The line with the rectangle shape marker indicated the original power grid load profile, which resembled the power grid load profile in Fig. 1. The lines with diamond and round shape markers indicated the uncoordinated charging and coordinated V2G scheduling respectively. During the period from 00:00 to 07:00, it can be observed that both the uncoordinated charging and coordinated V2G scheduling had similar load profile pattern. The reason was because both cases had similar initial SOC and connection probability input which required EV battery charging. During the period from 08:00 to 17:00 and from 19:00 to 21:00, the uncoordinated charging continued to receive charging from the power grid to charge the EV battery, since uncoordinated charging did not take any constraint/limit into consideration. On the other hand, the coordinated V2G scheduling had the same load profile pattern as the original grid load profile because the grid loading occurred between the target loadings ($P_{min} \leq P_{load} \leq P_{max}$), where the algorithm instructed the EV to not perform any charging or discharging. At 18:00, the uncoordinated charging generates a new peak, which is unfavorable. Meanwhile, for coordinated scheduling, the algorithm performed peak load shaving by discharging EV battery energy to the power grid. A reduction in the peak demand loading can be observed in the original grid load profile. However, the peak load shaving service cannot be achieved completely due to the lack of number of EV to provide the necessary energy capacity and also due to slow charging and discharging rate of only at 3.3 kW/-3.3 kW. From 22:00 to 23:00, the uncoordinated charging result was different from the coordinated V2G even though both of the cases were performing the same load leveling mode. Coordinated charging scenario can perform a better load leveling operation because there were more EVs available to receive charging from the power grid.

B. *SOC of EV battery*

1) *Load leveling*

Fig. 7 and 8 illustrate the difference of battery SOC between uncoordinated charging and coordinated V2G in

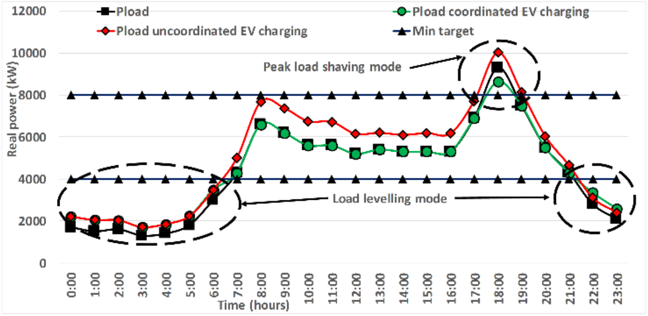

Fig. 6. Results of uncoordinated charging and coordinated V2G scheduling.

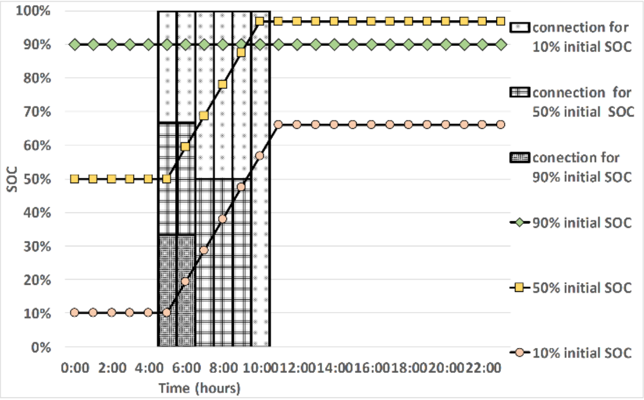

Fig. 7. SOC profile in load leveling phase for uncoordinated charging.

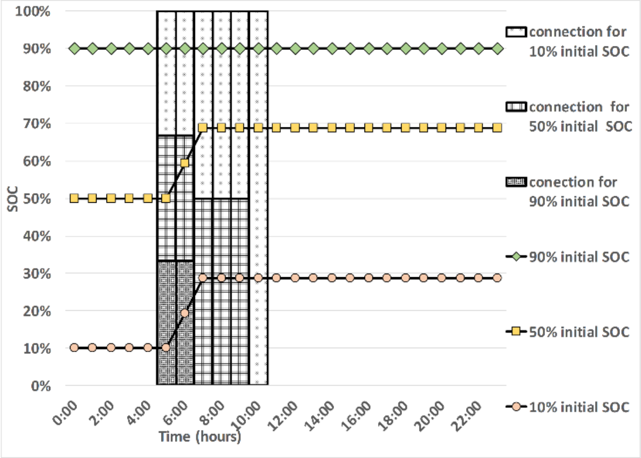

Fig. 8. SOC profile in load leveling phase for coordinated charging.

load leveling mode. In both figures, the line graphs represented the SOC of EV batteries while the bar graphs represented the connection probability of EVs. For both figures, the same connection probability and initial SOC of EV battery were used for proper comparison. In uncoordinated charging case, the constraint for the grid target loading was inapplicable but EV will abide to the connection probability constraint. Therefore, EV charged its battery whenever the vehicle was connected to the grid as shown in Fig. 7. However, if the initial SOC of EV battery was already at 90% or above, the constraint will prevent the battery from charging even though the EV was connected to the grid. This was done to protect the health of the battery.

For the coordinated scheduling case, EV battery would not receive charging in some instances even though the car was connected to power grid. This was due to preset constraints in the algorithm that prevented charging from happening. In Fig. 8, EV with 50% initial SOC was supposedly to receive charging from 05:00 to 09:00. Nevertheless, at 07:00, the charging stopped although the EV was connected because of the grid loading had exceeded the minimum grid target loading and fallen into no action region, as can be seen in Fig. 6. Therefore, the SOC of EV increased only during period from 05:00 until 07:00.

2) *Peak load shaving*

The difference between the two modes was that EV battery SOC increased in load leveling mode, while the battery SOC was reduced in peak load shaving mode. Fig. 9 illustrates the peak load shaving mode in uncoordinated case. The EV battery did not discharge since EV will only receive charging in uncoordinated case. The battery SOC of EVs was increased followed by the connection probability constraint as seen in Fig. 9. Meanwhile, the EV with initial SOC of 100% had its SOC remained unchanged because it was fully charged.

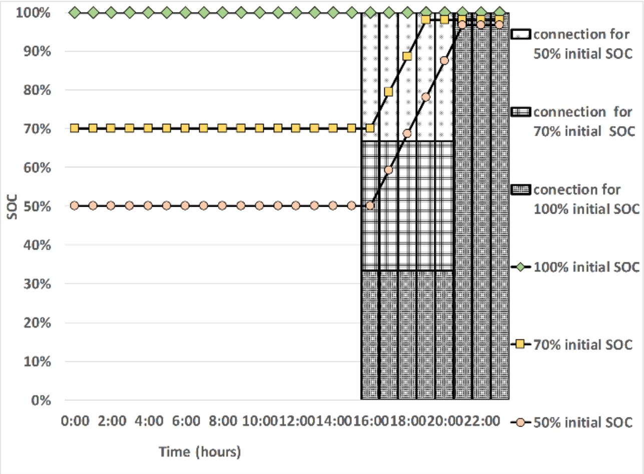

Fig. 9. SOC profile in peak load shaving phase for uncoordinated case.

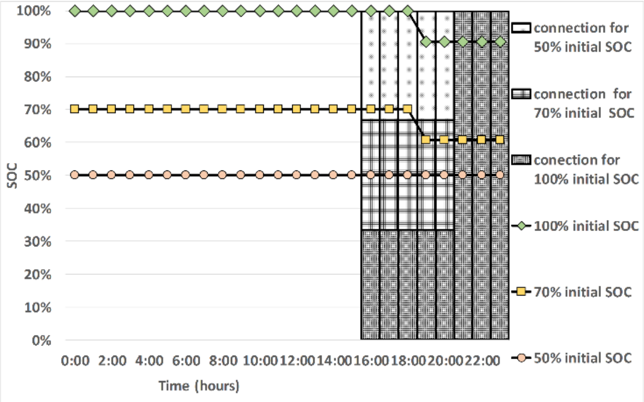

Fig. 10. SOC profile in peak load shaving phase for coordinated discharging.

For coordinated scheduling case, EVs with 100% and 70% initial SOC were supposedly to discharge their battery energy during periods from 16:00 to 23:00 and from 16:00 to 20:00, respectively. However, peak load shaving was only performed at 18:00 because that was the only time that the grid loading was higher than the maximum target loading. Meanwhile, EV with 50% initial SOC was not discharging at 18:00 to ensure that the EV battery had enough energy for propulsion.

C. *Further discussion*

Fig. 11 and 12 show the combination of different parameters for further analysis to validate the proposed algorithm. The chosen parameters were EV battery SOC, connection probability and charging/discharging power rate of EV. The line with round shape marker indicated the battery SOC of EV, the line with triangle shape marker indicated the

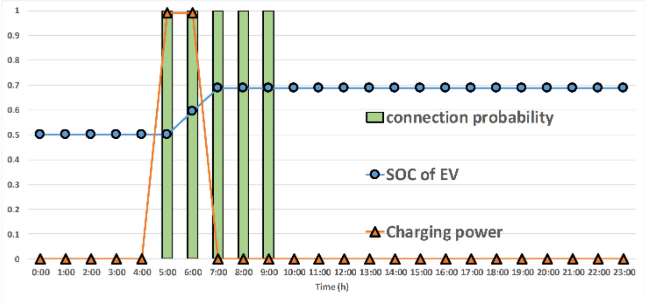

Fig. 11. Further analysis in load leveling mode.

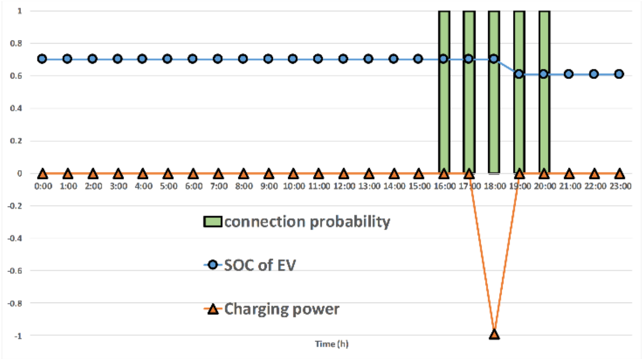

Fig. 12. Further analysis in peak load shaving mode.

charging power of EV and the bar shape marker represented the connection probability of EV. Fig. 11 shows the algorithm in the load leveling mode. The battery SOC will only increase if the EV was connected and received charging. For peak load shaving mode, the battery SOC will decrease if the EV was connected and discharging, as can be seen in Fig. 12. The charging and discharging of EV depended on the connection probability whether EV was connected to the charger. In some cases, the algorithm will ignore the connection probability status and EV did not perform any charging/discharging. This situation happened if the grid loading was equal or dropped in between the maximum and minimum target loadings. By judging the results in Fig. 11 and 12, the algorithm was validated and worked in accordance to the objective function and constraints.

V. CONCLUSION

This paper presents a V2G optimization algorithm of coordinated EV scheduling for grid load variance minimization. The uncoordinated and coordinated scenarios were compared and analyzed. For uncoordinated cases, the SOC will increase proportionally with the EV connection probability. For coordinated cases, the battery SOC was increased in load leveling mode but decreased in peak load shaving mode. Another finding was a new peak demand was introduced for uncoordinated charging scenario. Meanwhile, for coordinated scheduling scenario, the algorithm was able to achieve peak load shaving and load leveling. The SOC profile of selected EVs was presented and proved to perform as intended in both load leveling and peak load shaving modes. The grid load variance were successfully minimized and the effectiveness of the proposed algorithm was proven by the in-depth analysis.

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