Chapter 3

Advanced Charging System for Plug-in Hybrid Electric Vehicles and Battery Electric Vehicles

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Additional information is available at the end of the chapter

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Abstract

The increase of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) results in higher electricity demand for their charging. In addition, the uncontrolled and timely concentrated charging is potential to decrease the quality of electricity. This condition has encouraged the development of advanced charging system, which is able to facilitate quick charging with minimum impacts on the electrical grid. This chapter explains some issues related to charging of PHEVs and BEVs including some available charging systems, charging behaviour and developed charging system employing battery for assistance during charging. In analysis of charging behaviour, the effect of ambient temperature to charging rate is clarified. Higher ambient temperature, such as during summer, leads to higher charging rate compared to one during winter. As advanced charging system, a battery-assisted charging system for PHEVs and BEVs is also described. The evaluation results in terms of their performance to facilitate a quick, simultaneous charging as well as reduce the stress of electrical grid due to massively uncontrolled charging are also provided. This system is considered as one of the appropriate solutions that can be adopted in the near future to avoid problems on electrical grid due to massive charging of PHEVs and BEVs.

Keywords: simultaneous charging, battery assistance, charging behaviour, charging rate

1. Introduction

Electric vehicles (EVs) have received an intensive attention during the last decade due to their characteristics as vehicles as well as other additional benefits that cannot be offered by conventional vehicles. A massive deployment of electric vehicles can reduce the total consumption of fossil fuel, therefore, cuts down the greenhouse gas emission [1]. In addition, as they have higher energy efficiency, lower running cost can be achieved than conventional internal combustion-engine vehicles. Recently, value-added utilization of electric vehicles also has been proposed and developed including the ancillary services for the electrical grid and electricity support to certain energy management system [2–5]. Therefore, the economic performance of the electric vehicles can be significantly improved.

Some literatures have proposed and described well the grid integration, especially the introduction of renewable energy, and electric vehicles [6]. The fluctuating renewable energy sources, such as wind and solar, require a fast-response energy buffer to cover their intermittency as well as and to store the surplus electricity due to higher supply side than demand side. Electric vehicles are considered as the appropriate resource to balance and store these kinds of renewable energy sources [7]. The battery owned by the electric vehicles can absorb and release the electricity from and to the electrical grid, respectively, to balance the electrical grid promptly.

In general, there are four types of electric vehicles currently running and developed: (i) conventional hybrid electric vehicle (HEV), (ii) plug-in hybrid electric vehicle (PHEV), (iii) battery electric vehicle (BEV) and (iv) fuel-cell electric vehicle (FCEV). HEV combines electric motor and internal combustion engine; hence, it is also fitted with a battery to power the motor as well as store the electricity. The energy to power the motor comes from the engine and regenerative breaking. However, recently, many HEVs have been redeveloped and shifted to PHEV due to the excellent characteristics and higher flexibility of PHEV than HEV. Like HEV, PHEV also owns electric motor and internal combustion engine.

According to IEEE standards, PHEV is HEV having following additional specifications: battery storage of larger than 4 kWh, charging system from external energy source and capability to run longer than 16 km [8]. Furthermore, BEV is generally defined as the vehicle driven solely by electric motors and the source of electricity is stored and converted from chemical energy in the battery. Therefore, BEV relies on external charging and its driving range depends strongly on its battery capacity. As the battery capacity of BEV is significantly larger than HEV and PHEV, battery makes up a substantial cost of BEV. Advanced development of battery and decrease of its price is highly expected in the near future; hence, more massive deployment of PHEVs and BEVs can be realized.

On the other hand, FCEV uses only electric motor like BEV. However, it utilizes hydrogen as the main fuel that is stored in the tank. The oxidation of hydrogen produces electricity to power the electric motor and if there is any surplus it is stored in the battery. In practice, as the hydrogen refuelling can be performed in a very short time, almost similar to one of the gasoline refuelling, FCEV basically facilitates no charging from the external charger.

Although it varies, the battery capacity of PHEV is generally larger than HEV. According to survey conducted by Union of Concerned Scientists (UCS), about 50% of drivers in US drive less than 60 km on weekdays [9]. Therefore, many available PHEVs can hold for a weekday commuting without additional charging outside. In addition, although its battery capacity is lower than BEV, PHEV has higher flexibility on driving range as the power can be supplied by the engine once the battery capacity drops to certain low value. Both PHEV and BEV are believed will dominate the share of vehicles in the future. In addition, according to Electric Power Research Institute (EPRI), around 62% of vehicles will encompass of PHEVs [10].

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High share of PHEV and BEV results in high demand of electricity due to charging; hence, it strongly correlates to the supply and balancing of electrical grid.

Unmanaged charging of PHEVs and BEVs potentially results in several grid problems including over and under voltage and frequency in distribution networks, especially when individual charging of PHEVs and BEVs takes place in large number and capacity [11]. Some methods to minimize the impact of unmanaged charging of PHEVs and BEVs have been proposed and developed by some researcher. They include coordinated charging [12], demand response [13], battery-assisted charging [14] and appropriate charger distribution [15]. In addition, an integrated vehicle to grid (V2G) is also potential to avoid the concentrated charging, as well as facilitate the other services [16].

In the coordinated charging, the charging behaviour of PHEVs and BEVs are controlled by certain entities; therefore, the electrical grid can be maintained stable and balance. Further, this charging behaviour control is then correlated strongly with the V2G services, especially for load-shifting or valley filling strategy [17]. However, the algorithm for valley filling under large-scale vehicles deployment is very sophisticated; hence, computational complexity becomes a very crucial factor [18].

Demand response encourages the users or drivers of PHEVs and BEVs to manage their charging demand during peak-load hours or when the electrical grid system is at risk [19]. Therefore, it is usually divided into two types: time-based and incentive-based. The former deals strongly with the real-time pricing and critical peak pricing. On the other hand, the latter is related to the incentive due to utilization of PHEVs and BEVs for frequency regulation and spinning reserve [20]. Pricing system in the electrical grid requires accurate prediction on both supply and demand sides. Therefore, the uncertainties clarification and their impacts minimization become the major concern in demand response.

Although they are promising methods, both coordinated charging and demand response require further theoretical developments and demonstrations on to ensure the system and standard in a relatively massive control system. On the other hand, the battery-assisted charging is considered simple and applicable, due to its simplicities and convenience in structure and control.

This chapter discusses the charging system for both PHEV and BEV including the recently developed battery-assisted charger. At the beginning, available charging levels and systems for PHEVs and BEVs are explained initially in terms of charging rate and standards. In addition, the charging behaviour of the PHEV and BEV in different ambient temperature (seasons) are also described, clarifying the effect of ambient temperature to the charging rate. At the last, an advanced charging system with battery assistance is also explained including their quick-charging performance during simultaneous charging of electric vehicles.

2. Charging system for PHEV and BEV

Charging of PHEVs and BEVs correlates strongly with some parameters including charging devices, cost, charging rate, location, time and grid condition. Therefore, relevant selection and distribution of chargers are very crucial to be able to accommodate those parameters appropriately. PHEV and BEV basically share the same charging standards; therefore, there is no peculiar charger features or requirements for each vehicle. Charger is designed to be able to communicate with the vehicle to ensure the safety and appropriate electricity flow. In addition, charger also monitors the earth leakage at the surrounding ground.

On the other hand, battery management system (BMS) is installed in the vehicle as a very vital component, which is performing a thermal management, cell balancing and monitoring of over-charge and discharge of the battery pack. The battery pack consists of many individual cells having certain safe low working voltage. Therefore, it is very crucial to ensure that they are operating within the permitted range to avoid shorter battery life and battery failures, including fire.

Chargers can be installed on-board and off-board. The on-board charger limits its electricity flow because of some constraints, such as weight and space. It can be performed though conductive (direct contact through charging connector and cable) and inductive ways (using the electromagnetic field). On the other hand, the off-board charger is installed externally; therefore, there is no limitation related to size and weight. The electricity flow from the charger to vehicle is a DC flow; hence, high charging rate can be achieved.

The direction of electricity between charger and vehicle can be classified into unidirectional and bidirectional flows. The former only facilitates a single direction charging from external charger to the vehicle (battery). The latter provides the possibility of charging and discharging the electricity to and from the vehicle. Through bidirectional charging the utilization of PHEVs and BEVs is greatly widen.

Correlated to the charging rate, chargers or electric vehicle supply equipment (EVSEs) can be classified by its maximum amount of electricity possibly charged to the battery of PHEV or BEV, as follows:

a. Level-1 charging

Level-1 charging utilizes the on-board charger and is compatible with the household electrical socket and power, which generally has voltage of 100 or 200 V (AC) depending on the region. This level of charging can facilitate charging rate up to about 4 kW. This level of charging is suitable for the overnight charging at the ordinary household without the need of additional device installation.

b. Level-2 charging

This level of charging has the purpose of improving the charging rate by using the dedicated mounted-box. This level-2 charging can supply power of 4–20 kW, with a maximum voltage of 400 V (AC three phase), depending on the available capacity of local supply. Generally, this kind of chargers is installed at dedicated charging facilities including residential areas or public spaces. The charging connectors for both level-1 and level-2 chargers vary across the countries and manufactures.

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c. Level-3 charging

Different to the above levels of charging, level-3 charging is performed in DC system. DC electricity is supplied by the charger, bypassing the on-board charger. Therefore, very high charging rate, higher than 50 kW, can be achieved. Currently, there is no single standard for this kind of fast charging which is accepted by all vehicle manufactures. The charging plug (including EV socket) and the communication protocol between the charger and vehicles are different between the standards, although the basic principles are similar.

Currently, there are three major standards of charger, especially for quick charging: CHAdeMO, combined charging system (CCS) and Tesla Supercharger. The detailed specifications of each charging standard are shown in **Table 1**.

CHAdeMO was the first, DC fast charging standard originally developed by Japanese companies including Tokyo Electric Power Companies (TEPCO), Fuji Heavy Industries, Nissan, Mitsubishi Motors and Toyota, which are organized by CHAdeMO Association. CHAdeMO standard also complies with international standard of IEC 62196-3. This standard is designed only for DC fast charging. According to the development roadmap [21], high power CHAdeMO is also developed with which is able to charge with 100 kW continuous power and 150–200 kW peak power (350 A, 500 V). In addition, further higher power CHAdeMO is also planned in future (2020) which can charge with charging rate of 350–400 kW (350–400 A, 1 kV). Currently, CHAdeMO has the largest global coverage, including Japan (about 7000 chargers), Europe (about 4000 chargers) and USA (about 2000 chargers).

Properties	**CHAdeMO**	**Combo 1 (CCS)**	**Combo 2 (CCS)**	**Tesla supercharger**
DC charging				
Max. voltage (V)	500	600	850	480
Max. current (A)	125	150	200	
Connector	CHAdeMO	Combo 1 (IEC 62196-3/SAE J1772)	Combo 2 (IEC 62196-3)	Special
Max. power (kW)	50	90	170	120
AC charging				
Voltage (V)		250	400 (3 phase) 230 (1 phase)	
Current (A)		32	63 (3 phase) 70 (1 phase)	
Max. power (kW)		13	44	
Others				
Charging signal	CAN	PLC		
Charging protocol	CHAdeMO	HomePlug Green Phy		Special

Table 1. Specification of charging standards for DC fast charging.

On the other hand, CCS standards, including Combo 1 and 2, are capable to facilitate both AC charging, including level-1 and level-2 charging, and DC charging. It was developed by several European and US car manufactures in around 2012. Society of Automotive Engineers (SAE) and European Automobile Manufacturer's Association (ACEA) strongly supported this initiative with the main purpose of facilitating both AC and DC charging with only single charging inlet in the vehicle. CCS is able to facilitate AC charging at maximum charging rate of 43 kW and DC charging at maximum charging rate of 200 kW with the future perspective of up to 350 kW [22]. CCS chargers are currently installed mainly in Europe and the USA with approximate numbers of 2500 and 1000, respectively.

Tesla Supercharger uses its own charging standard. Currently, Tesla Supercharger includes multiple chargers that are working in parallel and able to deliver up to 120 kW of DC charging [23]. Tesla Superchargers are currently installed in about 800 stations, having about 5000 superchargers in total.

Other charging method for PHEV and BEV includes inductive charging, which is conducted wirelessly. The electromagnetic induction is created by the induction coil, which is charged with high-frequency AC. The generated magnetic field will induce the vehicle-side inductive power receiver; thus, the electricity can be transferred to the vehicle. Inductive charging uses the family of IEC/TS 61980 standards. The application of inductive charging is potential to eliminate the range anxiety, as well as reduce the size of battery pack. However, there are some technical barriers in its application, especially related to lower efficiency, slower charging rate, interoperability and safety.

3. General charging behaviour of electric vehicles

In general, PHEVs and BEVs adopt lithium-ion battery for energy storage due to high energy density, longer charging and discharging cycles, lower environmental impacts and more stable electrochemical properties [24]. In general, charging and discharging of lithium-ion batteries are greatly influenced by the temperature. According to literatures [25, 26], lower rates of charging and discharging occur under relatively lower temperature. This is due to the change of interface properties of electrolyte and electrode such as viscosity, density, dielectric strength and ion diffusion [27]. Furthermore, the transfer resistance also increases, which could be higher than the bulk and solid-state interface resistances, as the temperature decreases [28].

Aziz et al. [14] have performed a study to clarify the influence of ambient temperature or season to charging rate of PHEV and BEV. The study was performed during both winter and summer, using CHAdeMO DC quick charger having rated power output of 50 kW. In addition, Nissan Leaf having battery capacity of 24 kWh was used as the vehicle. The results of their study are explained below.

Figure 1 shows the obtained charging rate and battery state of charge (SOC) under different seasons. Although the rated output capacity of the quick charger is 50 kW, the realized charging rate to vehicle is lower, especially during winter. Charging during summer (higher ambient temperature) leads to higher charging rate; therefore, shorter charging time can be

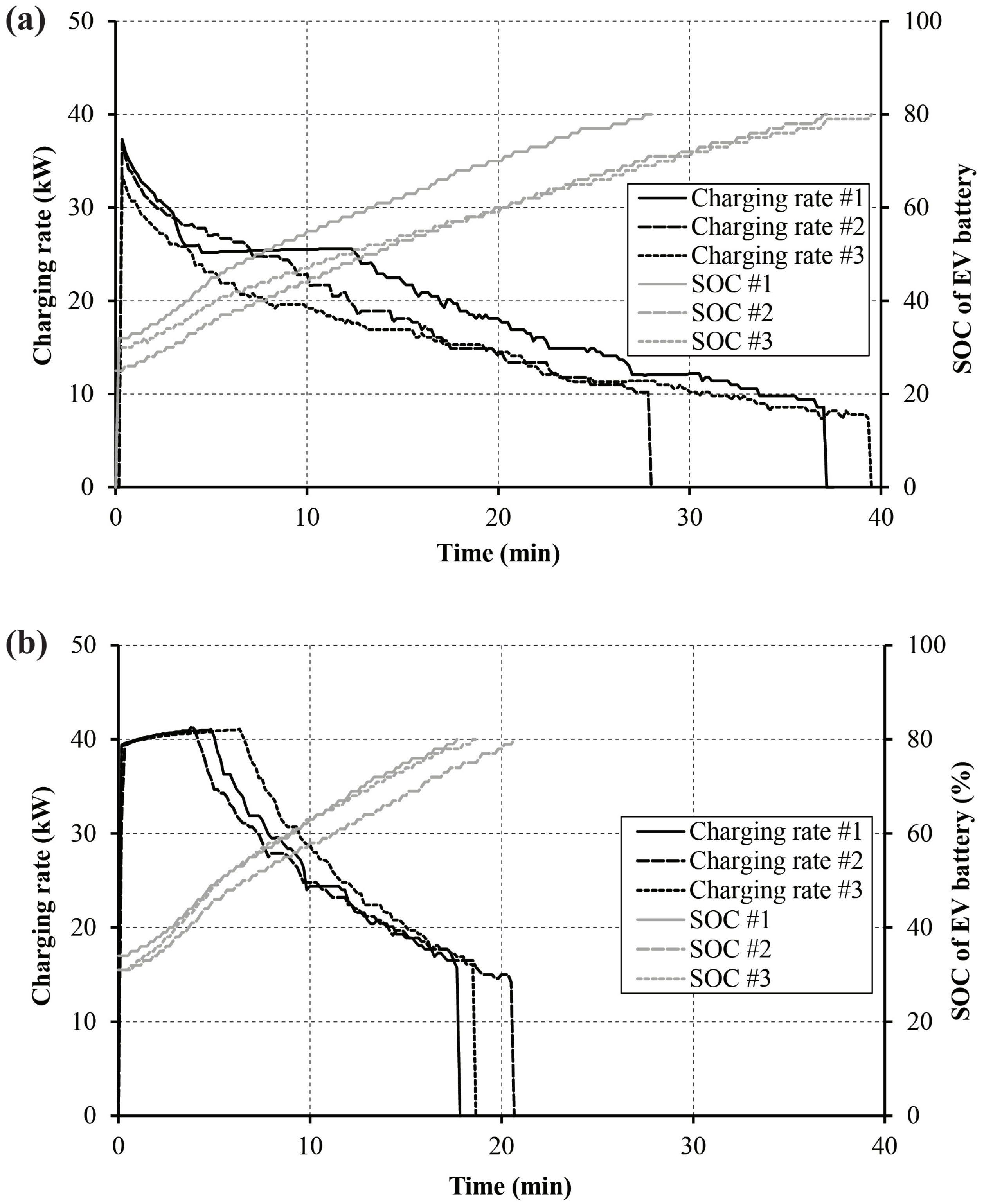

Figure 1. Charging rate and SOC change of battery in different season of charging: (a) winter, (b) summer.

achieved. To charge to battery SOC of 80% from about SOC of 30%, the required charging durations in both winter and summer are 35 and 20 min, respectively. During summer, a relatively high charging rate (about 40 kW) can be achieved up to an SOC of about 50%. However, the charging rate decreases moderately in accordance with the increase of battery

SOC. The charging rate at battery SOC of 80% is about 16 kW. On the other hand, during winter, the charging rate reaches about 35 kW instantaneously in relatively short duration and then decreases following the increase of battery SOC. In addition, the charging rate at battery SOC of 80% is about 10 kW.

Figure 2 shows both current and voltage changes during charging under different seasons. The curves of charging current are almost similar to charging rates in **Figure 1**. Lithium-ion

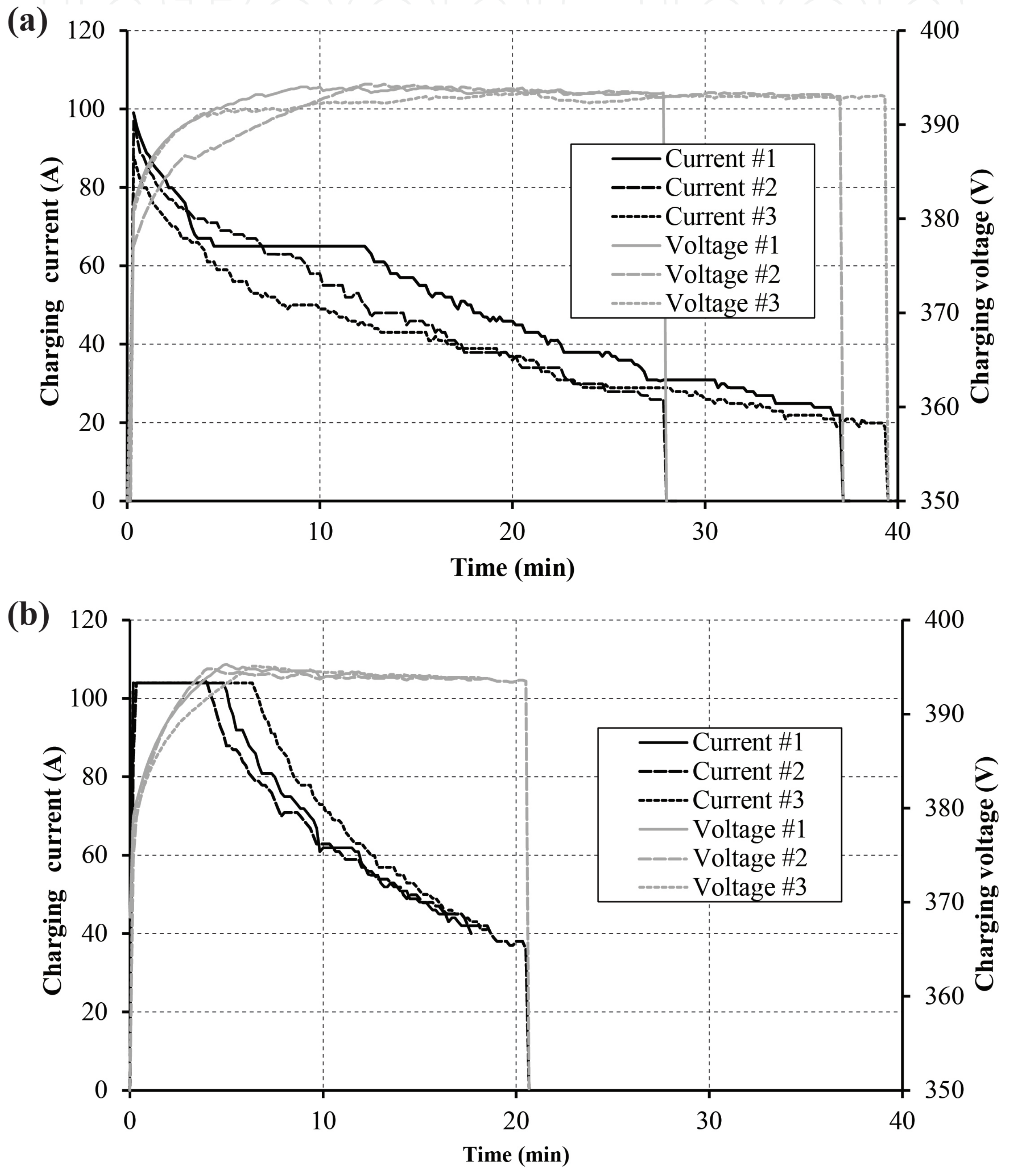

Figure 2. Current and voltage during charging in different seasons: (a) winter, (b) summer.

batteries are generally charged with a constant current (CC)–constant voltage (CV) method [22]. Charging under lower temperature leads to a gradual decrease in the charging current with charging time or increase in battery SOC. In contrast, charging under relatively warmer conditions resulted in a higher charging current, especially at low battery SOCs. Higher CC of about 105 A is obtained at the initial charging of 5–10 min (battery SOC of up to about 50%). With regard to charging voltage, although there is no significant difference between charging in both conditions, charging in a relatively higher temperature (summer) results in a higher initial charging voltage before it is settling down to a certain constant value. Therefore, the CV condition can be reached faster.

It is clear that the ambient temperature affects significantly the charging behaviour of PHEVs and BEVs. Charging under relatively high ambient temperature (such as summer) facilitates a higher charging rate, especially because of higher charging current and faster increase in the charging voltage. Hence, a shorter charging time can be achieved.

When the vehicles are near to empty, the electricity can flow at a high rate and it starts to pace down when the battery SOC is higher than 50%. In addition, it gets really slower when SOC is higher than 80%. This phenomenon is generally called as tapering.

4. Advanced charging system

The widespread deployment of PHEV and BEV charging, especially fast charging, has some critical impacts on the electrical grid including the quality deterioration of the grid and grid overload. Therefore, it is very crucial to schedule and control the charging of PHEVs and BEVs. One strategic method to charge the vehicles with minimum impact on the electric grid is to adopt a battery to assist the charging. Aziz et al. [14] have proposed and studied the battery-assisted charger (BAC) for PHEV and BEV. The battery is embedded inside the charger with the aims of improving the quick-charging performance and minimizing the concentrated load to the grid.

The developed BAC is able to limit the received power from electrical grid, as well as control the charging rate to the vehicles. It is important to manage the received power from the grid in order to avoid the electricity demand larger than the contracted capacity and also optimize the electricity demand following the grid conditions. In future, as the share of renewable energy increases, the electrical grid also faces some problems including intermittency. This leads to the requirements of energy storage and demand control.

BAC manages the electricity distribution inside the system, such as electricity received from the grid, battery and chargers, to realize the optimum performance. Therefore, BAC is able to satisfy both supply side (minimizing the grid load through load shifting and reduction of electricity cost) and demand side (fascinating the vehicle owners through quick charging, although during peak hours).

The purposes of BAC covers: (1) reducing the contracted power capacity from the electrical grid, (2) avoiding the high electricity demand during peak hours due to PHEV and BEV charging, (3) shortening the charging time, as well as the waiting/queueing time, (4) facilitating a possible participation to the grid-ancillary programs such as spinning reserve and frequency regulations, (5) facilitating as storage for surplus electricity in the electrical grid due to high generated power by renewable energy and excess power and (6) providing an emergency back-up to the surrounding community in which it is installed.

Figure 3 represents the schematic diagram of the proposed BAC (solid and dashed lines serve both electricity and information streams, respectively). A community energy management system (CEMS) correlates to the whole management of energy throughout the community, covering supply, demand and storage. It monitors and controls the energy inside the community to ensure the comfort and security of community members as well as minimize the environmental influences and social cost. Concretely, CEMS communicates with other EMSs under its authority including electricity price and supply and demand forecast. In addition, it also negotiates with other CEMS or utilities outside the community to achieve the largest benefits for the whole community.

In the electricity stream, there are three main components that are connected by high-capacity DC lines: 1) AC/DC inverter, 2) stationary battery for storage and buffer and 3) quick charger for vehicles. The AC/DC inverter receives the electricity from electrical grid and converts it to

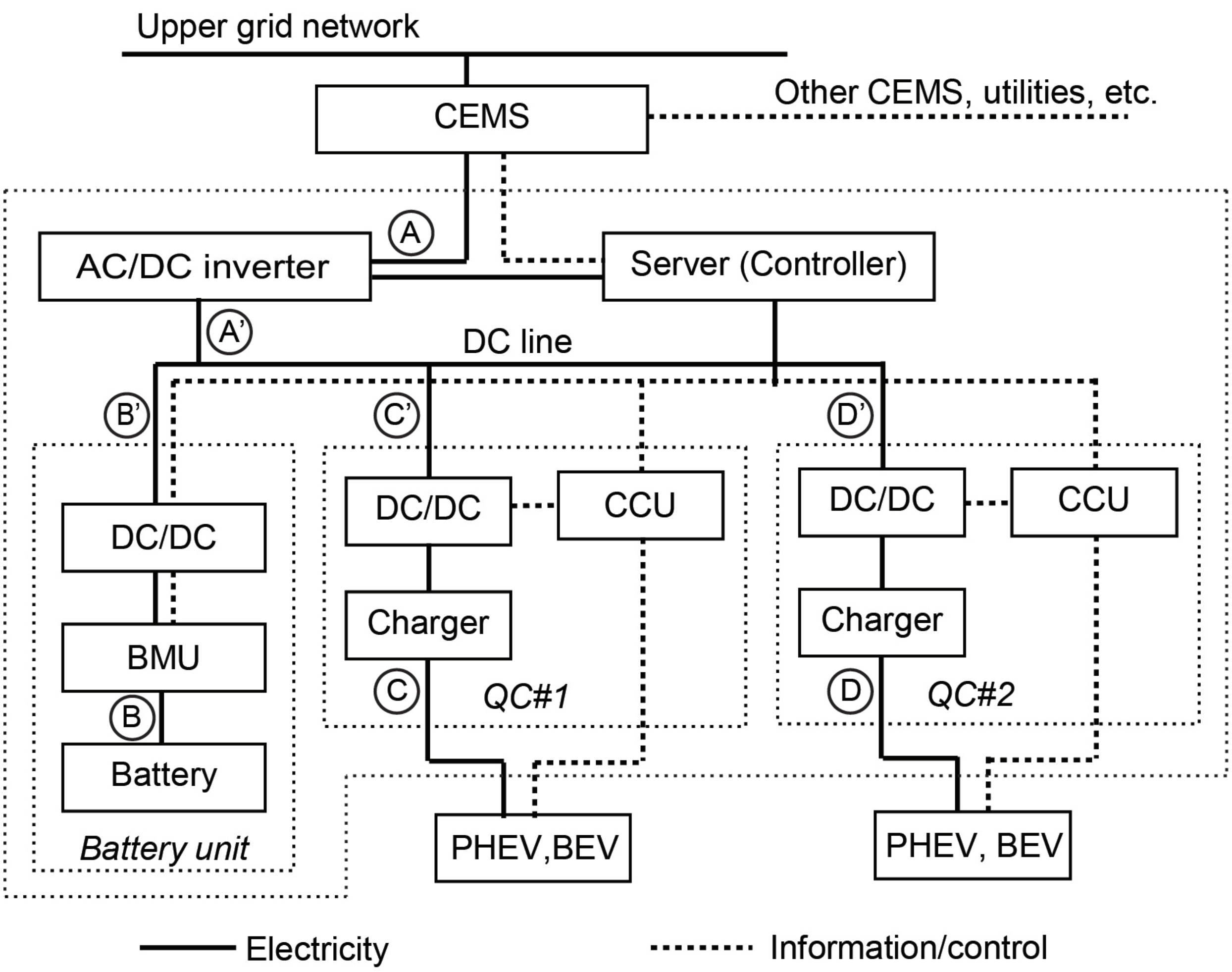

Figure 3. Schematic diagram of BAC system for PHEV and BEV.

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relatively high voltage DC, which is about 400 V. In addition, the server/controller monitors, calculates and controls the amount of electricity received from the electrical grid based on some data, including electricity price and grid condition. Furthermore, the server manages the electricity to and from the battery and the charging rate from a quick charger to the connected vehicles. In the battery unit, a bidirectional DC/DC converter and battery management unit (BMU) are introduced to facilitate controllable charging and discharging behaviours according to the control values from the server. In the quick charger, a DC/DC converter and a charging control unit (CCU) are introduced to facilitate active management during vehicle charging. The number of quick chargers can be more than one, depending on the conditions.

The battery is adopted to store the electricity in case of the presence of remaining contracted power capacity and lower electricity price (during off-peak hours). In addition, the battery discharges its stored electricity in case of high electricity price due to high demand for charging or peak hours. The stationary battery having relatively large capacity is generally employed to sufficiently facilitate simultaneous charging of multiple vehicles. Therefore, the charging service can be maintained with high quality.

According to the charging and discharging behaviours of the employed stationary battery and the source of electricity for charging, quick-charging modes of the BAC are classified as follows:

a. Battery discharging mode

Stationary battery releases its electricity to assist the charging. Therefore, vehicle charging is conducted using electricity received from the electrical grid and discharged from the stationary battery. This mode is introduced when a simultaneous quick charging of multiple vehicles occurs, especially in case of high electricity price. Electricity in the battery discharging mode can be shown as follows:

$$P_{\mathrm{grid}} + P_{\mathrm{bat}} = P_{\mathrm{QC1}} + P_{\mathrm{QC2}} + P_{\mathrm{loss}} \tag{1}$$

where P_{grid}, P_{batt}, P_{qc} and P_{loss} are electricity received from electrical grid, charged (negative value) or discharged (positive value) electricity from stationary battery, discharged electricity for quick charging of vehicles and electricity loss, respectively.

b. Battery charging mode

When there is remaining electricity (margin between the contracted power capacity and the used electricity) or the electricity prices is getting down (because of surplus electricity in the grid, night time, etc.), the stationary battery is charged to store electricity. The flow in this mode is expressed as Eq. (2).

$$P_{\mathrm{grid}} - P_{\mathrm{bat}} = P_{\mathrm{QC1}} + P_{\mathrm{QC2}} + P_{\mathrm{loss}}. \tag{2}$$

c. Battery idling mode

Stationary battery might be in the idling (stand-by) mode in case of several conditions: (a) contracted power capacity can sufficiently cover the electricity demand for simultaneous charging of vehicles (low charging demand), (b) stationary battery is empty or under certain threshold value due to high and continuous charging of vehicles (stationary battery is not able to supply the electricity unless being recharged). In the latter, BAC manages the charging rate of each charger to corresponding vehicle; hence, the contracted power capacity can be maintained avoiding any penalty. Electricity flow in the battery idling mode can be represented as follows:

$$P_{grid} = P_{QC1} + P_{QC2} + P_{loss}. \tag{3}$$

BAC always maintains that the value of P_{grid} must be lower than or maximally equal to the contracted power capacity. Furthermore, P_{loss} is the total power loss in the system due to some factors, such as AC/DC and DC/DC conversions and internally consumed electricity the system. Therefore, the value of P_{loss} in each quick-charging mode might be different.

Table 2 shows the specification of the developed BAC system and the used vehicles during experiments. Nissan Leaf having battery capacity of 24 kWh is used as the vehicle. **Figure 4** shows the results of simultaneous quick charging of two vehicles during winter conducted using conventional quick charger and BAC under contracted power capacity of 50 kW. The electricity received from the grid is kept at 50 kW or below. In case of charging using the conventional charging system, the first connected vehicle is charged with higher charging rate than the vehicles connected later. This is due to the limit on contracted power capacity as well as the available power for charging. The charging rate of the second connected vehicle increases gradually as the charging rate of the first connected vehicle starts to decrease; therefore, the total electricity can be maintained to be lower or equal to the contracted power

Component	Property	Value
Installed battery in the charger	Battery type	Li-ion
	Total capacity	64.2 kWh
	Nominal voltage	364.8 V
	Maximum charging voltage	393.6 V
	Cut-off voltage during discharge	336.0 V
	Maximum current during discharge	176 A
	SOC threshold during charge	90%
	SOC threshold during discharge	10%
Quick charger	Number	2 units
	Standard	CHAdeMO
	Output voltage	DC 50–500 V
	Output current	0–125 A
	Rated output power	50 kW
Vehicle	Vehicle type	Nissan Leaf
	Battery type	Laminated li-ion
	Total battery capacity	24 kWh
	Maximum voltage	403.2 V
	Nominal voltage	360 V
	Cell rated capacity	33.1 Ah (0.3 C)
	Cell average voltage	3.8 V
	Cell maximum voltage	4.2 V

Table 2. Specifications of the developed BACS.

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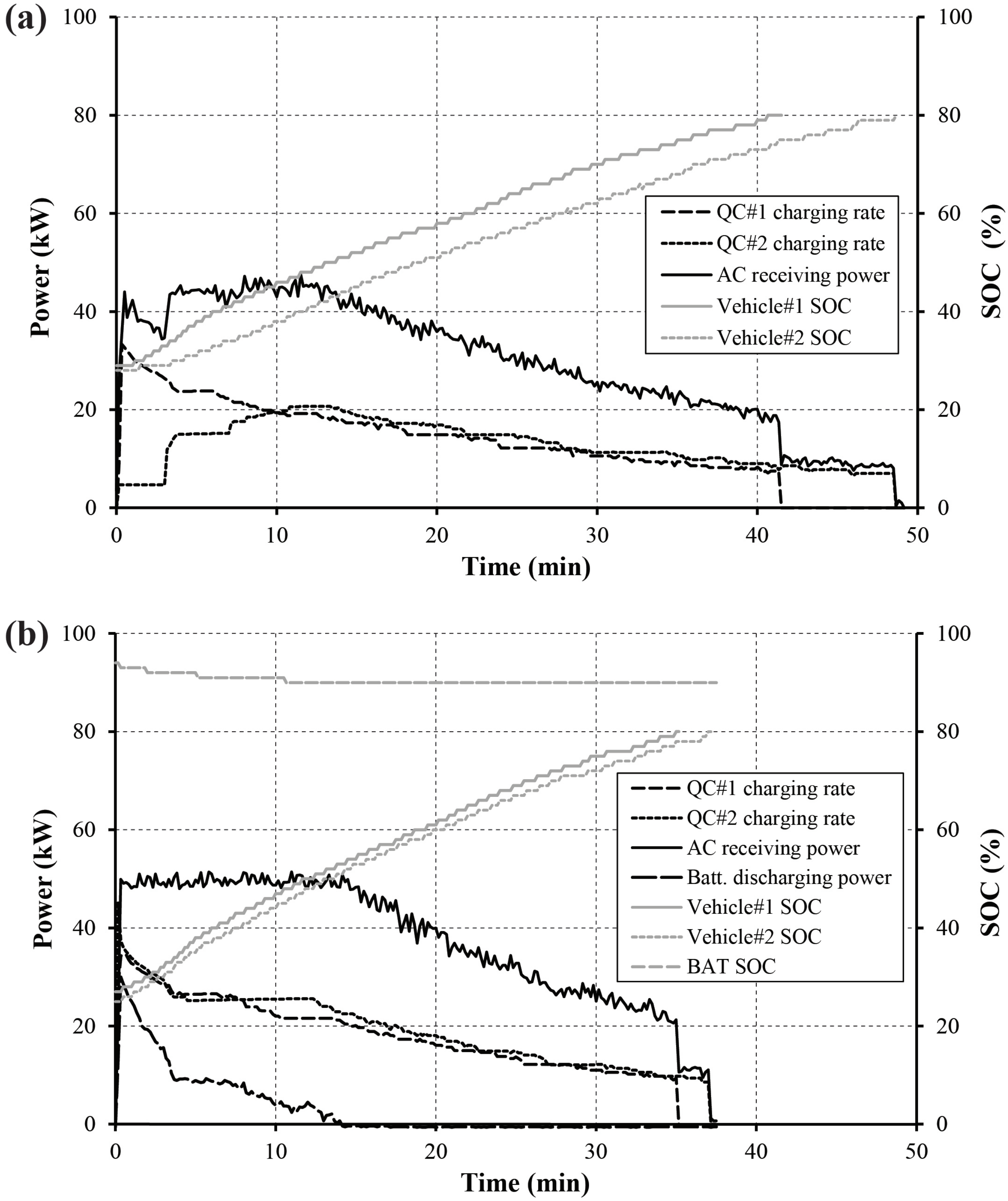

Figure 4. Charging of two BEVs during winter with different charger: (a) conventional charger, (b) developed BAC.

capacity. In addition, when the charging rate of both the connected vehicles decreases due to an increase of battery SOC, the total electricity purchased from the electrical grid decreases. The first and second vehicles are charged to SOC of 80% after charging for 40 and 50 min, respectively.

In contrast, in case of charging using the BAC, the first and second vehicles can enjoy almost the same charging rate, and both vehicles reach battery SOC of 80% in almost the same time (about 35 min). Furthermore, the electricity from electrical grid can be kept below the contracted power capacity, although the total charging rate for both vehicles is larger than the contracted power capacity. This is because the battery assisting the system was discharged to supply electricity. Hence, compared to a conventional charging system, BAC is able to achieve high-quality charging with higher charging rate during simultaneous charging.

Figure 5 shows the results of simultaneous charging of two vehicles during summer performed using conventional charging system and BAC. A same tendency with charging during

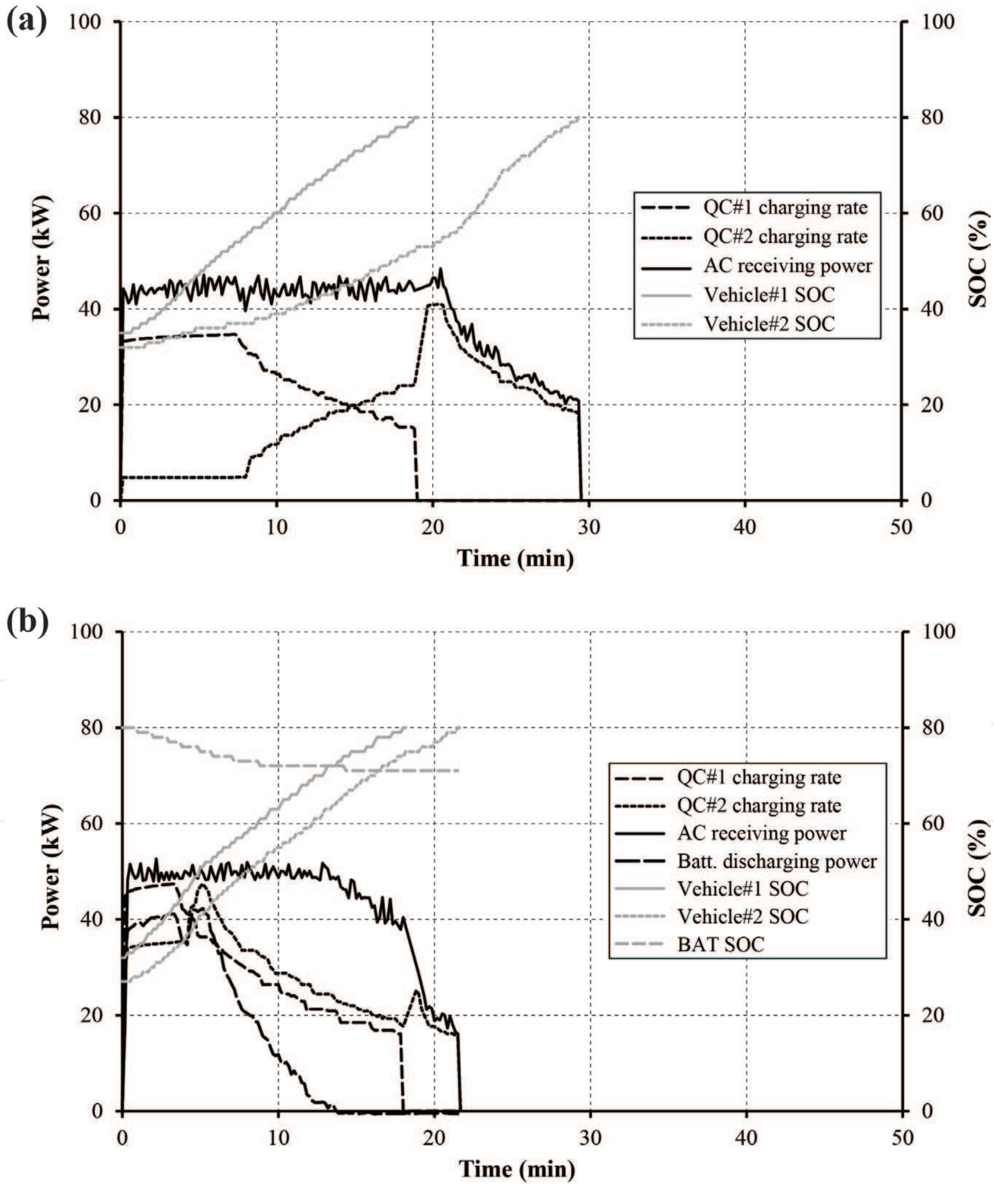

Figure 5. Charging of two BEVs during summer with different charger: (a) conventional charger, (b) developed BAC.

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winter, in the conventional charging system, the first connected vehicle enjoys a higher charging rate, while the second vehicle must contend with significantly lower charging rate because of limited contracted power capacity. The first and second vehicles reach battery SOC of 80% after charging of about 20 and 30 min, respectively.

When charging with BAC, similar to the case in winter, both vehicles could be charged almost at the same charging rate while maintaining the contracted power capacity. Both vehicles could be charged in a relatively short time of about 20 min. The stationary battery discharges its electricity until the total charging rate of two vehicles is equal or lower than the contracted power capacity.

It is clear that BAC improves the charging quality, especially during simultaneous charging of multiple vehicles. In addition, from the point of view of the electricity grid, application and deployment of BAC can reduce the stress on the grid because of the high demand for vehicle charging.

5. Simultaneous charging with developed BAC system

Figure 6 shows the demonstration test results during winter and summer under the contracted power capacity of 30 kW. Simultaneous charging of eight vehicles during summer can be conducted quicker than one during winter because of higher charging rate. However, the SOC of the stationary battery decreases considerably. It is because of the high discharging rate of the stationary battery to assist the quick chargers as well as cover the electricity demand due to limit of the contracted power capacity. In addition, the stationary battery cannot be charged because of no available marginal electricity from the electrical grid.

On the other hand, the discharging rate of the stationary battery is significantly lower during winter due to slower charging rate to the vehicles. Hence, the total charging rate of two quick chargers can be maintained to be lower than the contracted power capacity. It results in the marginal electricity that can be utilized to charge the stationary battery. Therefore, the SOC of the stationary battery in winter does not largely decrease compared to one during summer.

Figure 7 shows the simultaneous charging of eight vehicles during summer under a contracted power capacity of 15 kW. Compared to **Figure 6**, there is almost no significant change in the charging rate of vehicles, except that of the last connected vehicle. However, the discharging rate of the stationary battery is very high, resulting in significant decrease in its SOC. The SOC of stationary battery drops rapidly and reaches 10% during charging of the last two vehicles. As the result, the last connected vehicle is charged only using the electricity received from the electrical grid, with no assistance from the stationary battery. As the contracted power capacity is very low, the very last connected vehicle is not charged until the vehicle before it is charged completely. The stationary battery cannot be charged during simultaneous charging because of the lack of marginal electricity and the high charging rate of vehicles.

Based on the results of the demonstration test, the application of BAC is potential to improve significantly the charging performance of quick chargers, especially during the simultaneous charging of multiple vehicles. The balance among vehicle charging rate, contracted power capacity and stationary battery SOC seems to be very important. Therefore, PHEVs and BEVs charging demand must be forecast initially.

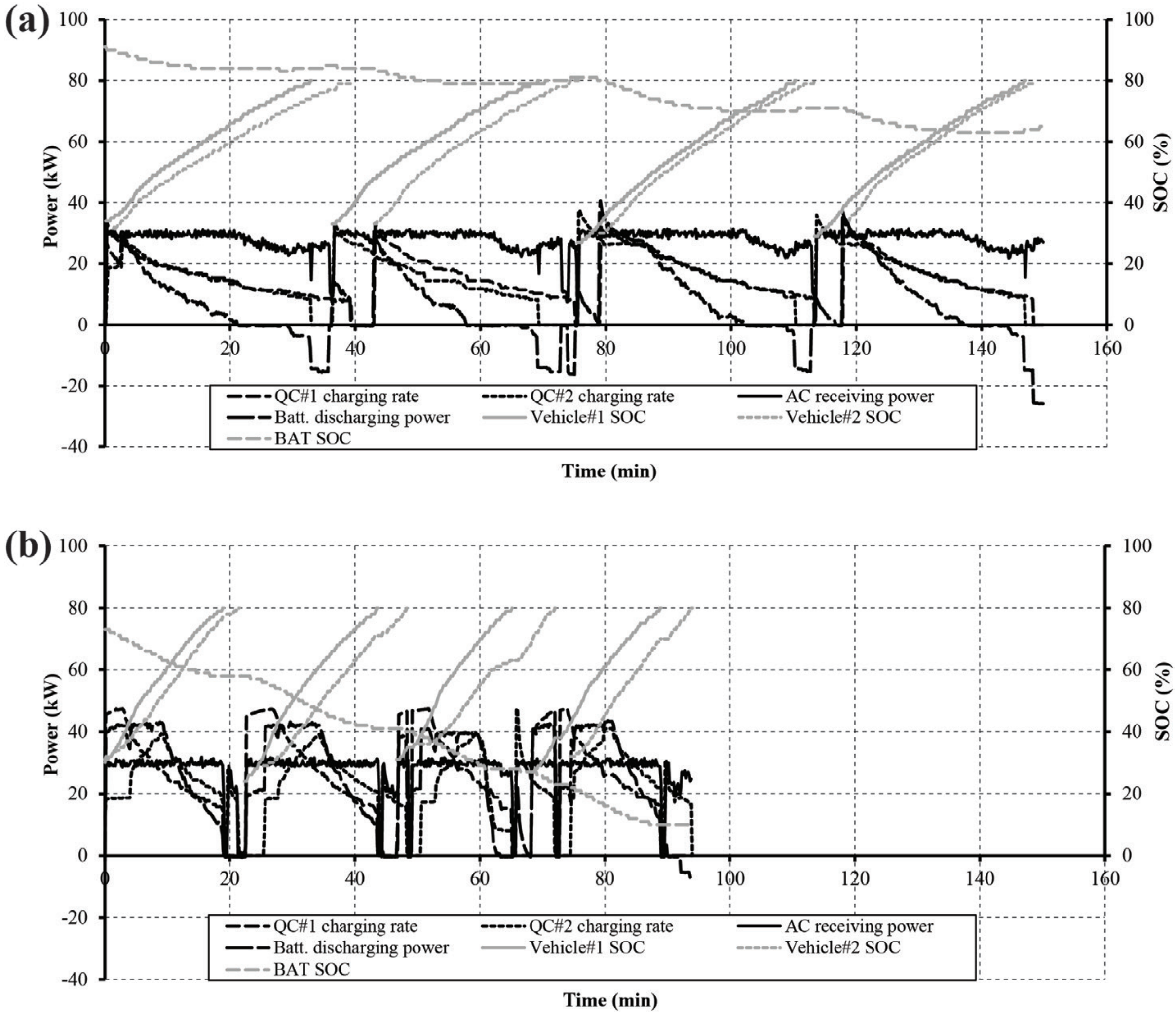

Figure 6. Simultaneous charging of eight vehicles using BAC under contracted capacity of 30 kW: (a) winter, (b) summer.

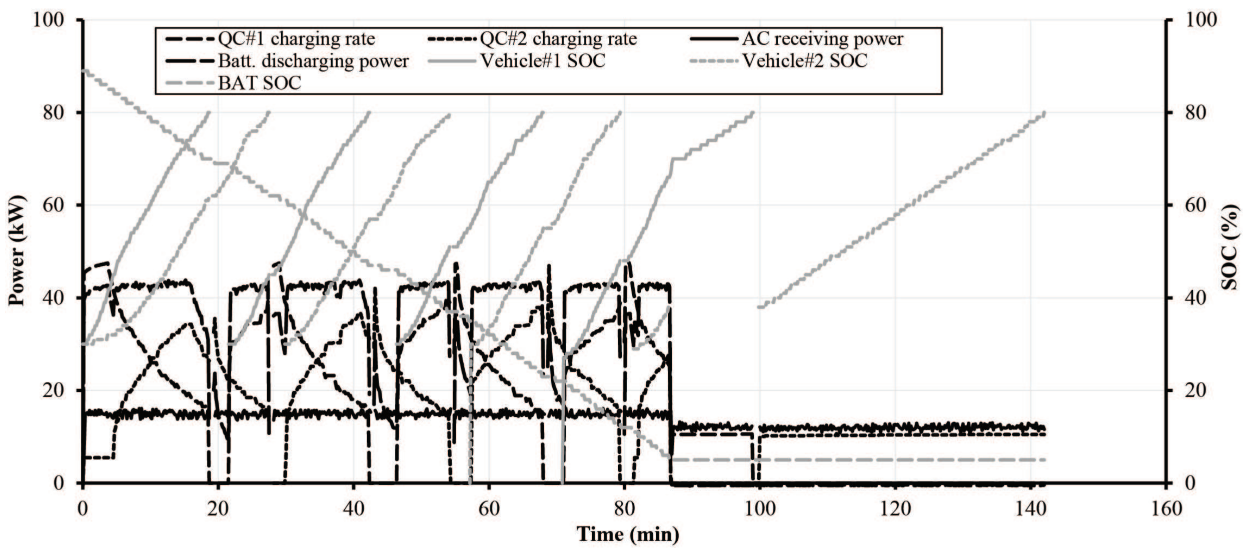

Figure 7. Simultaneous charging experiments of eight vehicles using developed BAC under contracted capacity of 15 kW during summer.

6. Conclusion

As the number of PHEVs and BEVs is massively increasing, their charging becomes a very important issue due to fluctuating and high demand of electricity. Therefore, it is very important to manage their charging through coordinated charging, battery-assisted charging and demand respond. Among these three methods, coordinated charging and demand respond require advanced theoretical development, massive demonstration and coordination in the electrical grid, therefore, they need couple of years in the future for realization. On the other hand, battery-assisted charging is considered very applicable in terms of economy and technology.

Charging behaviour of PHEV and BEV is strongly influenced by ambient temperature. Charging under relatively high ambient temperature (summer) leads to higher charging rate; therefore, shorter charging time can be realized. In addition, battery-assisted charger (BAC) has been developed especially to facilitate simultaneous charging of multiple vehicles under certain limited contracted power capacity. The demonstration test of BAC proves that it can facilitate high quality of charging, while minimizing the electrical grid stress due to massive and concentrated charging of PHEVs and BEVs.

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