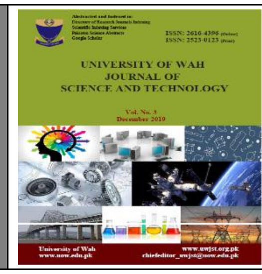
UW Journal of Science and Technology Vol. 3 (2019) 35-40
ISSN: 2523-0123 (Print) 2616-4396 (Online)

University of Wah
Journal of Science and Technology

www.uow.edu.pk



A Smarter Energy Management System for Lithium-ion Battery and Super Capacitor Based Hybrid Energy Storage System

Muhammad Umair Ali, Sadam Hussain, Sarvar Hussain Nengroo and Hee-Je Kim

***Abstract*— The electrical energy storage system is still the tailback for the commercialization of many electrical appliances. The battery storage system (BSS) has a high energy density but lower power density, and vice versa in case of the super capacitor storage system (SCSS). In this work, a hybrid energy storage system (H-ESS) with smart energy management system (EMS) is designed. The proposed EMS is based upon fuzzy logic that controller smartly distribute the power between BSS and SCSS depending upon the state of charge (SOC). This technique reduces the stress (high value current) of BSS during the challenging condition to prolong its life. The methodology is simulated on MATLAB™ Simulink 2019. The simulation and comparative analysis with other EMS techniques have been carried out and the results showed that the smart EMS reduces almost 17% stress on BSS. This technique can be used to design EMS for other electrical appliances such as electric vehicles, electric wheelchairs, smart grid system, etc.**

***Index Terms*— Hybrid energy storage system (H-ESS), energy management system (EMS), fuzzy logic controller, and state of charge (SOC).**

I. INTRODUCTION

The need for electrical energy is increasing exponentially in the last few years, and it conduces to steadily increase in the future due to growth in population and economy [1-3]. According to a report, the annual energy demand of the world will increase 35% at the end of 2040 [4]. Now a days, fossil fuels are the foremost source of electrical power generation and transportation. However, the use of fossil fuels will reduce due to climate effects, high prices, and depletion of crude oils. To surmount these concerns, progress in technology has yielded diverse liberties of generating energy using renewable energy (RE) sources [5-6]. In the transportation industry, electric vehicles (EVs) are developed to reduce environmental pollution and energy crisis concerns of the conventional vehicle [7]. In 2018, according to a report, the generation of electrical energy from RE and fossil fuels sources will be equal [8]. The RE sources are episodical, so RE and EVs also require energy system to store electrical energy [9]. There are two main categories of the electrical energy storage system (ESS): (i) Batteries storage system (BSS) and (ii) Super capacitor storage system (SCSS) [7].

There are various types of BSS, reported in the literature such as lithium-ion (LI), zinc-bromine flow (ZBF), vanadium redox flow (VRF), nickel-cadmium (NiCd), sodium nickel chloride (NaNiCl), sodium sulphur (NaS), and lead-acid (LA) [10]. The comparison of the various properties of BSS is presented in *Fig. 1*, which shows that the lithium ion battery storage system (LIBSS) has the best energy and power density, better life cycle, and reasonable cost [9, 10]. On the other hand, the SCSS has the energy and power density in the range of 4–14 Wh/L and 3000–40000 W/kg, respectively [11]. The charging and discharging time of SCSS is almost 20 times lesser than the LIBSS. The LIBSS and SCSS are compared in Table I.

Table I shows that the SCSS has very high-power density and LIBSS has very high energy-density. In EVs, the high current value is needed during uphill climbing and in high acceleration mode, which degraded the LIBSS resulting in the shorting the life span of LIBSS. The combination of LIBSS and SCSS can be utilized to tackle these challenging working conditions in EVs as well as in smart grids [12]. This combination of LIBSS and SCSS is also known as hybrid-ESS (H-ESS). Besides it, an energy management system (EMS) is needed to smartly exploit the properties (high power density of SCSS and high energy density of LIBSS) of H-ESS. The main working of smart EMS is to reduce the stress (high value current) on the

Manuscript received; Sept 7, 2019; accepted Oct 10, 2019.

M. U. Ali (email: umairali.m99@gmail.com), S. Hussain (email: sadamengr15@gmail.com), S. H. Nengroo (email: ssarvarhussain @gmail.com), and H. J. Kim (email: heeje@pusan.ac.kr) are affiliated with School of Electrical Engineering, Pusan National University, Busandaehak, Busan 46241, South Korea.
Corresponding author email: umairali.m99@gmail.com

LIBSS during high demanding conditions [13].

In a study [14], the H-ESS has been categorized into three different categories (i.e passive H-ESS, semi active H-ESS, and fully active H-ESS) based upon working. Wavelet-fuzzy logic controller to design an EMS was based on the frequency decoupling method was utilized in [15]. In passive H-ESS, the LIBSS and SCSS can be easily coupled directly without using any converter [16]. The passive H-ESS is very cheap at the loss of the system's uncontrollability, whereas the semi-active H-ESS is the tradeoff between the performance and the cost. In semi active H-ESS, one converter is used to partially control the H-ESS. It can only control the output power of a single ESS (LIBSS or SCSS). The fuzzy logic controller to charge the LIBSS was utilized and a rule base EMS was designed to draw the discharging current for an electric wheelchair in [17]. The complete controllability of the power utilization of H-ESS is the main drawback of semiactive strategy. The fully active H-ESS addressed the controllability issues of the passive H-ESS [18]. Dual active bridge based converter were also proposed to control the H-ESS [19]. However, the fully active H-ESS has the complete control of H-ESS, it increases the complexity of the system [14]. To address this issue, a smart and simple controller is required for smart distribution of currents in H-ESS.

In this work, a fuzzy logic-based, fully active H-ESS is proposed to smartly distribute the output current of H-ESS between LIBSS and SCSS depending upon their SOC. The fuzzy logic controller regularly monitors the SOC of the LIBSS and SCSS. The rule-base of the controller is designed in such a way that it can reduce the stress of LIBSS by utilizing the high-power density of SCSS in demanding condition to prolong its life cycle. The MATLAB™ Simulink 2019 was used to implement and verify the smart EMS. The results shows that the proposed system reduces the stress of LIBSS in H-ESS.

II. Design of Smart EMS

The proposed system consists of LIBSS, bank of SCSS, DC-DC converters, DC bus bar, two SOC measured units, and fuzzy logic based smart EMS, as shown in *Fig. 2*.

The smart EMS regularly monitors and measures the SOCs of SCSS (SOC_{SCSS}) and LIBSS (SOC_{LIBSS}) by using SOC measurement unit. These measured SOCs are fed to the smart fuzzy logic-based controller and the fuzzy logic controller generates the PWM signals for the converters, depending upon the fuzzy rule-base in order to find the optimum discharge currents value for both ESSs.

Table I
Comparison Of Libss And Scss [11]

Property	LIBSS	SCSS
Energy Density (Wh/L)	200–400	4–14
Power Density (W/kg)	1500	3000–40000
Voltage (V)	3.6–4.3	2.7–3.5
Life Cycle (years)	5–10	10–15

A. *Fuzzy Logic Controller Design*

Since fuzzy logic controller is bormally simpler, easily implementable, and robust, but it also does not need a mathematical model of the system for its working [20], which make it well suited for anticipating the behavior of any non-linear system. The fuzzy logic controller can easily be categorized as; i) Fuzzifier, ii) Rule base, iii) Inference engine, and iv) Defuzzifier as shown in *Fig. 3* [21].

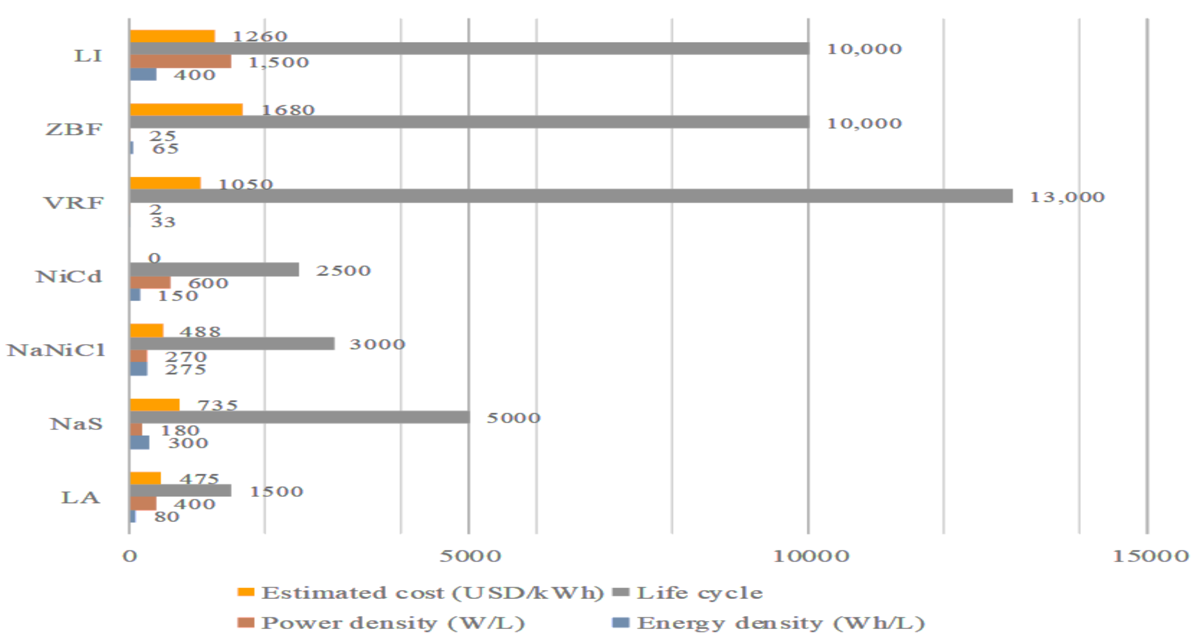


Fig. 1. Properties of various BSS [9, 10].

UW Journal of Science and Technology Vol. 3 (2019) 35-40
ISSN: 2523-0123 (Print) 2616-4396 (Online)

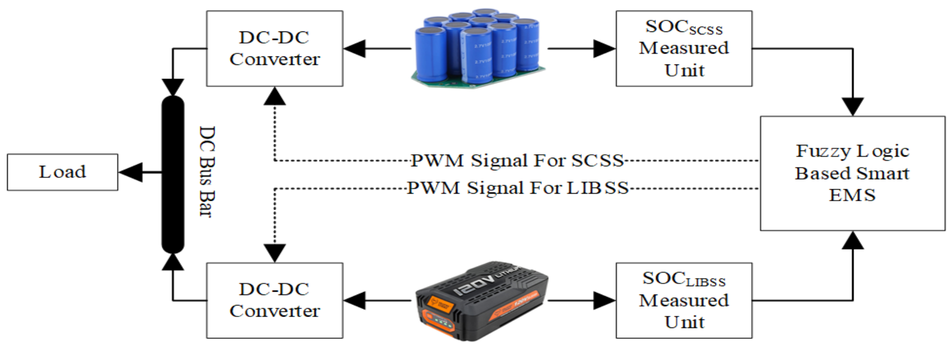


Fig. 2. Schematic diagram of proposed EMS.

Fuzzifier: it changes the input values SOC_{SCSS} and SOC_{LIBSS} into crisp values $a_b(y)$ and $a_d(x)$ using the membership function of linguistic fuzzy sets, respectively. Rule base: the main controlling mechanism of the system is stored in the rule base. It needs a lot of expertise to design the rule base of the fuzzy logic controller. The rule-base of the proposed system is listed in Table II and III.

Fuzzy interface engine: it changes the crisp values $a_b(y)$ and $a_d(x)$ into output crisp value $a_i(z)$ using control law saved in the rule-base, as shown in *Fig. 3*.

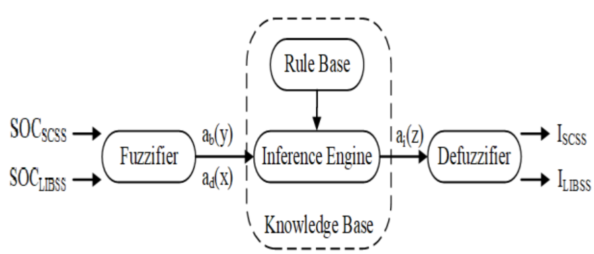


Fig. 3. Overview of fuzzy logic controller.

TABLE II
RULE BASE FUZZY LINGUISTIC VARIABLE FOR LIBSS

		SOC_{LIBSS}				
	I_{LIBSS}	VL	L	M	H	VH
SOC_{SCSS}	**VL**	VL	M	M	H	VH
	L	VL	L	M	M	H
	M	VL	L	L	M	H
	H	VL	L	L	M	M
	VH	VL	VL	L	M	M

Table II and III list the five rule-base linguistic variables: VL (very low), L (low), M (medium), H (high), and VH (very high).

Defuzzifier: it converted $a_i(z)$ to the true value of LIBSS current and SCSS current (I_{SCSS}) by using the membership function of the proposed fuzzy logic controller.

The conversion of true input values to crisp value and crisp value to output values using the membership function is shown in *Fig. 4*. The max-min and center of gravity method are used for fuzzification and defuzzification process [22].

TABLE III
RULE BASE FUZZY LINGUISTIC VARIABLE FOR SCSS

		SOC_{LIBSS}				
	I_{SCSS}	VL	L	M	H	VH
SOC_{SCSS}	**VL**	VL	VL	VL	VL	VL
	L	L	L	VL	VL	VL
	M	M	L	L	VL	VL
	H	H	M	L	L	VL
	VH	VH	H	M	M	L

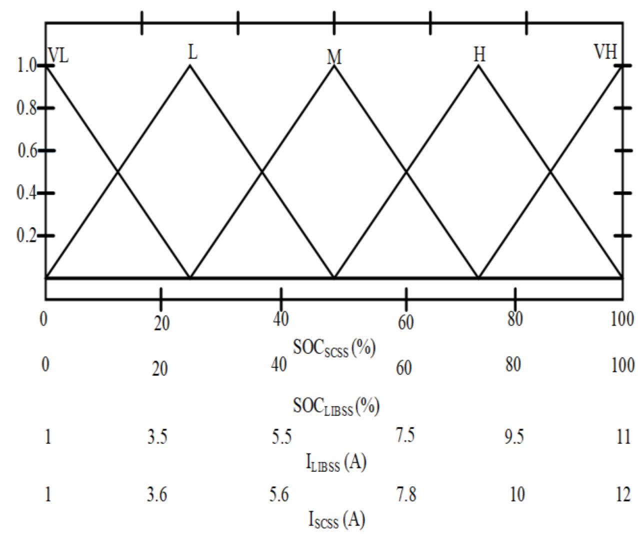


Fig. 4. Values of membership function of proposed fuzzy logic controller for smart EMS.

The 3-dimensional output surfaces of the I_{LIBSS} and I_{SCSS} is shown in *Fig. 5a and Fig. 5b.*

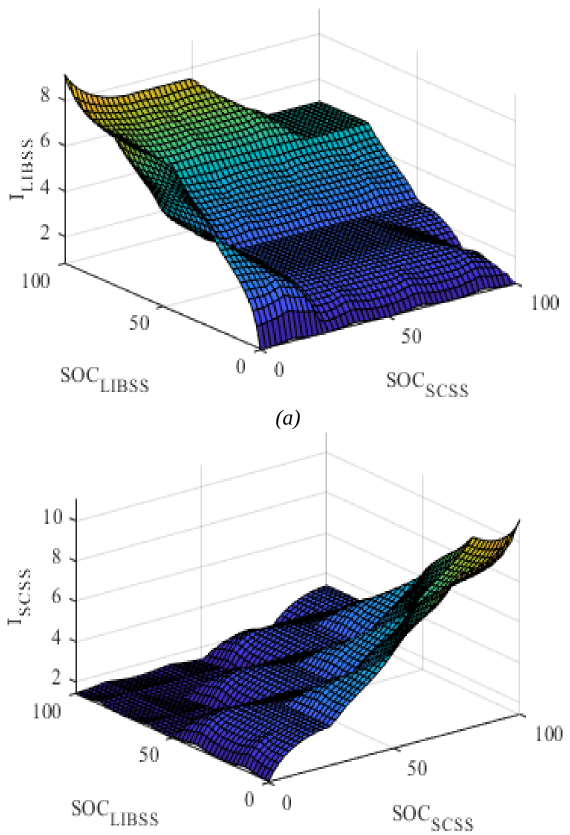
B. State of Charge (SOC) Estimation

The SOC of the ESS, is interpreted as the proportion of current capacity at any instant to the maximum nominal capacity of the ESS [23]. Several methods can be found in the literature for SOC estimation such as book keeping, model-based, computer intelligence-based, and direct measurement methods [9,24]. In this work, a simple coulomb counting SOC estimation method (a type of book- keeping method) is adopted to find the SOC of both the ESS. The discrete mathematical form of coulomb

ISSN: 2523-0123 (Print) 2616-4396 (Online)

counting method can be expressed as follows:

$$SOC^{k} = SOC^{k-1} - \frac{I_{ESS}T}{\text{Maximum Nominal Capacity}} \quad (1)$$



(a)

(b)

Fig. 5. 3-D surfaces; a) I_{LIBSS} and b) I_{SCSS}.

The SOC^{k} is the SOC at current time step, I_{ESS} is the current of ESS (I_{ESS} is the I_{LIBSS} and I_{SCSS} in case of LIBSS and SCSS, respectively), and T is the sampling time in equation (1).

III. Simulation Results

The MATALB™ Simulink 2019 was used to implement and validate the proposed smart EMS. Firstly, the stored data of LIBSS and SCSS was used to find the SOCs of both EMS. The estimated SOC of both ESS was then fed to the fuzzy logic controller. The proposed controller was designed as discussed in Section II. The fuzzy logic controller calculates the optimum values of discharging current of both ESS depending upon SOCs. The Simulink model of the proposed system is shown in *Fig. 6*.

In this work, the only aim is to design a smart controller to minimize the stress of LIBSS, and the power of SCSS is smartly utilized in challenging condition to prolong the lifetime of LIBSS. The designing of the DC-DC converter is not part of this research. The fuzzy logic controller can easily generate the PWM signals for the converters to draw the currents.

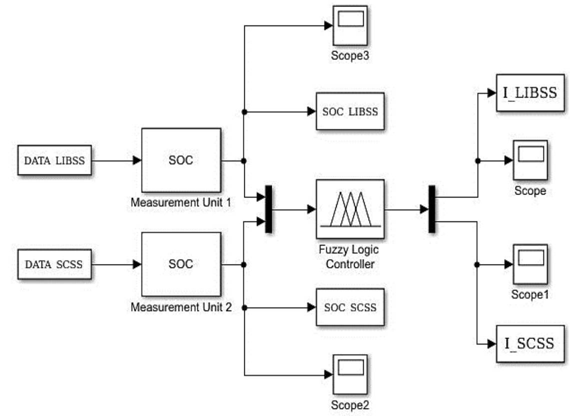
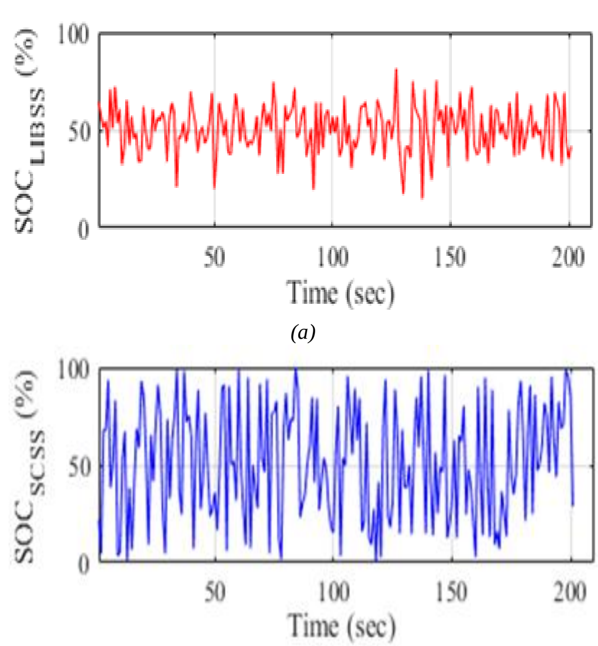


Fig. 6. Simulink model of proposed EMS.

Fig. 7 shows the results of the proposed smart EMS for H-ESS. *Fig. 7(a) and Fig. 7(b)* show the SOCs of LIBSS and SCSS, respectively. *Fig. 7(c) and Fig. 7(d)* show the current profiles of both ESS types. *Fig. 8* compares the current values of proposed and passive H-ESS.

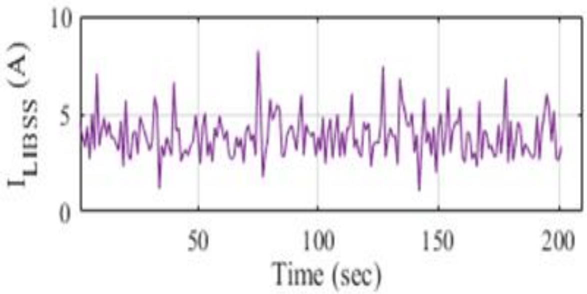
IV. Discussion

In a passive system, the SCSS and LIBSS are connected in parallel without any current control mechanism as discussed in Section I. The passive system is a low-cost ESS, and it has more advantages in contrast to standalone LIBSS. But the issue of uncontrollability of power-sharing between both the ESS cannot be resolved due to direct coupling of LIBSS and SCSS. On the other hand, the proposed fully active system has the capability of full control on both ESS. The fuzzy logic controller based upon the SOC levels is designed to reduce further stress on LIBSS as compared to the passive system.

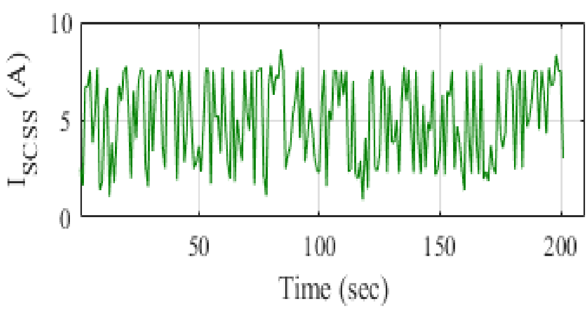


(a)

(b)



(c)



(d)

Fig. 7. Simulation results of the proposed EMS; a) SOC_{LIBSS}, b) SOC_{SCSS}, c) I_{LIBSS} and d) I_{SCSS}.

Several simulations were performed to validate the proposed H-ESS under different SOC values of both ESS. The results are also compared with the passive system. The *Fig. 7* shows the results of the proposed EMS for H-ESS. The SOC of LIBSS is more stable as compare to SCSS due to high energy density. The basic aim of this research is to reduce the stress of LIBSS by tackling the high current values using the SCSS. It is evident from the *Fig. 7,* that the proposed controller maintains the current of LIBSS up to a certain limit. The current of SCSS keeps on changing according to the conditions. Low value of SCSS current is discharged during the low demanding condition because it can be easily tackled by LIBSS.

Fig. 8 shows the comparison of the passive and proposed H-ESS, the LIBSS current of the proposed H-ESS is less compared to the passive system. In case of passive system, the values of distribution currents of LIBSS and SCSS mainly depend upon their internal resistances. In this research, it is considered that the internal resistances of both ESS are same. The second plot shows the amount of extra current taken by LIBSS in case of passive system. Similarly, the third graph shows the comparison of SCSS current of both systems. Fourth graph are on negative side, it shows that the proposed EMS smartly utilize the power of SCSS to reduce over burden on LIBSS to prolong its live cycle.

Table IV shows the average current value of both the system for whole cycle. It can be clearly seen that the proposed system took almost 0.7935A lesser average LIBSS current using the proposed technique. The stress of LIBSS is reduced. In future, the proposed system should be checked and implemented in real time application. The SOC estimation accuracy can be improved using advance techniques and quality of sensors [25].

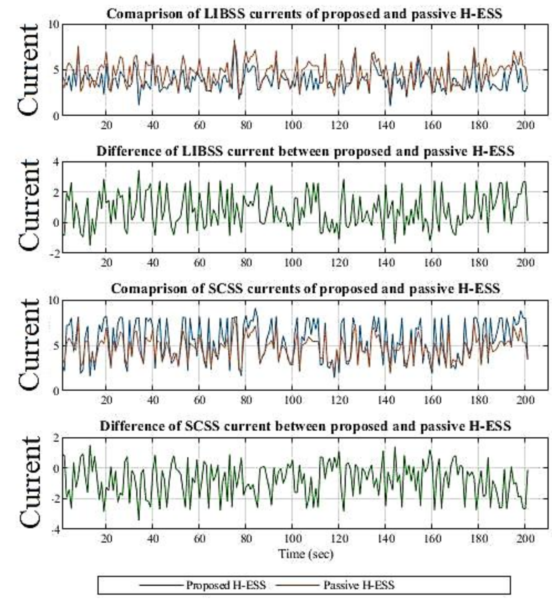


Fig. 8. Comparison of the proposed and passive H-ESS.

TABLE IV
COMPARISON OF PROPOSED AND PASSIVE H-ESS.

Type of H-ESS System	I_{LIBSS} (A)	I_{SCSS} (A)
Proposed	3.8822	5.4692
Passive	4.6757	4.6757

V. CONCLUSION

In this work, a new approach for H-ESS based upon fuzzy logic controller is introduced. The proposed approach separately monitors and measures the SOCs of both types of ESS. The SOCs of both ESS are fed to the fuzzy logic-based controller. The controller determines the discharge current values of LIBSS and SCSS based upon input SOCs. The simulation study is carried out to examine and validate the proposed technique. The simulation and comparative analysis suggests that the proposed algorithm reduces the stress of LIBSS upto 17%. The proposed controller can be easily used to tackle the abrupt changes of current in EVs, smart grids, electric wheelchair, etc. Furthermore, it also protects LIBSS from damages.

REFERENCES

[1] N. Khaboot, R. Chatthaworn, A. Siritaratiwat, C. Surawanitkun, and P. Khunkitti. Increasing PV penetration level in low voltage distribution system using optimal installation and operation of battery energy storage, Cogent Engineering, Vol. 6(1), pp. 1641911, 2019.

[2] M. Khan, K. Zeb, W. Uddin et al. Design of a Building-Integrated Photovoltaic System with a Novel Bi-Reflector PV System (BRPVS) and Optimal Control Mechanism: An Experimental Study, Electronics, Vol. 7(7), pp. 119, 2018.

[3] H. Singh, P. Kumar, M. Ali et al. High frequency transformer's parasitic capacitance minimization for photovoltaic (PV) high-frequency link-based medium voltage (MV) inverter, Electronics, Vol. 7(8), pp. 142, 2018.

[4] S. Nengroo, M. Kamran, M. Ali et al. Dual battery storage system: An optimized strategy for the utilization of renewable photovoltaic energy in the United Kingdom, Electronics, Vol. 7(9), pp. 177, 2018.
[5] J. A. Turner. A realizable renewable energy future, Science, Vol. 285(5428), pp. 687-689, 1999.
[6] K. Zeb, W. Uddin, M. A. Khan et al. A comprehensive review on inverter topologies and control strategies for grid connected photovoltaic system, Renewable and Sustainable Energy Reviews, vol. 94, pp. 1120-1141, 2018.
[7] Z. Li, A. Khajepour, and J. Song. A comprehensive review of the key technologies for pure electric vehicles, Energy, Vol, 182, pp. 824-839, 2019.
[8] L. Capuano. International energy outlook 2018, IEO2018. US Energy Information Administration, Washington DC, USA, 2018.
[9] M. U. Ali, A. Zafar, S. H. Nengroo, S. Hussain, M. J. Alvi, and H.-J. Kim. Towards a smarter battery management system for electric vehicle applications: A critical review of lithium-ion battery state of charge estimation, Energies, Vol. 12(3), pp. 446, 2019.
[10] P. Ralon, M. Taylor, A. Ilas, H. Diaz-Bone, and K. Kairies, Electricity storage and renewables: costs and markets to 2030, IRENA. International Renewable Energy Agency, Abu Dhabi, 2017.
[11] A. H. Alami, A. A. Hawili, R. Hassan, M. Al-Hemyari, and K. Aokal, Experimental study of carbon dioxide as working fluid in a closed-loop compressed gas energy storage system, Renewable Energy, Vol. 134, pp. 603-611, 2019.
[12] N. S. Hussain, M. U. Ali, A. Zafar et al. An optimized methodology for a hybrid photo-voltaic and energy storage system connected to a low-voltage grid, Electronics, Vol. 8(2), pp. 176, 2019.
[13] J. M. Miller, Energy storage technology markets and application's: ultracapacitors in combination with lithium-ion, 7th International Conference on Power Electronics, 2007, pp. 16-22.
[14] R. Xiong, H. Chen, C. Wang, and F. Sun, Towards a smarter hybrid energy storage system based on battery and ultra-capacitor-A critical review on topology and energy management, Journal of cleaner production, Vol. 202, pp. 1228-1240, 2018.
[15] O. Erdinc, B. Vural, and M. Uzunoglu. A wavelet-fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid vehicular power system, Journal of Power sources, Vol. 194(1), pp. 369-380, 2009.
[16] Z. Chen. High pulse power system through engineering battery-capacitor combination, 35th IEEE Intersociety Energy Conversion, Engineering Conference and Exhibit, 2000, Vol. 2, pp. 752-755.
[17] S. Hussain, M. U. Ali, S. H. Nengroo, I. Khan, M. Ishfaq, and H. J. Kim. Semi-active hybrid energy management system: A solution for electric wheelchairs, Electronics, Vol. 8(3), pp. 345, 2019.
[18] T. Zimmermann, P. Keil, M. Hofmann, M. F. Horsche, S. Pichlmaier, and A. Jossen. Review of system topologies for hybrid electrical energy storage systems, Journal of Energy Storage, Vol. 8, pp. 78-90, 2016.
[19] M. Khan, K. Zeb, P. Sathishkumar et al. A novel super capacitor/lithium-ion hybrid energy system with a fuzzy logic-controlled fast charging and intelligent energy management system, Electronics, Vol. 7(5), pp. 63, 2018.
[20] X. Cui, W. Shen, Y. Zhang, and C. Hu. A Fast Multi-Switched Inductor Balancing System Based on a Fuzzy Logic Controller for Lithium-Ion Battery Packs in Electric Vehicles, Energies, Vol. 10(7), pp. 1034, 2017.
[21] M. U. Ali, S. H. Nengroo, M. A. Khan, K. Zeb, M. A. Kamran, and H. J. Kim. A real-time simulink interfaced fast-charging methodology of lithium-ion batteries under temperature feedback with fuzzy logic control, Energies, Vol. 11(5), pp. 1122, 2018.
[22] D. Driankov, H. Hellendoom, and M. Reinfrank. An introduction to fuzzy control (Springer), Vol. 6, pp. 245-258, 1996.
[23] C. Zhang, L. Y. Wang, X. Li, W. Chen, G. G. Yin, and J. Jiang. Robust and adaptive estimation of state of charge for lithium-ion batteries, IEEE Transactions on Industrial Electronics, Vol. 62(8), pp. 4948-4957, 2015.
[24] M. U. Ali, M. Kamran, P. Kumar, S. Nengroo, M. Khan, A. Hussain, H. J. Kim. An online data-driven model identification and adaptive state of charge estimation approach for lithium-ion-batteries using the lagrange multiplier method, Energies, Vol. 11(11), pp. 2940, 2018.
[25] M. U. Ali, A. Zafar, S. H. Nengroo, S. Hussain, and H. J. Kim. Effect of sensors sensitivity on lithium-ion battery modeled parameters and state of charge: A comparative study, Electronics, Vol. 8(6), pp. 709, 2019.

Muhammad Umair Ali received the BS Electrical Engineering degree in 2009 from University of Engineering and Technology, Lahore, Pakistan and the MS degree in electrical power engineering in 2015 from University of Wah, Pakistan. Since 2017, he is Ph.D. student under the supervision of Prof. Hee-Je Kim at Pusan National University, South Korea. His research interests include battery modeling, identification, state estimation, and optimal charge control of different energy storage system.

Sadam Hussain received BSc degree in Electrical Engineering from University of Engineering and Technology Peshawar, Pakistan in 2015. In 2015 he joins Telenor as PS core specialist on behalf of ZTE for three years. Currently, he is doing MS in Electrical and Computer Engineering at Pusan National University Busan, South Korea. His main research interests include Power conversion system, Smart grid, Energy management system, Hybrid electric vehicle and Renewable energy system.

Sarvar Hussain Nengroo received his B.Tech. degree in Electrical and Renewable Energy Engineering from the Baba Ghulam Shah Badshah University, Jammu and Kashmir, India. Currently, he is a graduate student at Pusan National University, Busan, Republic of Korea. His research interests include renewable energy aggregation, smart microgrids, power system protection, power electronics, and intelligent control for high-power electronics applications.

Prof. Hee-Je Kim got PhD of Energy Conversion, Kyushu University, Fukuoka city, Japan. (1990, March). At present he is professor of Department of Electrical Engineering in Pusan National University (Busan, South Korea), and the group leader of BRL (Basic Research Lab). He is also currently working as an Associate Editor of "New Journal of Chemistry", Editorial Board Member of "Energies", the permanent member of "Korea Institute of Electrical Engineers" and "Renewable Energy". He is also the Reviewer of Solar Energy, Electrochimica Acta, Material Chemistry and Physics, Renewable Energy, Optics and Lasers in Engineering, Optics and laser technology, Solar Energy Materials and Solar Cells, Current Applied Physics, Electrochemistry Communication, IEE, IET, J of Electronics and so on. His main research area is dynamic, multi-objective, practical solution-based research with a focus on highly efficient solar energy conversion and effective energy storage system. That main four focal area are: i) Fabrication and commercialization of next-generation solar cells such as dye synthesized solar cells, quantum-dot, and perovskite solar cells. ii) Improving efficiency of existing solar PV and wind hybrid systems using different tools and techniques. iii) High energy and power density flexible super-capacitor for hybrid energy storage system. v) Dual active bridge (DAB), DC/DC Converter, MPPT, PV Inverter, and remotely control using smart-phone with novel algorithm for power conditioning system.