

Available online at www.sciencedirect.com**ScienceDirect**

Energy Procedia 68 (2015) 429 – 437

Energy

Procedia

2nd International Conference on Sustainable Energy Engineering and Application, ICSEEA 2014

Energy storage system using battery and ultracapacitor on mobile charging station for electric vehicle

Tinton Dwi Atmaja^{a,*}, Amin^a

^a*Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences,
Komp LIPI Bandung, Bld 20, 2nd Floor, Bandung, 40135, Indonesia*

Abstract

The deployment of electric vehicle (EV) as the new era of green transportation needs a continuous support on charging infrastructure. Charging mechanism could be provided in residential area or in the public area. In public area, charging infrastructure could be in the form of fixed charging station (FCS) or delivered as a mobile charging station (MCS). MCS unit should be in the form of truck-type vehicle equipped with several charging outlet to conduct charging for EVs inside or outside FCS area. When conducting off-grid charging outside FCS area, MCS power source would come from energy storage equipped inside the MCS. There are several energy storages widely used in EV application such as battery and ultracapacitor. This paper determined that Lithium–iron phosphate (LiFePO₄) is the most suitable battery and electric double-layer capacitor (EDLC) is the most appropriate ultracapacitor for MCS application. The combination of battery and ultracapacitor provide current and voltage respond which is fit to conduct fast or ultrafast charging. This paper also provides an energy storage system to facilitate battery and ultracapacitor to be installed in MCS truck utilizing back compartment, side panels, and dash board.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Scientific Committee of ICSEEA 2014

Keywords: mobile charging station; energy storage system; lithium–iron phosphate; electric double-layer capacitor

1. Introduction

Fossil fuel depletion and global warming issues have changed the perspective of public transportation mode from internal combustion engine vehicle into greener vehicular system. Green transportation issues in the last decade has

* Corresponding author. Tel.: +62-22-2503055; fax: +62-22-2504773.

E-mail address: tinton_dwi@yahoo.com; tint002@lipi.go.id

either goes into alternative fuel development or goes back to electric based vehicle system whose development was mostly abandoned since early 1930s [1]. Electric vehicle (EV) has become one technology that dominates the sustainable transport research for its zero emission and green technology. EVs later development was not only using batteries, but also using other power sources as the hybrid electric vehicle (HEV). HEV continues its feature by equipping itself with a grid connection inlet and become Plug-in hybrid electric vehicle (PHEV) which excels previous battery electric vehicle (BEV). Grid connectivity between PHEV and the distribution grid recall the need of charging infrastructure to be deployed in the EV working range. Therefore, charging infrastructure research start emerging rapidly as EV start promising as the future transportation mode [2].

Operating charging infrastructure should need reliable interface to the distribution grid which is need cooperation from the operator and the provider. Charging infrastructure concept interface need independent system operator or regional transmission organization (ISO/RTO) who have responsibility to operate and control the bulk power system and also required coordination with energy service provider (ESP) who provide the electricity supply through the distribution grid [3]. Regardless of the charging point at the EV owner's home, the public charging point should be carefully deployed to provide optimum service to the working EV. Many research and development have been conducted to optimize the charging station as the primary public charging point [4-6]. Later researches have also considered charging station as the main subject in the smart grid development to support vehicle-to-grid (V2G) transition [7-10].

Based on its flexible mobility, charging station could be categorized into two types: fixed charging station (FCS) and mobile charging station (MCS). The FCS usually in the form of a fixed facility built in designated parking lot whether the MCS usually in the form of electric vehicle which is not affiliated with fixed parking lot. MCS concept was made to give extra capacities for fully occupied FCS and more importantly to give emergency charging to the EV outside FCS. Some case occurred when an EV determined not being able to reach nearest available FCS with its current power. That's why MCS deployment will be very helpful. In the other side, emergency call service was highly needed for the EV provider to optimize after sales support [11]. When MCS was serving an EV outside FCS with no connection to the power grid, the MCS should use energy from its energy storage to conduct charging. The energy storage carried by the MCS could be consisted of single type energy storage or multiple type energy storage. This paper will discuss the using of multiple energy storage in one MCS. The designated energy storage is battery and ultracapacitor in purpose to provide optimum charging.

2. Charging system for EV

Electric vehicle charging station basically stated in two common ways: slow charging point and fast charging point [12, 13]. However in many reasoning, charging station started to be classified in four modes based on its electrical characteristic, charging period, and charging activity method [14].

Based on the charging activity method, there are on-board method and off-board method. On-board method is conducting charging activity inside the vehicle where off-board method is using external charger to charge vehicle's ESS. Based on its location, the charging could be done in residential area (level 1), public area (level 2) or in typical place like highway (level 3). Charging level 1 usually use $120/240V_{AC}$ single phase with 6-8 hours charging time or $400V_{AC}$ three phase with 2-3 hours charging time, both in 16 A. In 32 A, it use $240V_{AC}$ single phase with 3-4 hours charging time or $400V_{AC}$ three phase with 1-2 hours charging time. Charging level 2 would use $400V_{AC}$, 63 A three phase with 20-30 minutes charging time. At the top, charging level 3 would use $50-700V_{DC}$, 100-125 A direct current with less than 20 minutes charging time. Detailed description has been shown in Table 1[14].

These criteria would be one of main consideration for designing the MCS on the right energy storage for the right charging mode. The choosing of the energy storage would affect the electrical characteristic and determine the possible given charging service.

Table 1. EV charging station classification [14].

Charging Mode	Mode 1		Mode 2		Mode 3	Mode 4
Level	Level 1		Level 2		Level 3	Level 4
Activity method	On-board		On-board		On-board	Off-board
Location	Residential area		Residential area		Public facility	Highway / expressway
Electrical characteristic	1-Phase	3-Phase	1-Phase	3-Phase	3-Phase	Direct current
	120/240 V _{AC}	400 V _{AC}	240 V _{AC}	400 V _{AC}	400 V _{AC}	50-700 V _{DC}
	16 A	16 A	32 A	32 A	63 A	100-1,250A
	3.3 kW	10 kW	7 kW	24 kW	43 kW	50-300 kW
Charging period	6-8 h	2-3 h	3-4 h	1-2 h	20-30 min	< 20 min

3. Mobile charging station

Charging Station (CS) will be defined as charging infrastructure for electric vehicle composed one or several charging poles (CPs) and their connection to the distribution grid [4]. Grid connection will be equipped with transformer, generators, or energy storage device to provide reliable service for the charged EV. The investment, operation and maintenance of EV charging infrastructure is responsibility of owner of the installed parking area and the energy supply will be responsibility of the ISO/RTO.

Based on its mobility, charging station could be classified into two type of charging station i.e. fixed charging station (FCS) and mobile charging station (MCS). FCS will be in a fixed facility the shape of small or big building equipped with several CPs. The power was gained directly from the power grid or from local energy generator such as wind turbine or photovoltaic (PV) cell. MCS will be in the shape of electric or hybrid vehicle equipped with several CPs which can travel a distance in certain range. The MCS power source may come from the connection to the power grid via FCS inlet or the MCS itself can be equipped with limited energy storage [15]. MCS can be stationed in the designated FCS which has extra parking area to be connected to the power grid and charge its energy storage.

MCS could be dispatched in two different charging modes i.e. off-grid charging mode and on-grid charging mode. When MCS was stationed in certain FCS, it was connected to the power grid and can charge nearby EV. In this state, MCS was in on-grid charging mode because it charges the nearby EV using its connection with the power grid. When the MCS was deployed to charge EV outside FCS, MCS will use its energy storage and invoke off-grid charging mode because this MCS utilize its energy storage without connected to the grid. Fig.1 shows the illustration for on-grid charging and off-grid charging.

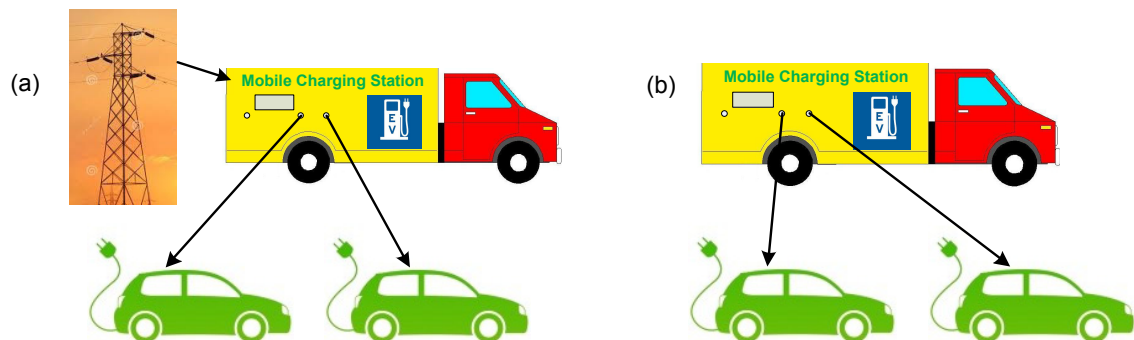


Fig.1. MCS working mode; (a) on-grid charging mode; (b) off-grid charging mode.

4. Energy storage for MCS

MCS unit should be equipped with designated energy storage to conduct optimum charging to EV. There is a lot of energy storage type to be installed in MCS unit. This paper will discuss battery and ultracapacitor as two main energy storages. There are other energy storage such as flywheel, hydrogen and fuel cell, however, the author consider that there are many early disadvantages occurred from those energy storage rather than battery and ultracapacitor. Further discussion will be needed for comparing any other energy storage against battery and ultracapacitor.

4.1. Battery for MCS

Battery is a storage device that converts chemical energy into electrical energy. There are several parameters that should take into account in selecting battery for MSC. The most important parameter is the battery capacity (ampere-hours/Ah). Besides that, the energy stored in battery (watt-hours/Wh) should be carefully considered. Today, several types of battery are available in the market which is suitable for automotive application (shown in Table 2). A lead-acid battery is the most common and cheapest battery used by electric vehicle. The use of this battery is more recommended when weight is least concern. The disadvantage of lead-acid battery is not environmental friendly either during production or disposal process.

Several types of nickel based batteries also have their advantage and disadvantage. Nickel-zinc battery is more environmental friendly but has a short life cycle. Nickel-iron battery is heavy weight, high self-discharge rate, and high maintenance cost. Nickel-cadmium (Ni-Cd) battery is not suitable for high charge/discharge rate like in automobile application because of their memory effect. Others drawbacks of this battery are high maintenance cost and contains toxic materials. The advantage of Ni-Cd is performs well under rigorous working conditions. Nickel-metal hydride (Ni-MH) is also one of the environmental friendly nickel batteries. Ni-MH has a higher self-discharge compared to Ni-Cd. In addition, Ni-MH has longer charging time and produces a large amount of heat during charging. Consequently, Ni-MH battery needs more complex charging algorithm and expensive chargers despite being widely used in EV.

One of the promising batteries could be used as energy storage devices is lithium battery. Lithium battery has light weight, high energy density, high specific energy, and high specific power. In addition, lithium batteries do not have poisonous metals (lead, mercury or cadmium) and memory effect. The main disadvantage of lithium battery is requires high production cost. In lithium battery pack, a protection circuit is needs in order to maintain safe operation. In lithium based battery, lithium metal is the most expensive but less safe than lithium-ion battery. Lithium-sulfur battery has higher energy capacity with low weight. However, lithium-sulfur has low life cycle. Lithium-ion polymer can package to wide variety of packaging shapes, reliability and ruggedness but it has a poor conductivity and a low power density. For a high power density lithium battery, lithium-iron phosphate is one of selections in other word it has higher discharge current then most of lithium battery. Besides that, lithium-iron phosphate is a superior thermal and chemical stability battery, which provides better safety characteristics than lithium-ion batteries. The lithium-titanate battery has the advantage of being faster to charge than other lithium-ion batteries.

Table 2. battery storage energy comparison [14].

	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life cycle	Energy efficiency (%)	Production cost (\$/kWh)
Lead acid	35	100	180	1000	>80	60
Nickel–cadmium (Ni–Cd)	50-80	300	200	2000	75	250-300
Nickel–metal hydride (Ni–MH)	70-95	180-220	200-300	<3000	70	200-250
Lithium–iron sulphide (FeS)	150	-	300	1000+	80	110
Lithium–iron phosphate (LiFePO ₄)	120	220	2,000-4,500	>2000	80-95	350
Lithium-ion polymer (LiPo)	130-225	200-250	260-450	>1200	80-95	150
Lithium-ion	118-250	200-400	200-430	2000	>95	150
Lithium–titanate (LiTiO/NiMnO ₂)	80-100	-	4000	18000	80-95	2,000

4.2. Ultracapacitor for MCS

Ultracapacitor (UC) or supercapacitor has a similar structure with a normal capacitor, but the difference is that UC have high capacitance (high energy capacity with factor of 20 times) than capacitor. The ultracapacitor characteristic includes maintenance-free operation, longer operation cycle life and insensitive to environment temperature variation are shown in Table 3. Currently, there are three types UC technologies commonly used in EV, that is, electric double-layer capacitors (EDLC), pseudo-capacitors and hybrid capacitors [14, 16]. The difference between those UC is in their energy storage mechanisms and their electrode materials used. The specific power density for these three types UC is almost similar around 1,000–2,000 kW/kg for 95% efficient pulse but EDLC has a more power density than other types of UC. Specific energy density of EDLC is the lowest (5–7Wh/kg). However, the other two have almost similar energy density (10 - 15 Wh/kg). The UC lifetime can reach 40 years, which is the longest among all ESS[16].

Research conducted by [14] has comparing those three ultracapacitor and stated that the use of pseudo-capacitance has being rare because such devices are not presently commercially available. Furthermore, the use of hybrid capacitor is due to its high power density. However, even though the power density of hybrid capacitor devices is relatively high (about 1,000 W/kg, 95%), the power capability has not increased proportional to the increase in energy density. That's why this paper concludes that for present availability, EDLC is the best option for MCS application.

Table 3. Ultracapacitor storage energy comparison [14, 16].

	Electrode material	Specific energy (Wh/kg)	Power density (kW/kg)	Life cycle	Energy efficiency (%)
Electric double-layer capacitor (EDLC)	Activated carbon	5-7	1-3	40 years	>95
Pseudo-capacitors	Metal oxides	10-15	1-2	40 years	>95
Hybrid capacitors	Carbon/metal oxide	10-12	1-2	40 years	>95

When EDLC comes against lithium battery in the term of cost per kWh (\$/kWh), EDLC cannot compete with batteries. However, they can compete in terms of cost per kW (\$/kW) [14]. EDLC costs of .5-1.0 cents/Farad are competitive with lithium battery costs in the range of \$500-700/kWh. EDLC cost per kW is about 7.3 \$/kW in comparative with battery cost per kW at 300 \$/kW. It is concluded that the \$/kW cost of the EDLCs are about one-fourth those of the batteries.

5. Result and discussion

5.1. Combining energy storage

Discussion on battery type has emerged Lithium–iron phosphate (LiFePO_4) as the most suitable battery for MCS and electric double-layer capacitor (EDLC) is the most proven technology for ultracapacitor. Designed in this paper is an energy storage system (ESS) using combination of battery and ultracapacitor (B-UC). Fig.2 shows the output characteristic of B-UC [17]. Fig. 3(a) show that ultracapacitor current will respond instantly according to the load current and then slowly decreased as the capacitor depleted. In the other hand, battery current increase slowly according to the load current and then increased exponentially until the time is up. Ultracapacitor current respond is very suitable to conduct level 4 charging which need short period of charging time as the ultracapacitor will discharge the whole load as the trigger invoked. Fig. 3 (b) shows how the combination of battery and ultracapacitor help the voltage change decrease slightly instead of significantly dropped when battery is working alone. This graphs shows that B-UC combination has voltage change advantages while MCS is discharging the power to the EV.

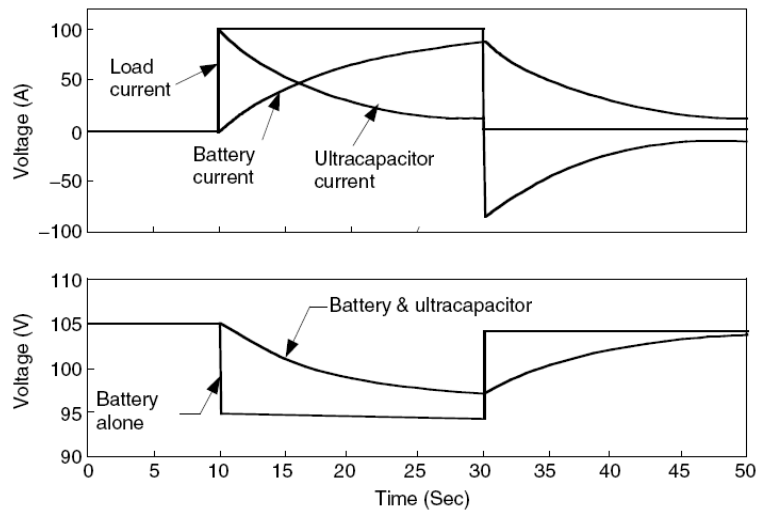


Fig.2. output characteristic for current and voltage on battery and ultracapacitor combination; (top) current step; (down) voltage change [17].

5.2. ESS architecture for MCS

An energy storage system (ESS) shown in Fig.3 was developed to facilitate both energy storages to be able to provide service for all four level of charging modes. Therefore there is two kind of charger outlet i.e. AC charger outlet and DC charger outlet. DC charger outlet will conduct fast or ultra fast charging (level 4) and equipped with a DC/DC converter. On the other side, AC charger outlet will conduct slow charging (level 1, 2, or 3) equipped with the DC/AC inverter.

Either battery or ultracapacitor provides DC output which can easily converted to undertake fast or ultrafast charging. Battery itself can be supplied to DC/AC inverter to provide slow charging. Battery monitoring will be installed to monitor the energy status and alert the operator when charged is needed. Both energy storages could be charged when MCS was connected to the power grid via its AC charger inlet. AC charger was equipped with an AC charger inlet to be able to connect to the power grid. Further development of battery management system (BMS) would optimize the use of this combined energy storage. Besides having a monitoring function, BMS also control the AC charger to determine whether the energy storage is needed to be charged. The ESS last feature is a metering and billing system to calculate the ongoing charged process and display it to the customer.

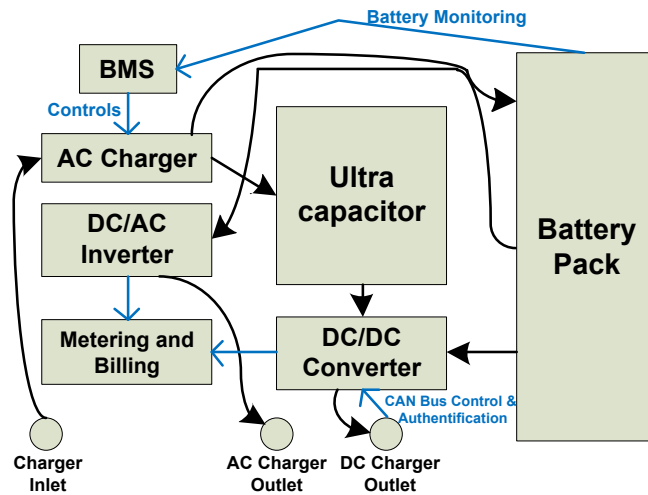


Fig.3. ESS architecture for the MCS.

5.3. ESS installation on MCS unit

MCS unit should be in the form of electric vehicle capable of carrying both battery and ultracapacitor. Most suitable vehicle type should be a truck with in duty or medium duty class. Light duty truck should be ranged between 2 – 6 ton and medium duty truck should be ranged between 6 – 12 tons. The ESS will be mounted in the back compartment containing module of battery pack, ultracapacitor, DC/DC converter, DC/AC inverter, and AC Charger. Fig. 4 illustrate the ESS installation on the MCS with Fig. 4(a) shows the top view of MCS truck and Fig. 4(b) shows the side view of the MCS truck.

The side of the truck, there are several interface to ease the charging service. AC charger outlet and DC charger outlet will be mounted in the middle of the side panel so the charging coverage area could be optimized. These charger outlets will be extended into one or several charging poles as needed. Charger inlet was located in the somewhat backward at this side panel. A metering and billing display was also located in this side panel so the customer can easily monitor the charging process. The metering and billing system should displays the duration time, charging mode, price per electricity unit, and real time claimed price. The side panel on the right and the left will have the same content and function to ease the charging system on the both side of MCS.

Beside the back compartment and side panel, the ESS also took the dashboard to monitor and control the whole ESS. Further development would be needed to provide a friendly user interface so the operator could control and monitor energy storage status, charging status, and also billing status. This dashboard module should be equipped with internet connection to supply real time information from and to MCS central. The information is needed to locate the MCS or to determine next task for the MCS.

Vehicle-to-Grid (V2G) connectivity concept was a concept to selling the electricity back to the grid [3, 18]. The PHEV would be charged at the home at the night time when the demand is low and then discharged the power back on the grid on the day time where the demand is high. This concept of selling back the power to the grid would need full cooperation from the ISO/RTO to operate bulk power system with the ESP. The dispatch of MCS unit with battery and ultracapacitor would facilitate the transition on this V2G connectivity concept so the PHEV outside the FSC, with enough power to discharge, can sell the the power back on the grid by requesting the MCS.

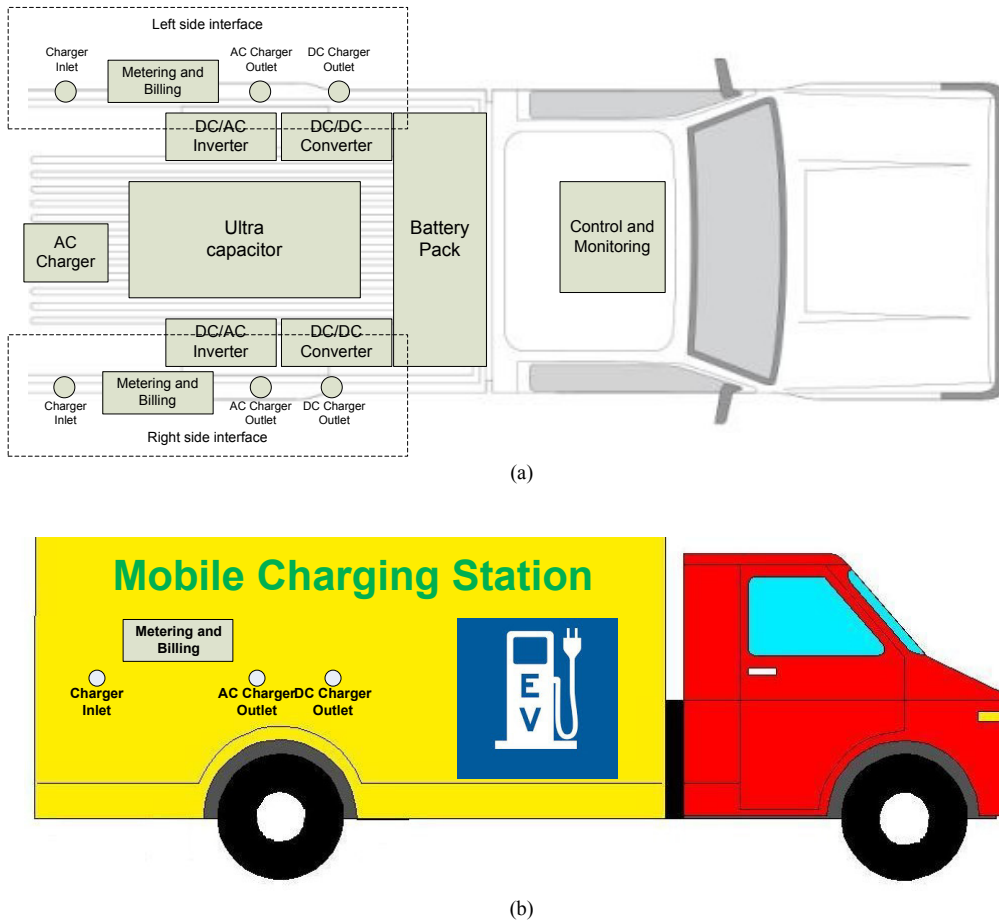


Fig. 4. MCS unit architecture; (a) top view; (b) side view.

6. Conclusion

Mobile charging station was needed to provide on-grid charging or off-grid charging for EV. While on the off-grid charging mode, MCS power source comes from the energy storage mounted on the back compartment. Lithium-iron phosphate (LiFePO_4) was the most suitable battery for MCS application because this battery has superior thermal and chemical stability and, most importantly, this battery has higher discharge current than other batteries. In ultracapacitor consideration, the most appropriate ultracapacitor is electric double-layer capacitor (EDLC) because of having high power density. The combination of those two energy storage could conduct all four charging levels as the DC/DC converter was needed to conduct level 4 charging and DC/AC inverter was needed to conduct level 1, 2, and 3 charging. This MCS was equipped with AC charger so it can charge the energy storage when MCS is connected to the power grid. MCS also equipped with a battery monitoring system to control and monitor the using of the energy storage. ESS should be installed in a truck type vehicle and utilize the back compartment, side panel, and the dashboard. The battery pack, ultracapacitor, DC/DC converter, DC/AC inverter, and AC Charger should be mounted in back compartment. AC charger outlet, DC charger outlet, AC charger inlet, and metering and billing display will be mounted in the middle of the side panel. The dashboard will show the whole control and monitoring system via general user interface. Hopefully, installing battery and ultracapacitor on the MCS unit could facilitate smarter transportation system that supports future electricity distribution system like smart grid and V2G concept.

Acknowledgement

The Authors would like to thank all researchers in research centre for electrical power and mechatronics, Indonesian Institute of Sciences for supporting the completion of this paper.

References

- [1] CEM, *et al.*, *Global EV Outlook - Understanding the Electric Vehicle Landscape to 2020*: International Energy Agency (IEA) and the Electric Vehicles Initiative of the Clean Energy Ministerial (EVI), 2013.
- [2] EPRI and NRDC, "Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions," July 2007.
- [3] C. Guille and G. Gross, "A conceptual framework for the vehicle-to-grid (V2G) implementation," *Energy Policy*, vol. 37, pp. 4379-4390, 2009.
- [4] T. G. S. Román, *et al.*, "Regulatory framework and business models for charging plug-in electric vehicles: Infrastructure, agents, and commercial relationships," *Energy Policy*, vol. 39, pp. 6360–6375, October 2011.
- [5] Y. M. Nie and M. Ghamami, "A corridor-centric approach to planning electric vehicle charging infrastructure," *Transportation Research Part B: Methodological*, vol. 57, pp. 172–190, November 2013.
- [6] J. Dong, *et al.*, "Charging infrastructure planning for promoting battery electric vehicles: An activity-based approach using multiday travel data," *Transportation Research Part C: Emerging Technologies*, vol. 38, pp. 44–55, January 2014.
- [7] J. Yang, *et al.*, "An improved PSO-based charging strategy of electric vehicles in electrical distribution grid," *Applied Energy*, vol. 128, pp. 82–92, 1 September 2014.
- [8] P. Sadeghi-Barzani, *et al.*, "Optimal fast charging station placing and sizing," *Applied Energy*, vol. 125, pp. 289–299, 15 July 2014.
- [9] S. G. Nurre, *et al.*, "Managing operations of plug-in hybrid electric vehicle (PHEV) exchange stations for use with a smart grid," *Energy Policy*, vol. 67, pp. 364–377, April 2014.
- [10] L. Jian, *et al.*, "A scenario of vehicle-to-grid implementation and its double-layer optimal charging strategy for minimizing load variance within regional smart grids," *Energy Conversion and Management* vol. 78, pp. 508–517, February 2014.
- [11] Wired.com. (2011). 'Quick Charge' Trucks Will Save Your Stranded EV. Available: http://www.wired.com/images_blogs/autopia/2011/07/AAA-mobile-EV-charger.jpg
- [12] M. o. London, "London's Electric Vehicle Infrastructure Strategy," ed. London, December 2009.
- [13] M. o. London, "London - An Electric Vehicle Delivery Plan for London," ed. London, May 2009.
- [14] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 82-102, 2013.
- [15] S.-N. Yang, *et al.*, "Mobile charging information management for smart grid networks," *International Journal of Information Management*, vol. 33 pp. 245–251, 2013.
- [16] A. Burke, "Ultracapacitor Technologies and Application in Hybrid and Electric Vehicles," *International Journal of Energy Research*, vol. 34, pp. 133–151, February 2010.
- [17] M. Ehsani, *et al.*, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*: CRC PRESS, 2005.
- [18] T. D. Atmaja and M. Mirdanies, "Vehicle-to-Grid Transition on Plug-in Hybrid Electric Vehicle Technology as the Support of Distributed Generation System," in *Proceeding of Seminar on Engineering on Energy, Mechatronics, and Vehicular Technology*, 2013, pp. 319-324.