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Design and development of dual mode on-board battery charger for electric vehicle

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ABSTRACT

In recent days there is growing interest in electric vehicle (EVs) technologies because of concern about global warming, energy crisis and security. Charging configurations of EVs play a vital role in the development of automobile transformation. Hence in an automobile industry increased demand of EVs require an efficient and reliable system for recharging the battery. This paper presents a topology that interface the two types of charging systems i.e. slow charging and fast charging as required by the user. TESLA S60 battery model is taken as an example for validation of the proposed topology in simulation. Cuk converter is designed and implemented for charging the battery in two modes. The MATLAB/Simulink software is used to simulate and analyze the performance of the system. The prototype hardware model of the charger is developed and results are validated with simulation. The results show that the slow charging 86% and fast charging efficiency is more than 82%.

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1. INTRODUCTION

Modern society relies heavily on fossil fuel-based transportation for economic and social development. A combustion engine-based transportation mechanism uses only 30% of the fuel and rest of all goes as loss. But in case of electric motor driven vehicles the efficiency is more than 80%. Electric powered locomotion is used for variety of vehicles like buses, forklifts, bicycle, rail cars, and scooters. As the electric vehicle (EV) is propelled with the help of an electric powered motor, and further the motor being powered by means of rechargeable battery packs, efficient charging mechanism is very essential and critical [1]–[5]. The beneficial instances in battery type and charging mechanism have undoubtedly influenced the electric car marketplace [3]. Electric vehicles depend on electric batteries to meet the essential or the auxiliary power. The sale of electrical automobiles (EVs) is swiftly increasing around the world because of EVs' efficiency and increased battery technology that is reducing EV's cost of buying. So, any effect on the demand for electric vehicles influence the battery market. Commonly used battery types are lithium ion and lead acid. The lithium-ion battery has several advantages over lead acid battery like reduced size for same battery capacity, cost, and maintenance. Efficient and optimum charging mechanism of batteries is the only area where modification is possible in EVs to achieve more efficiency and larger charge per distance [6]–[10]. On-board charging and off board charging are the two ways of charging schemes for EV's. In on-board charging, the charging circuitry is situated inside the vehicle and charging coupler is used to provide input power. In off-board charger, the charging circuitry is outside the vehicle. Charging systems generally categorized into three levels they are Level 1, Level 2, and Level 3. The 3 degrees of charging are Level 1 charging (1-phase slow charging), Level 2 charging (1-phase and 3-phase slow and fast charging), and Level 3 charging (3-phase fast charging) [11]–[14]. Table 1 gives the range for the levels of charging. Normally off board charging of electric vehicle is done in two ways, one is from home outlet and another is through charging station. In home outlet charging, only Level 1 charging is achieved but in charging station all charging modes are available i.e. slow, fast, and 3-phase charging. Power converters are the key components in charging mechanism of any type of battery, as per the literature there are various topologies used for battery charging purpose, so it is very important to identify the versatile topology to suit the battery charging application [15]–[19]. Depending on the level of charging independent power converter is essential, it is very beneficial to have multi-mode charging of batteries AC charging at homes or DC/AC charging at recharging stations [20]–[22]. Along with the selection of converter topology the battery management systems are equally important, there are various algorithms discussed in literature that controls the operation of the converter efficiently [23]–[25].

In this paper, an attempt is made to develop on board charger that can work in two modes slow and fast charging as per the requirement. The objective of this paper is to design a system that interface the on-board AC slow charging and DC fast charging with Cuk converter. Simulate the converter in MATLAB/Simulink software for different ratings of battery and the performance in both modes is analyzed. The developed system is practically tested to validate the simulation results. The organization of paper is as follows, section 1 details the introduction to electric vehicle, battery scenario, and charging schemes, section 2 describes design aspects of the proposed system with the block diagram of scheme and simulation of the system, sections 3 and 4 describes the hardware implementation of the prototype and the validation with results, and section 5 presents the conclusion of the system with scope for future work.

Table 1. Standard charging levels of battery of electric vehicle

Charging options	Current rating (amp)	Voltage rating (volt)	Power rating (kW)
Level 1 charging (1-phase slow charging)	12 to 16	120	1.3-1.9
Level 2 charging (1-phase and 3-phase slow and fast charging)	Up to 80	240	Up to 19.2
Level 3 charging (DC fast charging)	Up to 80	480	Up to 130

2. DESIGN OF PROPOSED DUAL MODE POWER CONVERTER

The block diagram of proposed dual charging scheme is shown in Figure 1. The on-board battery charger includes double circuit for slow as well as fast charging. Slow charging includes double conversion like AC to DC and DC to DC. Initially AC-DC conversion is obtained using rectifier to have makeover of voltage for output and DC-DC provides constant output to the battery using Cuk converter topology. The gating pulses are provided to DC-DC converters to maintain constant output current by taking feedback. This feedback signal is given to Arduino UNO to generate appropriate gating signals.

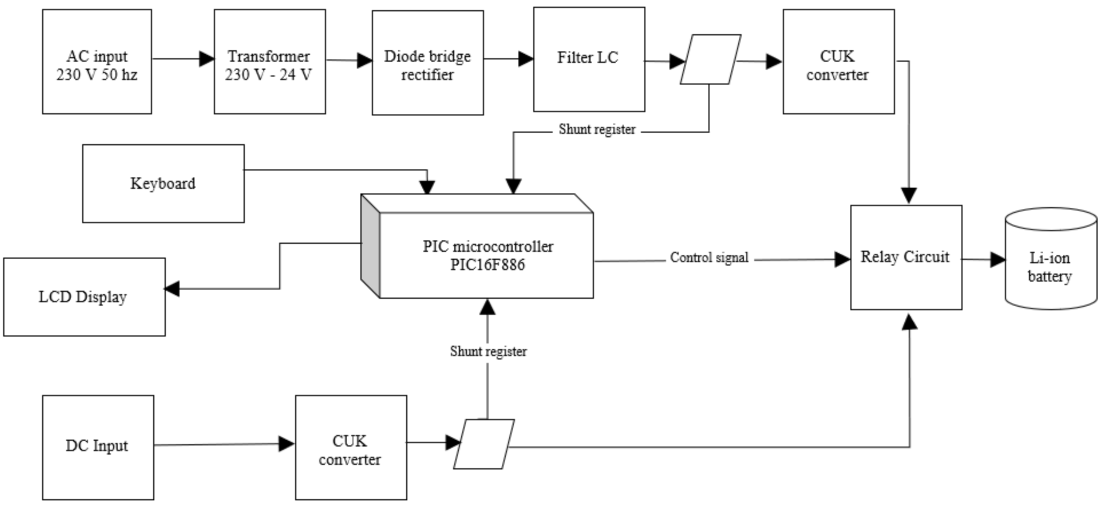

Figure 1. Block diagram of the charging system

The proposed system is validated considering the specifications of TESLA S 60 model. The details are given in Table 2. The specifications of the power converter are given in Table 3.

- Calculation of load power:

$$P = 890\ A * 320\ V = 285\ Kwh \quad (1)$$

- Battery capacity selection:

$$= 890\ A * T = 890 * 0.21$$
$$= 190\ Ah \quad (2)$$

- Charging time of the battery:

$$T = Battery\ power\ rating/load\ power$$
$$= \frac{60 \times 10^3}{285 \times 10^3}$$
$$= 34\ min \quad (3)$$

$$V_o = -V_s \frac{D}{1-D} = -400\ \frac{0.2}{1-0.2} = -72\ V \quad (4)$$

$$L_1 = \frac{V_S D}{f \Delta iL1} = \frac{230*0.35}{50000*1/100} = 100\ nH = L_3 \quad (5)$$

$$L_2 = \frac{V_S D}{f \Delta_{iL2}} = 1\ uH = L_4 \quad (6)$$

$$C_1 = \frac{VsD}{Rf \Delta iL1} = \frac{400*0.35}{0.9*50000*2/100} = 1.8\ pF \quad (7)$$

$$C_2 = \frac{1-D}{\left(\frac{\Delta V_\circ}{V_\circ}\right) 8 L_2 f^2} = 1000\ uF \quad (8)$$

Table 2. TESLA S60 model

EV in market	Battery rating	Range km	Wh/km
Tesla S 60	60 kWh	275 km	220 (335 mi)

Table 3. Specification of converter

SL. No	Parameter	Specification
1	Input voltage (DC)	22 V
2	Input voltage (AC)	230 V
3	Output voltage	12 V
4	Output current (fast charging)	1.4 A
5	Output current (slow charging)	0.8 A
6	Power rating	20 W
7	Switching frequency	40 kHz
8	Output voltage ripple	1%

3. RESULTS AND DISCUSSION

3.1. Simulation results

Figure 2 shows the compete circuit schematic of proposed charging scheme developed in proteus. It has the two inputs and a single battery as load to be charged. The output voltage and inductors values are designed using basic equations of Cuk converter [9]. The performance equations are given from (4) to (8).

Simulation is carried out in the MATLAB/Simulink software. Figure 3 shows the MATLAB circuit in which the converter is simulated to get desired battery characteristics i.e. charging and discharging plots. Figure 4 shows the schematic in fast charging mode. In Figure 5 shows the circuit schematic of slow charging scheme. Figure 6 shows the charging waveform and takes 190 A and charges in 1 hour in fast charging scheme, Figure 6 shows the fast-charging waveform and Figure 7 shows the waveforms of slow charging of battery, that takes 20 A and charges in 5.5 hours.

Similar simulation is carried out in MATLAB software for different actual EVs battery specifications and the results are tabulated in Table 4. For implementing the charging schemes in hardware lower battery rating of 12 V, 14 Ah is selected to test the developed circuit. Simulation results of the hardware specification are tabulated in Table 5.

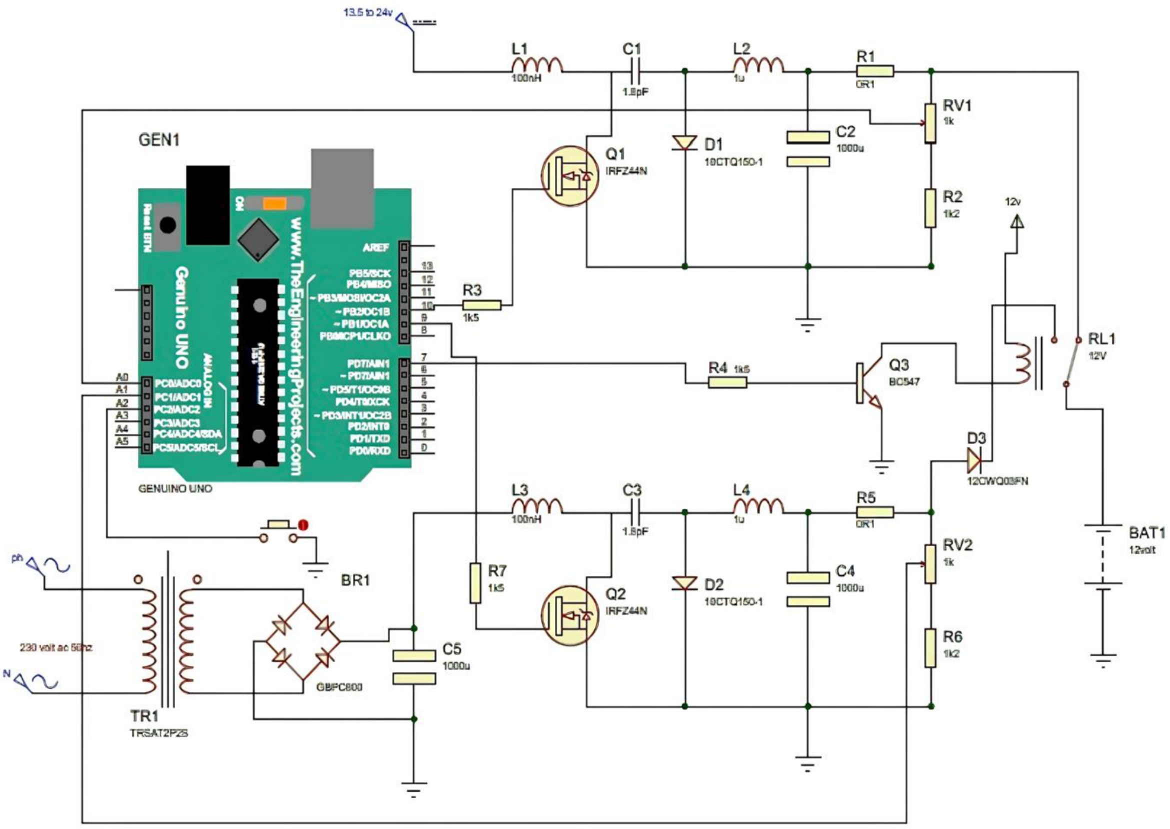

Figure 2. Circuit schematic in proteus editor

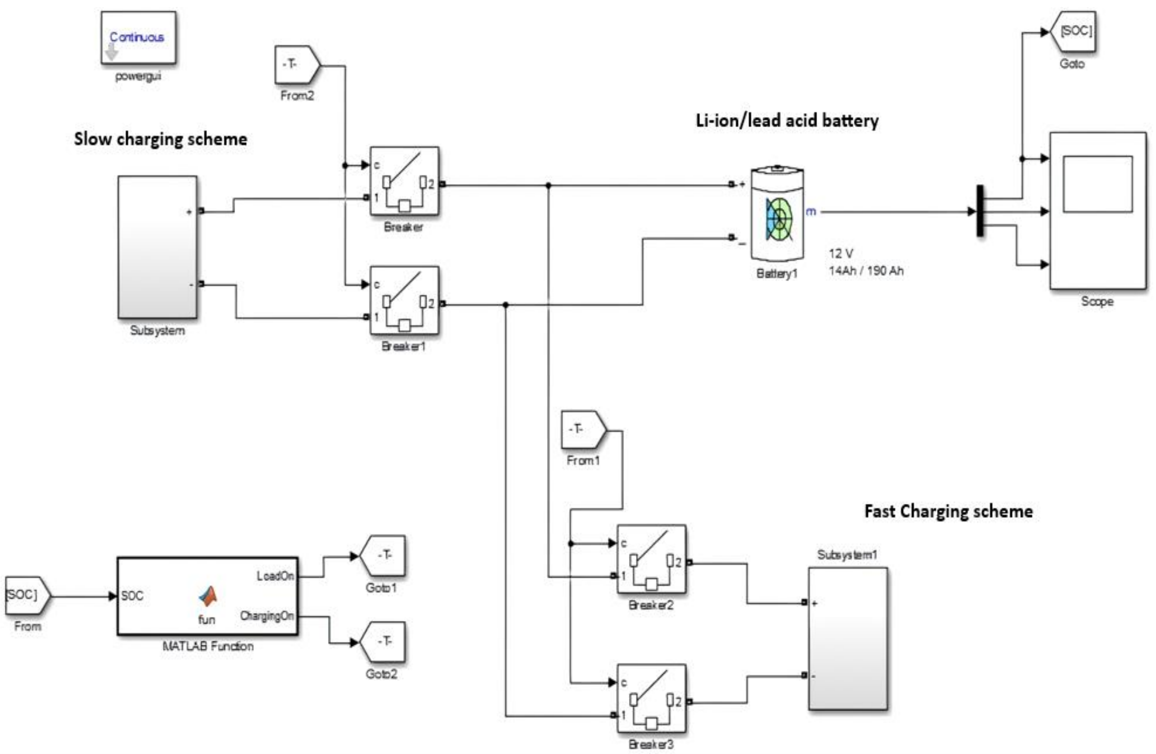

Figure 3. Circuit schematic of converter in dual mode in MATLAB

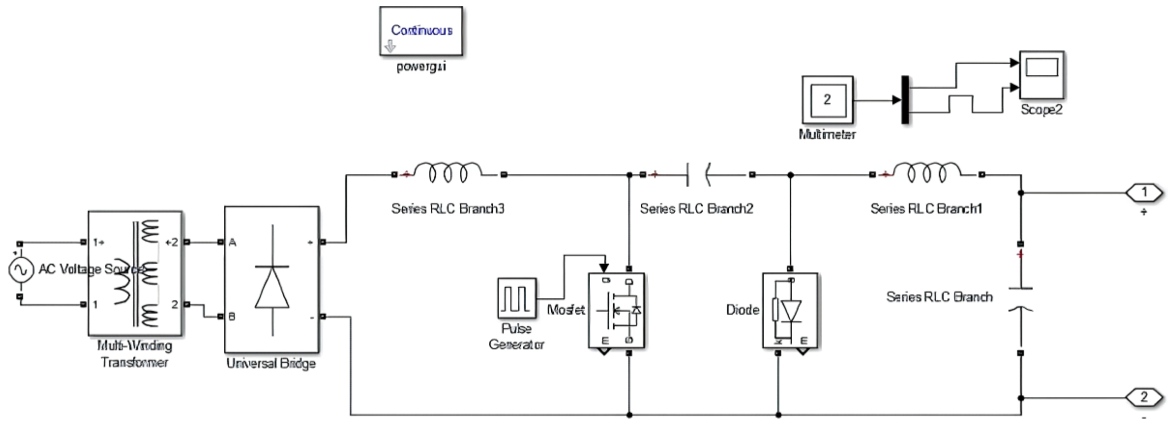

Figure 4. Simulation circuit for slow charging

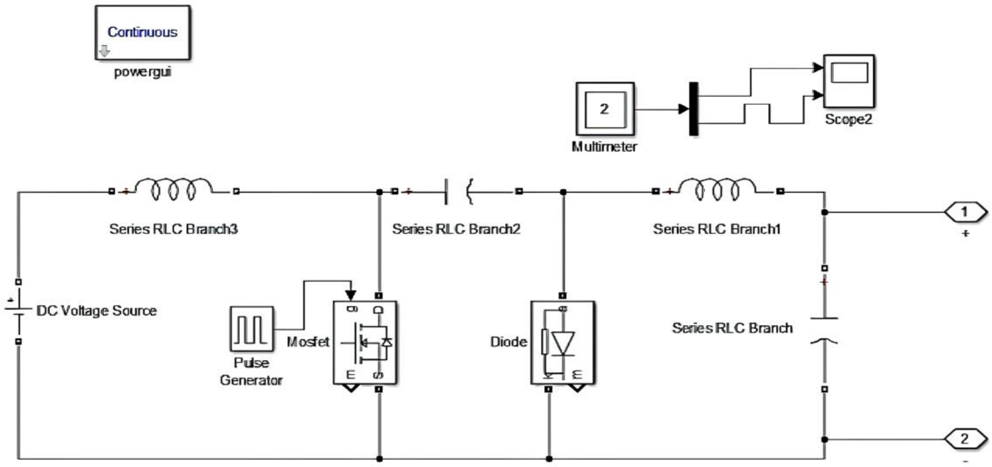

Figure 5. Simulation circuit for fast charging

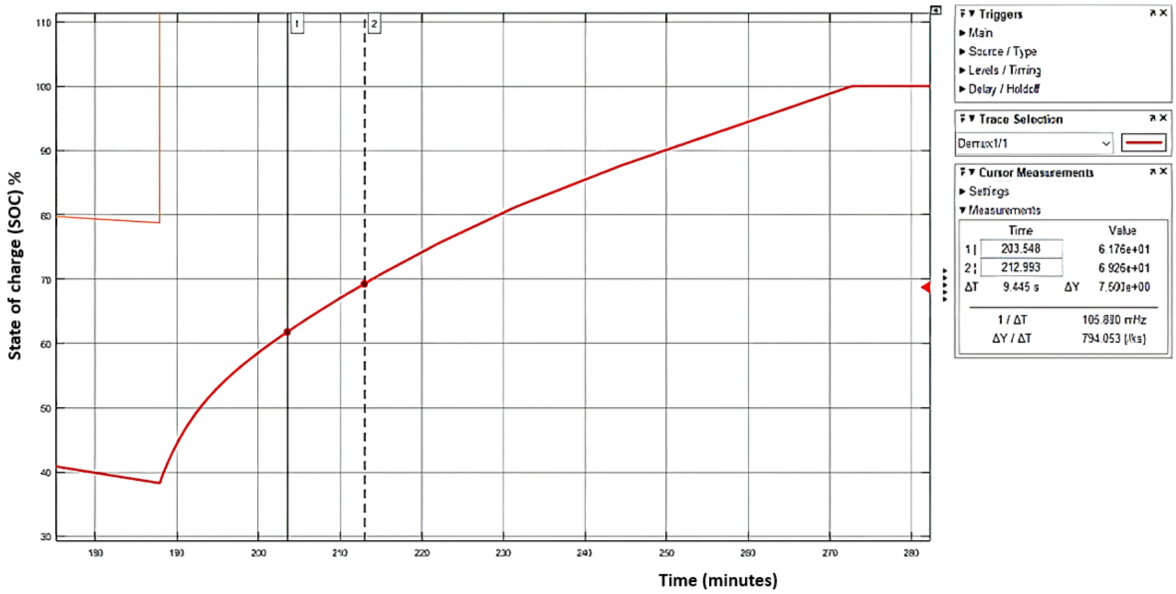

Figure 6. Simulation results of fast charging

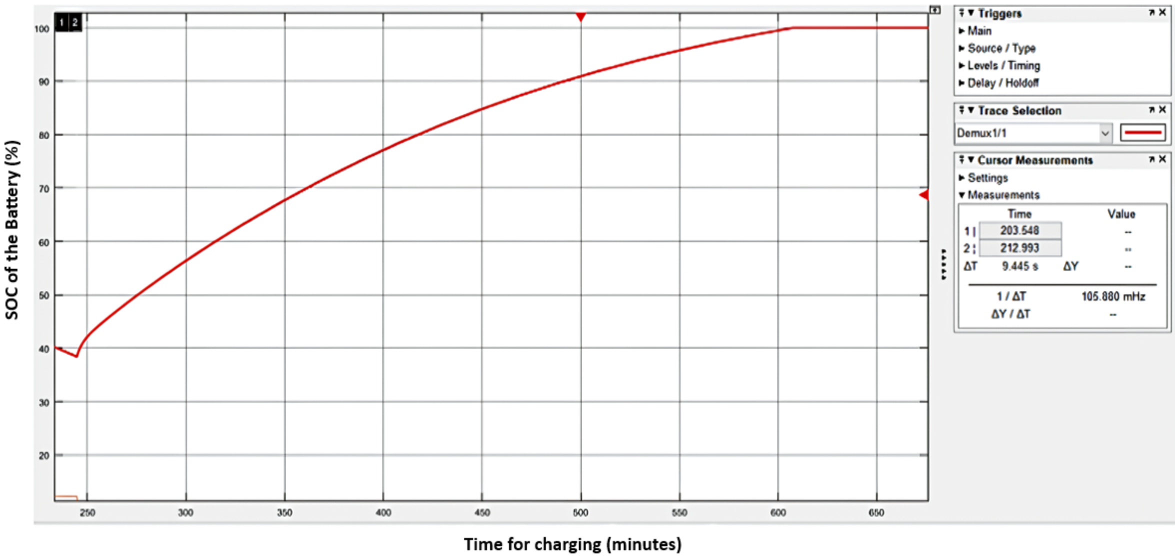

Figure 7. Simulation results of slow charging

Table 4. Simulation results of charging time of EV battery's

Battery (190Ah)		Charging schemes
Charging current	Time for charging	
190 A	1 hour	Slow charging
235 A	48 min	
450 A	25 in	Fast charging

Table 5. Charging time for 12V, 14 Ah battery

Mode of charging	Charging current	Charging time
Slow charging	0.8 A	17 hours
Fast Charging	1.4 A	10 hours

3.2. Hardware results

The hardware results of proposed battery charger in dual mode charging is presented below. Both fast charging and slow charging techniques are implemented as per the design details of the dual converter. The two key parameters of battery charging techniques are the charging time and state of charge which are very crucial that decides the figure of merit of charging system.

3.2.1. Slow charging scheme

The slow charging scheme for lead acid battery using Cuk converter is implemented and is shown in Figure 8. The AC input is fed from the home outlet i.e. of 230 V and it is stepped down to 24 V and fed to Cuk converter. Output of Cuk converter is 12 V, 0.8 A.

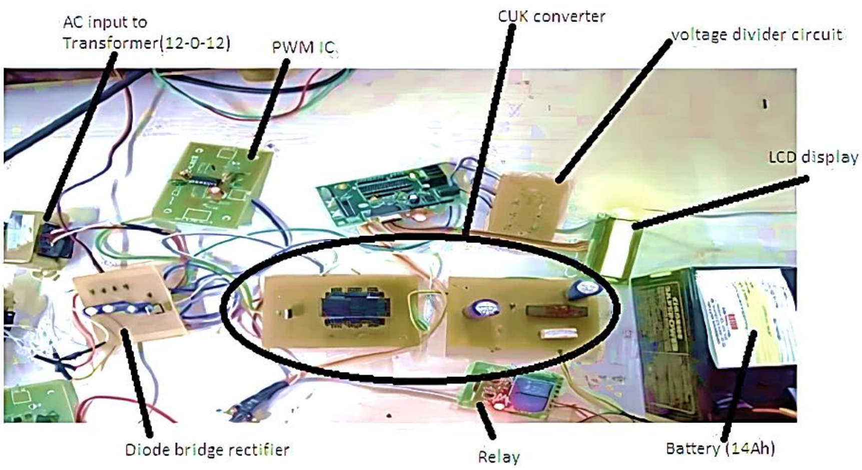

Figure 8. Slow battery charging scheme

Normal charging time of a lead acid battery is 10 hours is 600 min (for full charge), time required to charge 1% SOC of the battery is 6 min. The SOC of the battery is observed from 65% to 69% in hardware and compared with simulation results. The obtained results are matching with the simulation results. The readings are as shown in Table 6.

Table 6. Reading of battery SOC

SOC (%)	Time for charging per 1% increase in SOC (min)
65	8.15
66	8.32
67	8.5
68	9.29
69	9.08

3.2.2. Fast charging scheme

The fast-charging scheme for lead acid battery using Cuk converter is implemented is as shown in the Figure 9. The DC input is provided from the DC regulated power supply i.e. of 12 V, 1.4 A. The current at the output is high enough to charge the battery in fast mode without damaging the battery.

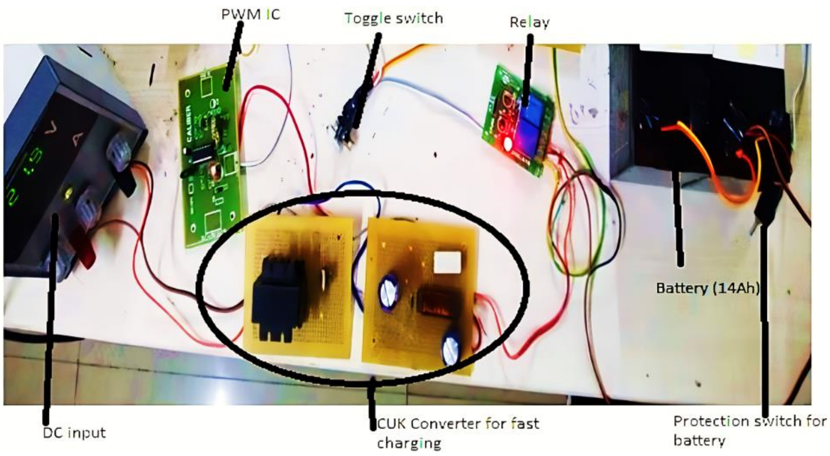

Figure 9. Fast battery charging scheme

The allowable fast charging time of a lead acid battery without battery being damaged is 5 hours (300 min) for full charge. Time considered to charge 1% SOC of the battery is 3 min. The output result of slow charging is fed from the LCD display and same is listed in Table 7. The SOC of the battery is observed from 69% to 73% in hardware and compared with simulation results. The obtained results are matching with the simulation results. Hardware results for one complete charge of the battery is tabulated in Table 8. From hardware results the battery voltage is varying from 11.8–13.4 V.

Table 7. Reading of battery SOC

SOC (%)	Time for charging per 1% increase in SOC (min)
69	3.12
70	3.01
71	3.08
72	3.3
73	3.14

Table 8. Hardware results

Battery (12 V, 14 Ah)		
Slow charging	0.8 A	5.5 hours
Fast charging	1.4 A	11.6 hours

3.2.3. Efficiency calculation

Efficiency of the converter used in both slow and fast charging is defined as the output power delivered by input power drawn. Efficiency calculation in fast charging is for input voltage of 22 V, drawing 0.89 A of input current. Output voltage is 12 V, delivering 1.4 A to load. Efficiency calculation in slow charging is for input voltage of 22 V, drawing 0.49 A of input current. Output voltage is 12 V, delivering 0.8 A to load.

$$\begin{aligned} Fast\ charging\ efficiency &= \frac{V_O I_O}{V_{in} I_{in}} \\ &= \frac{12 \times 1.4}{22 \times 0.89} \\ &= 85.2\% \end{aligned} \tag{9}$$

$$\begin{aligned} Slow\ charging\ efficiency &= \frac{12 \times 0.8}{22 \times 0.49} \\ &= 89\% \end{aligned} \tag{10}$$

4. CONCLUSION

In this paper the two types of charging systems that are interfaced to charge the electric vehicle battery in slow and fast charging mode are analyzed. The proposed converter is Cuk converter is connected to battery to charge either by using slow or fast charging. In DC fast charging 22 V input is fed and for AC slow charging 230 V input is fed to get 12 V output. In simulation, to charge the battery by fast charging mode it takes 5 hours and it takes 10 hours in slow charging mode for the same battery. In the hardware module, DC fast charging is provided by 22 V supply voltage and it provides a constant output voltage 12 V. The circuit charges the lead acid battery in 5 hours 30 minutes in fast charging mode. In case of slow charging mode, it charges in 11 hours 36 minutes. Efficiency of the charging scheme in slow charging is 89% and in fast charging it is 85.2%. As the demand for electric vehicles is continuously increasing multi-mode charging facility for a battery is an attractive solution. New charging schemes in multi-mode operation with different algorithms retaining high efficiency is the scope for future work.

REFERENCES

[1] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, 2013, doi: 10.1109/TPEL.2012.2212917.

[2] S. Kumar and A. Usman, "A review of converter topologies for battery charging applications in plug-in hybrid electric vehicles," *2018 IEEE Industry Applications Society Annual Meeting, IAS 2018*, 2018, doi: 10.1109/IAS.2018.8544609.

[3] I. Subotic and E. Levi, "A review of single-phase on-board integrated battery charging topologies for electric vehicles," *Proceedings - 2015 IEEE Workshop on Electrical Machines Design, Control and Diagnosis, WEMDCD 2015*, pp. 136–145, 2015, doi: 10.1109/WEMDCD.2015.7194522.

[4] K. A. Chinmaya and G. K. Singh, "A Plug - in Electric Vehicle (PEV) with Compact Bidirectional CuK Converter and Sturdier Induction Motor Drive," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2018, pp. 937–942. doi: 10.1109/IECON.2018.8595405.

[5] Y. H. Liao, "Reduced current stress bridgeless Cuk PFC converter with new voltage multiplier circuit," *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, vol. 2016-May, pp. 1831–1834, 2016, doi: 10.1109/APEC.2016.7468116.

[6] M. Gopinath and V. Sheela, "Efficency analysis of bridgeless Cuk converter for PFC applications," *2013 International Conference on Information Communication and Embedded Systems, ICICES 2013*, pp. 1052–1056, 2013, doi: 10.1109/ICICES.2013.6508253.

[7] E. H. Ismail, A. J. Sabzali, and M. A. Al-Saffar, "A High-Quality Rectifier Based on Sheppard–Taylor Converter Operating in Discontinuous Capacitor Voltage Mode," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 38–48, Jan. 2008, doi: 10.1109/TIE.2007.896132.

[8] B. Farhan, "A Novel Design Methodology for a 1 . 5 KW DC / DC Converter in EV and Hybrid EV Applications," *World Academy of Science, Engineering and Technology International Journal of Electrical and Computer Engineering*, vol. 8, no. 9, pp. 1490–1493, 2014.

[9] Y. Chen, H. Zhang, S. J. Park, and D. H. Kim, "A Switching Hybrid LCC-S Compensation Topology for Constant Current/Voltage EV Wireless Charging," *IEEE Access*, vol. 7, pp. 133924–133935, 2019, doi: 10.1109/ACCESS.2019.2941652.

[10] T. Kang, C. Kim, Y. Suh, H. Park, B. Kang, and D. Kim, "A design and control of bi-directional non-isolated DC-DC converter for rapid electric vehicle charging system," *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, pp. 14–21, 2012, doi: 10.1109/APEC.2012.6165792.

[11] M. Pahlevaninezhad, P. Das, J. Drobnik, P. K. Jain, and A. Bakhshai, "A novel ZVZCS full-bridge DC/DC converter used for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 27, no. 6, pp. 2752–2769, 2012, doi: 10.1109/TPEL.2011.2178103.

[12] K. Rajashekara, "Present status and future trends in electric vehicle propulsion technologies," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 1, pp. 3–10, 2013, doi: 10.1109/JESTPE.2013.2259614.

[13] J. Zhang *et al.*, "A hierarchical distributed energy management for multiple PV-based EV charging stations," *Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1603–1608, 2018, doi: 10.1109/IECON.2018.8591742.
[14] C. W. Lan, S. S. Lin, S. Y. Syue, H. Y. Hsu, T. C. Huang, and K. H. Tan, "Development of an intelligent lithium-ion battery-charging management system for electric vehicle," *Proceedings of the 2017 IEEE International Conference on Applied System Innovation: Applied System Innovation for Modern Technology, ICASI 2017*, pp. 1744–1746, 2017, doi: 10.1109/ICASI.2017.7988277.
[15] X. Liu, H. Wang, and Y. Bian, "An integrated converter topology combing the battery charging/discharging circuit with the battery balancing circuit," *19th International Conference on Electrical Machines and Systems, ICEMS 2016*, 2017.
[16] Q. Wang, I. S. Bayram, F. Granelli, and M. Devetsikiotis, "Fast power charging strategy for EV/PHEV in parking campus with deployment of renewable energy," in *2014 IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Dec. 2014, pp. 370–374. doi: 10.1109/CAMAD.2014.7033268.
[17] P. Y. Kong and G. K. Karagiannidis, "Charging Schemes for Plug-In Hybrid Electric Vehicles in Smart Grid: A Survey," *IEEE Access*, vol. PP, no. 99, 2016, doi: 10.1109/ACCESS.2016.2614689.
[18] R. Shankar, J. Marco, and F. Assadian, "Design of an optimized charge-blended energy management strategy for a plugin hybrid vehicle," *Proceedings of the 2012 UKACC International Conference on Control, CONTROL 2012*, pp. 619–624, 2012, doi: 10.1109/CONTROL.2012.6334701.
[19] A. Sheikhi, S. Bahrami, A. M. Ranjbar, and H. Oraee, "Strategic charging method for plugged in hybrid electric vehicles in smart grids; A game theoretic approach," *International Journal of Electrical Power and Energy Systems*, vol. 53, no. 1, pp. 499–506, 2013, doi: 10.1016/j.ijepes.2013.04.025.
[20] P. Richardson, D. Flynn, and A. Keane, "Optimal charging of electric vehicles in low-voltage distribution systems," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 268–279, 2012, doi: 10.1109/TPWRS.2011.2158247.
[21] M. Singh, P. Kumar, and I. Kar, "A multi charging station for electric vehicles and its utilization for load management and the grid support," *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 1026–1037, 2013, doi: 10.1109/TSG.2013.2238562.
[22] T. Ma and O. A. Mohammed, "Optimal charging of plug-in electric vehicles for a car-park infrastructure," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2323–2330, 2014, doi: 10.1109/TIA.2013.2296620.
[23] S. G. Kumar MTech and H. J. Assistant Professor, "Design, Specification and Simulation of Slow & Fast Battery Charging for Electric Vehicle Application," *International Journal of Emerging Technologies in Engineering Research (IJETER)*, vol. 7, no. 5, 2019.
[24] G. Preetham and W. Shireen, "Photovoltaic charging station for plug-in hybrid electric vehicles in a smart grid environment," *2012 IEEE PES Innovative Smart Grid Technologies, ISGT 2012*, 2012, doi: 10.1109/ISGT.2012.6175589.
[25] C. Shi, H. Wang, S. Dusmez, and A. Khaligh, "A SiC-Based High-Efficiency Isolated Onboard PEV Charger With Ultrawide DC-Link Voltage Range," *IEEE Transactions on Industry Applications*, vol. 53, no. 1, pp. 501–511, Jan. 2017, doi: 10.1109/TIA.2016.2605063.

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