International Journal of Applied Power Engineering (IJAPE)
Vol. 13, No. 3, September 2024, pp. 703~714
ISSN: 2252-8792, DOI: 10.11591/ijape.v13.i3.pp703-714

Charge sharing scheme for electric vehicles based on battery monitoring

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Article Info

Article history:

Received Jul 31, 2023
Revised Mar 19, 2024
Accepted Apr 26, 2024

Keywords:

Battery management
Electric vehicle
State of charge
Vehicle-to-vehicle
Wireless power transfer

ABSTRACT

The demand for electric vehicles (EVs) is rising due to the environmental impact of zero emission, high efficiency, and a deterioration in the levels of conventional fuels. Initial expense, the range, the time for charging and the availability of charging stations narrows their popularity. Alternately, smart approaches like vehicle-to-home (V2H), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G) charging schemes can modify this situation and shape the grid-side load curves. Vehicles in need can utilize V2V, where the transfer of charge between electric vehicles ensures the transit up to the nearby charging stations. There are wired and wireless modes in V2V topology. When equipped with the required switchgear, wireless power transfer (WPT) between electric vehicles offers great possibilities in charge sharing. A wireless charging system gives EV owner's freedom of easy charging without waiting in a queue. This paper compares the performance and utilities of wired scheme and wireless scheme for power transfer between vehicles. Both the strategies check the state of charge (SoC) of the batteries and facilitate the power transfer. Simulations in MATLAB/Simulink and experimental results validate the proposed schemes.

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1. INTRODUCTION

Higher fuel costs and concerns about environmental pollution by internal combustion engines have urged governments to enhance the production and usage of hybrid and pure electric vehicles. Electric vehicles (EVs) have the advantages of zero emissions, simplicity, better efficiency, higher comfort levels, accessibility and lower maintenance cost in comparison with conventional vehicles [1]. The batteries, electric drives and its selection [2]-[5] depend on various factors including the vehicular technologies and charging topologies [6]. Except for the initial cost, the EVs perform better than equivalent petrol or diesel vehicle. The distance between charging stations is another consideration in the choice of EVs. An increase in the number of charging stations can address this issue, but the upgrades required in the grid in this regard can be comparatively costly at a larger scale. Charging methods also extend from wired to wireless connection chargers [7]. EV owners also face the range anxiety problem, where vehicle-to-vehicle (V2V) charging can be a solution [8].

Available charging time allows the owner to select the mode and place of charging. There are two methods of charging electric vehicles, on-board charging and off board charging. The former has the necessary circuitry located in the vehicle and a coupler provides the power input, done at home or charging station. The latter has the circuit for charging situated outside the vehicle. Single phase slow charging represents Level 1 charging while single phase fast and three phase slow/fast charging comes under Level 2. Level 3 charging comprises of the DC fast charging. DC fast-charging off-board chargers are available, but add weight, size, and cost to the system [9]. Power conversion technologies play a vital role in the type, level and applications of the battery chargers. Details of vehicle-to-home (V2H), V2V, and vehicle-to-grid (V2G) technologies are available in [10]. The design and implementation of power converters for EV charging depends on battery capacity, voltage rating of equipment, type of drive and power rating [11]-[16]. The role of bidirectional DC-DC converters is important in the design and implementation of power converters as it allows feedback of energy during regeneration [17], [18] and enables other modes like V2G and V2V.

Technical challenges in the design of V2V chargers are numerous like compatibility between the circuits and attaining balance in power among electric vehicles [19], which is essential for improving efficiency. Both EVs and plug-in hybrid electric vehicles (PHEVs) are useful in managing the oil-energy crisis and addressing the issue of environmental pollution. The latter has bagged appreciable attraction and turned out to be an imperative part of the smart-grid topology. The quick advancement of PHEV diffusion into the grid will affect the residential electricity distribution network [20]. Plugged-in electric vehicles (PEVs) have gained popularity due to the availability of off-board fast charging stations. Off-board chargers help customers overcome range anxiety in PEVs by extending the time and kilometers of battery usage. The advancement in battery technology and associated power electronics have made the charging of batteries at high power levels possible. Dynamic factors like energy density, time for charging, and lifetime affects the evolution and commercialization of EVs with their weight and size. The attributes of the battery charger regulate and affect the charging time and lifetime of batteries [21]. The performance of the battery management system is crucial for the effective operation of the electric vehicle [22].

Charging without wires is an imminent technological advancement that is applicable not only to EVs but also to a large number of electronic devices. The expulsion of immediate electrical contacts makes the system user-friendly and safe. Wireless power transfer is useful in numerous applications including two and three-dimensional battery charging systems and for power delivery to appliances like tablets, and smartphones are 2D systems. Many devices get charge simultaneously at a speed the same as a wired charger. The devices are free to be located and oriented in any direction of the charging pad allowing convenient and easy charging of personal electronic devices [23]. A wireless charging system consists of a transmitter and receiver coils. These coils can be circular, square, rectangular or bipolar.

EVs generally do not utilize the major portion of the battery charge available for reaching their destination. Hence, vehicles are carrying surplus energy on the roads. An EV proceeding for a farther destination will always require an additional charge. If vehicles having shorter circuits can transfer their charge to a needy one, while in rest or motion, this problem can be tackled. However, the power transfer level may be low. The reception and emission capability of the coil used in wireless transmission allows power transfer between parallel running and adjacently parked vehicles. It utilizes resonant induction for power transfer. Hence, through mature technologies, V2V can address the issues of range anxiety and lack of charging stations.

The wireless power transmission system consists of two magnetically coupled coils allowing energy transmission between them. An alternating electric current passing through a coil (primary) can produce a magnetic field around it that varies in time. If a coil (secondary) in the proximity of this magnetic field intercepts it, there can be a voltage in the coil. Value of flux, the air gap length, number of turns in the coil and the rate at which flux changes in the coil will affect the value of this voltage. In near field technology, the transferrable energy stays around a small region of the transmitter whereas far field utilizes lasers for power transfer over a larger span [24]. The efficiency of wireless power transfer is also important [25]. The wireless charging also involves economic aspect [26] as well as communication and control [27]. As the technologies develop in parallel, matching of different transmitter and receiver coils and their inter-operability is necessary [28]. The application of heuristic controllers give efficient solutions for power sharing [29] as with fuzzy logic controllers (FLC) [30] which is effective for EV applications.

This paper will present a wired and wireless scheme of V2V topology in EV charging. A fuzzy logic controller is developed for effective battery management. Modelling and simulation of the strategies are done with MATLAB/Simulink. Experimental validation is done with laboratory prototype of the model.

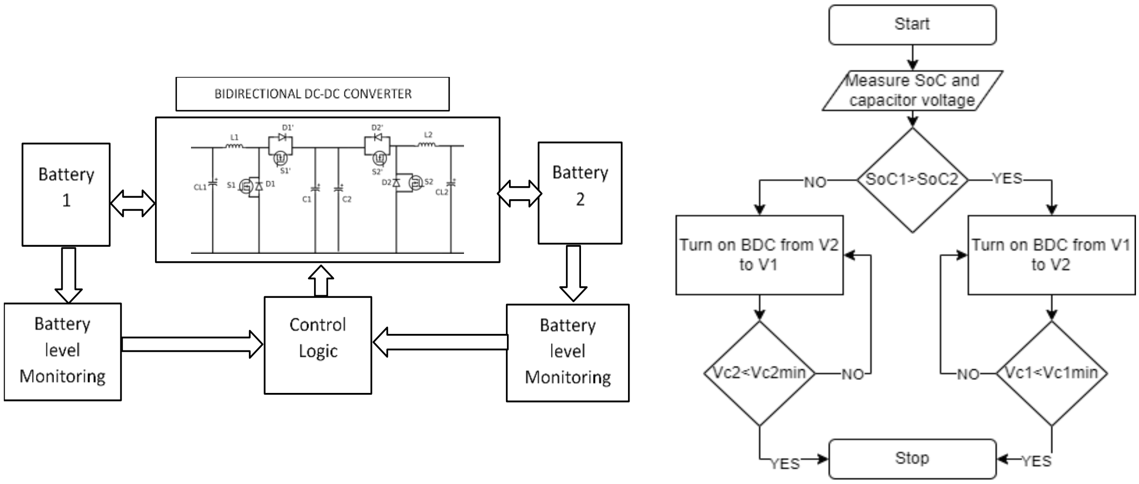
2. METHODOLOGY

Shortage of charging stations and battery capacity limitation of EVs keeps the users at wait for significant periods. Utilizing the energy storage capacity of the EV battery and bidirectional nature of the power converters, V2V charging offers solution to the range anxiety. In V2V mode, power flows between two electric vehicles, either conductively or inductively.

2.1. Wired V2V scheme

This section explains the simulation and implementation of a wired scheme for power transfer between two vehicles. Figure 1(a) shows the block schematic for the proposed system utilizing a modified bidirectional DC-DC converter. A modified version of the buck-boost converter allows the battery voltage to be converted to suitable levels for energy transfer. The modified buck-boost converter has source capacitors CL1= CL2, Load capacitors, C1= C2 and inductor L1= L2 connected to the vehicle batteries. S1 and S2 are the switches and D1, and D2, the diodes.

There are two similar modes of operation in both the directions as the back-to-back converter has a similar shape and design. Mode 1 is active when Battery 1 charge is greater than Battery 2 and hence the former is discharging and the latter is charging. With EV1>EV2, S1 is on and L1 and CL1 gets charged. Previously charged C1 and C2 discharges and charges L2 and CL2 with S2’ on. In mode 2, S1 and S2’ are turned off. With D1 and D2 forward biased, L1 and CL1 discharge to C1 and C2 while L2 and CL2 charge Battery 2. When EV2>EV1, the flow of charge occurs in the opposite direction as to modes 1 and 2. With this configuration, charge transfer is possible with an off-board charger when the receiving battery has less the state of charge (SoC) compared with the sharing battery. The charge transfer is best explained as in flowchart Figure 1(b). Figure 2 shows the Simulink model used for simulation of vehicle-to-vehicle wired charging. Their respective batteries in the diagram represent vehicle 1 and 2.



(a) (b)

Figure 1. A wired scheme for V2V power transfer: (a) schematic diagram for V2V transfer and (b) flowchart for V2V

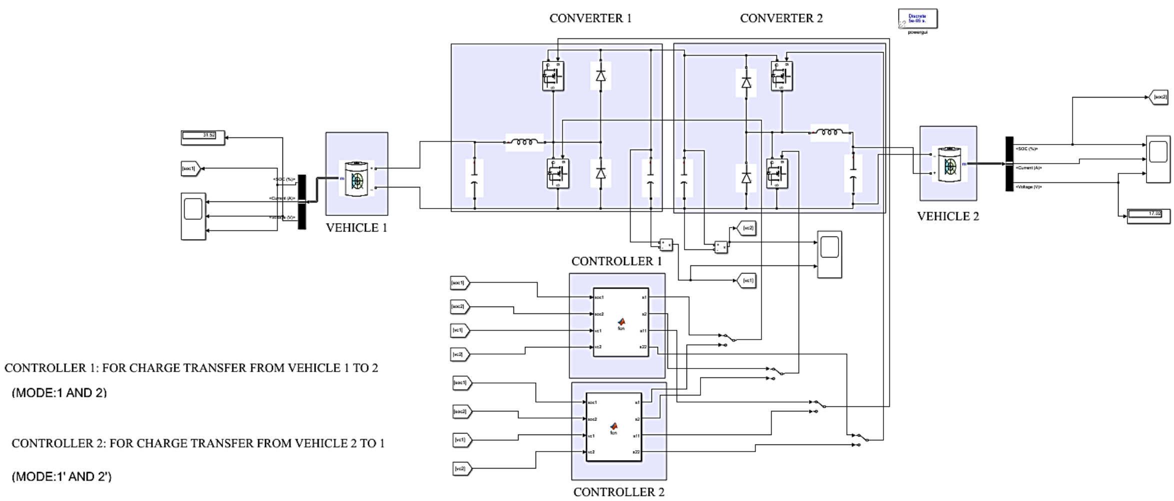
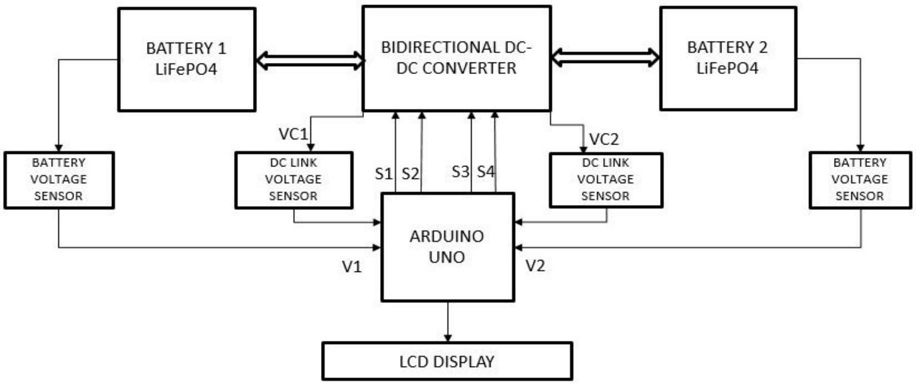


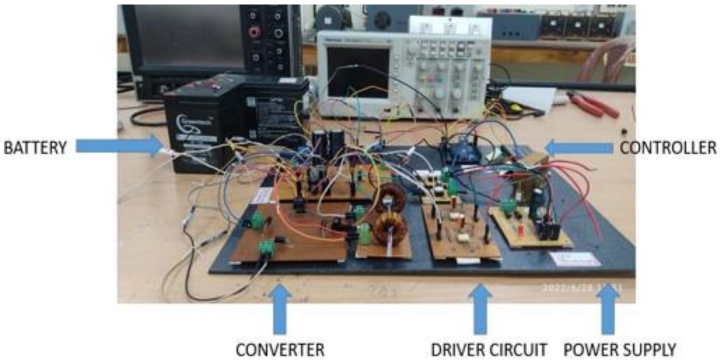
Figure 2. Simulink model for V2V wired charging

2.1.1. Experimental evaluation

Figure 3 shows the hardware description for the Bidirectional DC-DC converters (BDC). The controller is Arduino Uno microcontroller, which generates the PWM signals for the control of the converter as well as monitors the system for its SoC and facilitates the charge control. The switches are MOSFET (IRF244N), Diodes are IN5822, driver IC TLP 250. The inductance is a toroid wound as per the design and capacitors are electrolytic. The schematic for hardware implementation is shown in Figure 3(a). A prototype Figure 3(b) for the wired power transfer scheme is developed and tested in the laboratory.



(a)



(b)

Figure 3. Prototype development for evaluation (a) block diagram of hardware and (b) hardware implementation

2.2. Wireless V2V scheme

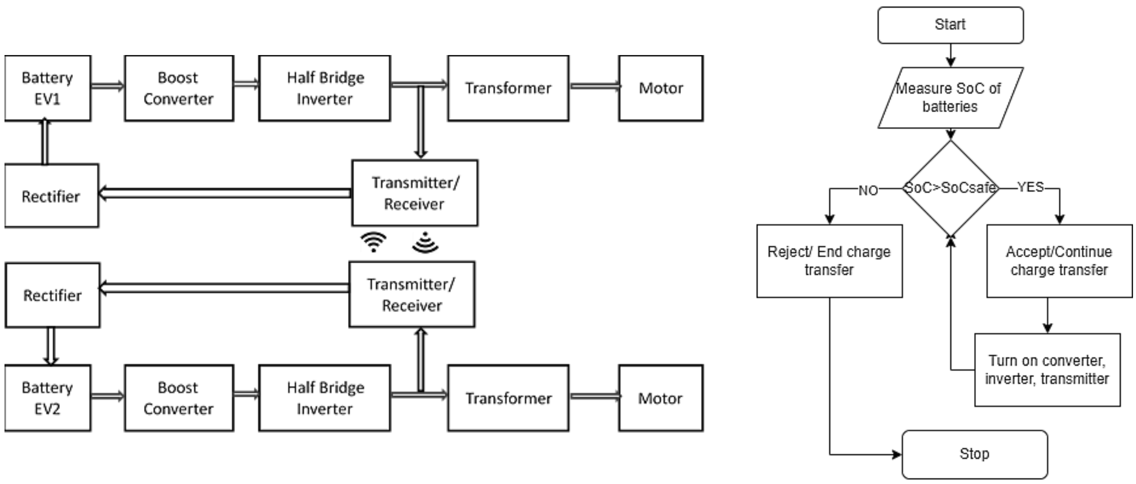
Wireless power transfer (WPT) technology is suitable for energy transfer between two circuits without involving any physical connection between them. Simplicity in design, system specific frequency selection and suitability in short distance applications make it an acceptable solution for numerous applications. It is very appealing in comparison with wired connection. Onboard battery charging of EVs allows charging while running and parking. The WPT needs a receiver and a transmitter coil. Inductive coupling between two circuits facilitates the energy transfer between them. The resonant type inductive coupling is suitable for medium and high power WPT as it offers greater efficiency.

Figure 4(a) depicts the block schematic of wireless power transfer between two EVs utilizing coils for transmission and reception. The charge transfer takes place with a knowledge of the state of charge of EV batteries. When EV1 battery has more charge left than that of EV2, power flow will happen from EV1 to EV2 and vice versa with suitable control strategies. Unlike the direct power flow in a conventional BDC, here the mutual transfer occurs due to induction between two coils. Both the EVs carry a coil, which can act as receiver and transmitter according to the direction of power flow. In order to facilitate mutual induction, the boost converter raises the DC voltage from battery to a higher magnitude. To transmit the power through induction, the inverter transforms it to AC. As the coil receives power, the rectifier converts it to DC voltage to charge the battery.

While running, the battery needs to feed the motor. The block diagram in the figure carries an induction motor. The battery has to supply power to the motor and share the available charge to the vehicle that needs power. Boost converter increases the level of DC and inverter transforms it to alternating waveform not only for the induction motor but also for transmission. Induction motor will receive a stepped-up AC voltage while the controller decides the activation of transmitter coil after evaluating the SoC of both batteries. When EV1 SoC is greater than that of EV2, then EV1 can transmit and EV2 can receive and vice versa. The controller chooses the mode of operation employing a single coil for both transmission and reception.

Figure 4(a) corresponds to wireless power transfer from EV1 to EV2 alone. EV1 is feeding an induction motor as the drive for the vehicle through boost converter and an inverter. The power flows from VB1, battery of EV1 through the boost converter and half bridge inverter. The high frequency inverter output feeds the motor and the bridge rectifier connected to battery VB2 of EV2. The filter ensures ripple less dc for battery charging. The selection of inverter frequency is important. The resonant frequency of the coil and connecting circuits for compensation affects the frequency of operation. The operation of the wireless power transfer from one vehicle to the other is best explained with the flowchart Figure 4(b).

Figure 5 represents the circuit diagram for the wireless charge transfer from one vehicle to other. When the charge in VB1 is higher than that of VB2 and switches Q4 and S5 turned on, will initiate transmitter coil and receiver coil. L1 stores charge from the battery VB1 with Q1 on. The battery voltage and stored energy across the inductor will be available for inversion with Q1 turned off. The boost operation increases the dc voltage level from 48 to 120 volts. Alternate operations with Q2 and Q3 presents the ac waveform across the step-up transformer. This completes the ac motor drive circuit.



(a) (b)

Figure 4. Wireless power transfer for EV: (a) schematic diagram for wireless transfer and (b) flowchart for wireless transfer

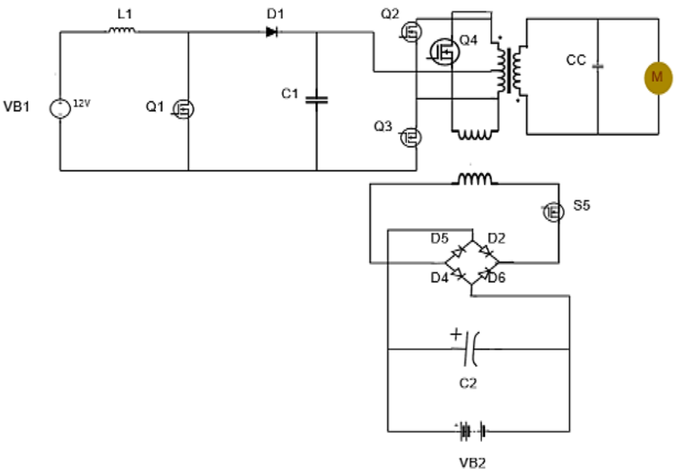


Figure 5. Circuit diagram for wireless power transfer

If EV1 represents a short distance vehicle and EV2 represents a vehicle in need, the latter can wirelessly charge from the former while running in parallel and with Q4 and S5 on. MATLAB/Simulink offers a platform for simulation of power electronic circuits. Figure 6 shows the Simulink model of the proposed strategy. The values of components for the bidirectional converter in simulation are: Battery – LiFePO4, 48 V, 24 Ah, Inductance – 30 mH, BDC Capacitor C1 - 10 µF, filter capacitor C2 -10 µF and load side capacitor Cc - 30 µF. Figure 6 shows the Simulink model for EV1>EV2.

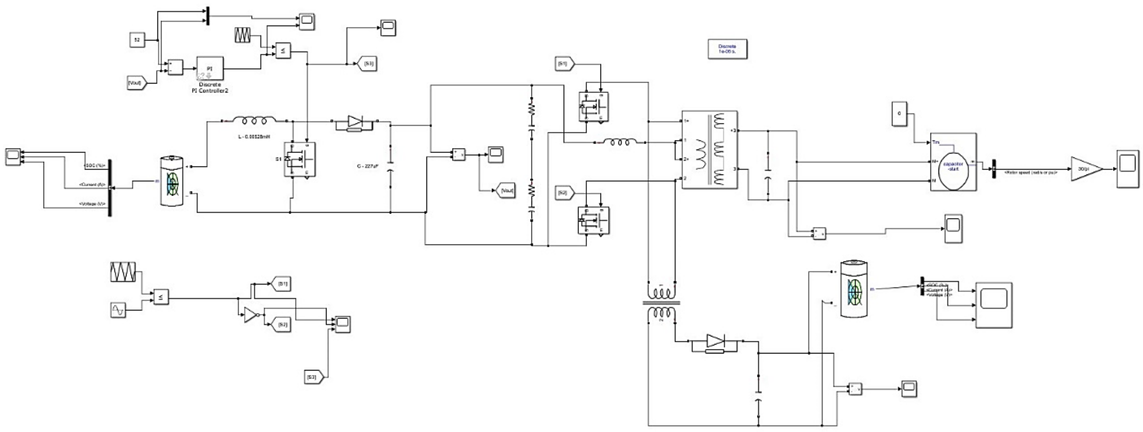


Figure 6. Simulink model for wireless power transfer

2.2.1. Experimental evaluation

The controller is Arduino Uno microcontroller with 8 analogue inputs, a 16 MHz ceramic resonator and 14 digital I/O pins. The controller has to monitor the SoC of the two batteries and generate the PWM signals for the control of the converter and inverter. The switches are MOSFET (IRF244N), diodes are IN5822, driver IC TLP 250. The inductance is a toroid wound as per the design and capacitors are electrolytic. The hardware and its components are shown in Figure 7.

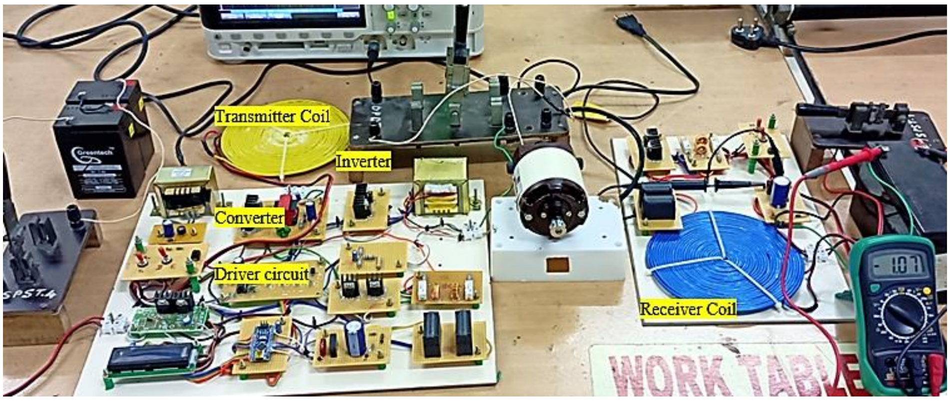


Figure 7. Hardware for wireless power transfer scheme

2.3. Fuzzy logic controller

A battery management system keeps the battery pack in safe mode and allows reliable operation. The parameters under consideration are V, the pack, T the temperature measured from temperature sensors and I the current flowing into or out of the path. The battery management systems (BMS) has to monitor and estimate the state of charge (SoC), the state of health (SoH), and the safe operating envelope (SoE). SoH shows its capacity relative to the beginning of battery life and SoE helps to calculate the current for given charge/discharge characteristics. When the input variables vary over a range of conditions, heuristic approaches as FLC offers accurate solutions, which are easy to develop, and accommodates large operating range.

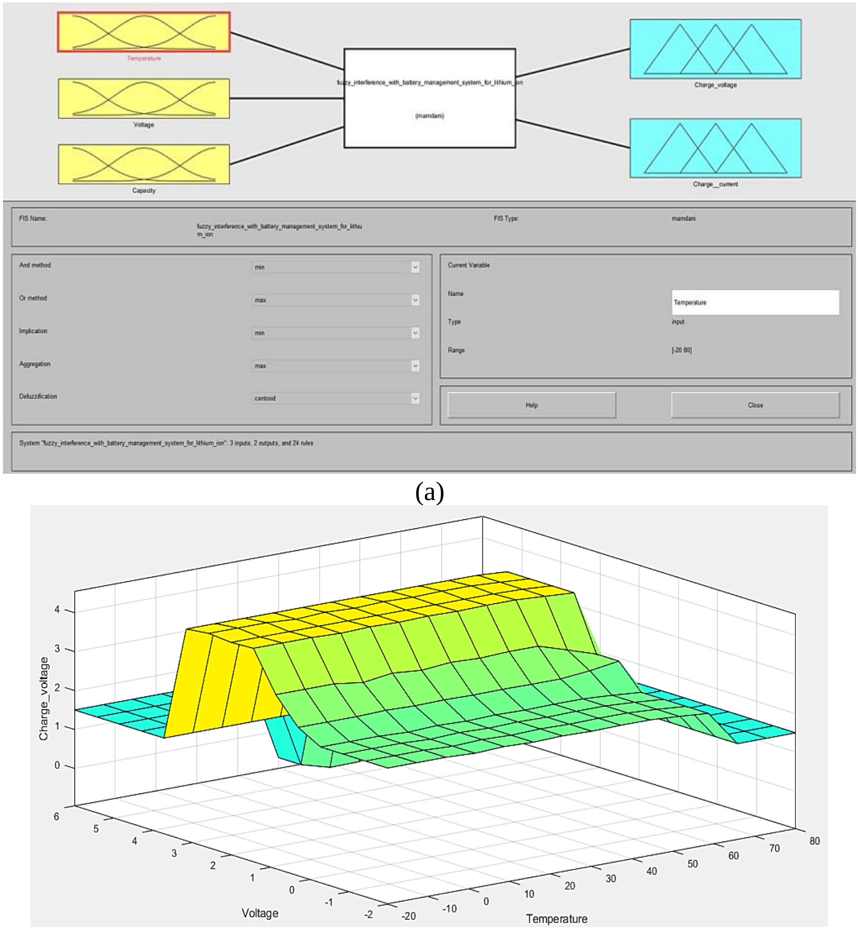
For the FLC, the input variables are temperature, voltage input and current capacity of the cell and the output variables are charge voltage and the charge current. The linguistic variables included for fuzzy rule are as follows:

- Voltage: Reverse potential-RP, over discharge-OD, low-L, nominal-N, over charge-OC, extreme over charge-EOC;
- Temperature: Critcal-C, extreme low-EL, low-L, operating-O, high-H, extremely low-EL; and
- Capacity: High-H, Low-L.

With the rules in Table 1, the IF-THEN relations are formed which gives the rule base for the fuzzy logic controller. Figure 8 shows the fuzzy logic controller as implemented in MATLAB. The FLC interface window Figure 8(a) shows the three input variables and the two output variables. The fuzzy decision surface is shown in Figure 8(b).

Table 1. Fuzzy logic rules

Rule	Voltage	Temper-ature	Capacity	Charge voltage	Charge current	Rule	Voltage	Temper-ature	Capacity	Charge voltage	Charge current
1	-	C	-	-	Hold	13	L	H	-	Fast Charge	Ch. Slow
2	RP	EL	-	Charge	Ch. Fast	14	OC	C	-	Hold	Hold
3	RP	L	-	Charge	Ch. Fast	15	OC	EL	H	Charge	Disch.fast
4	RP	O	-	Charge	Ch. Slow	16	OC	L	H	Charge	Disch.fast
5	RP	H	-	Charge	Ch. Slow	17	OC	O	H	Charge	Disch.fast
6	OD	EL	-	Fast Charge	Ch. Fast	18	OC	H	-	Charge	Disch.slow
7	OD	L	-	Fast Charge	Ch. Fast	19	EOC	C	L	Charge	Disch.slow
8	OD	O	-	Fast Charge	Ch. Slow	20	EOC	EL	H	Fast Discharge	Disch.fast
9	OD	H	-	Fast Charge	Ch. Slow	21	EOC	L	H	Fast Discharge	Disch.fast
10	L	EL	-	Fast Charge	Ch. Fast	22	EOC	O	H	Fast Discharge	Disch.fast
11	L	L	-	Fast Charge	Ch. Fast	23	EOC	H	-	Fast Discharge	Disch.slow
12	L	O	-	Fast Charge	Ch. Slow	24	EOC	C	H	Fast Discharge	Disch.slow



(a)

(b)

Figure 8. The fuzzy logic controller (a) fuzzy interface window and (b) fuzzy decision surface

3. RESULTS AND DISCUSSION

The simulation studies are carried out in MATLAB/Simulink platform. For the wired scheme of power transfer, the values for the BDC are Battery- LiFePO4, 48 V, 24 Ah (Seonex Energy), Inductance L=30 mH, Source Capacitor CL1=CL2= 10 µF and Load Capacitor C1=C2=10 mF. The first battery SoC is 90% with a voltage of 43.2 V and the second battery has an initial SoC of 30% with a nominal voltage of 14.4 V. Figure 9 shows the flow of charges. Figure 9(a) illustrates the powerflow from Battery 1 to the second battery. This improves the SoC of Battery 2 as shown in Figure 9(b). The charging time of the battery depends on the battery capacity and the charging current.

$$Charging\ time = \frac{Battery\ capacity\ (Ah)}{Charging\ current}$$

Further, the heat dissipation will increase the charging time at least by 30%. The discharging characteristics of the battery depends on battery voltage, its capacity and the power rating of the connected device. Discharging time is calculated as $Discharging\ time = \frac{Battery\ capacity\ x\ Battery\ Voltage}{Device\ wattage}$. Further, the discharging time is affected by the power efficiency of the battery. If we assume 90% power efficiency for Li-ion battery, the discharging time is depreciated by a factor of 0.9.

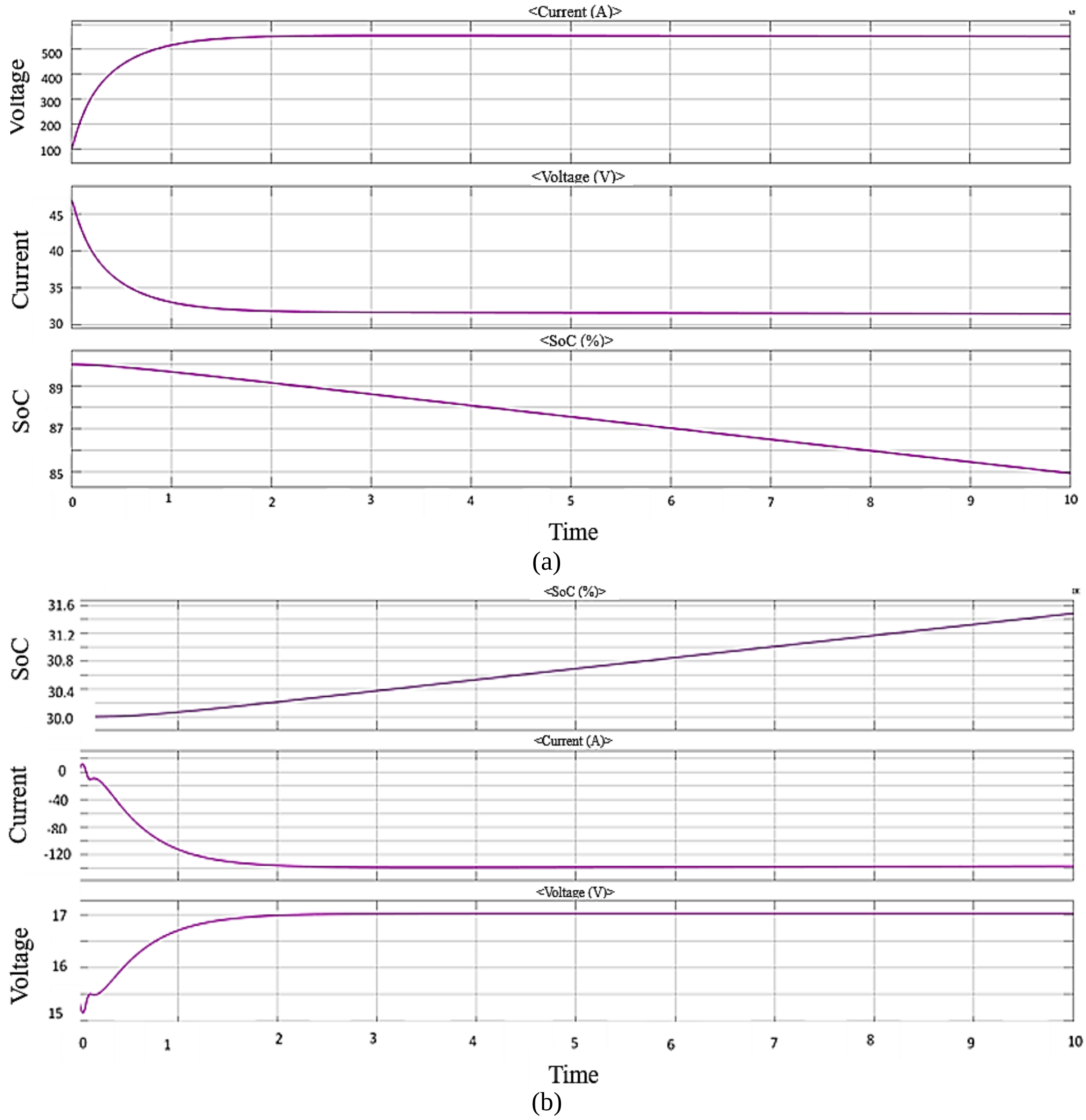
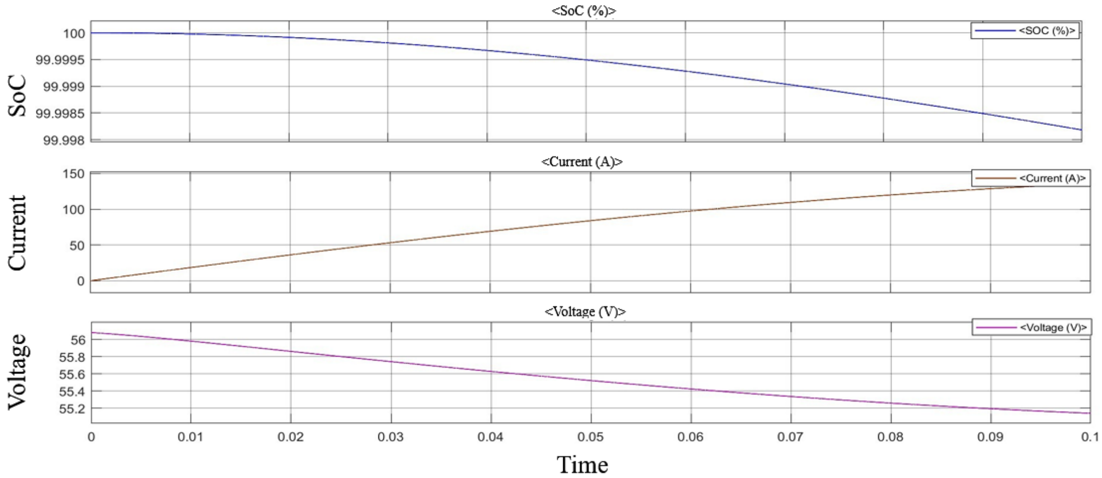


Figure 9. Transfer of charge for EV1>EV2 in wired scheme (a) powerflow from Battery 1 and (b) powerflow towards Battery 2

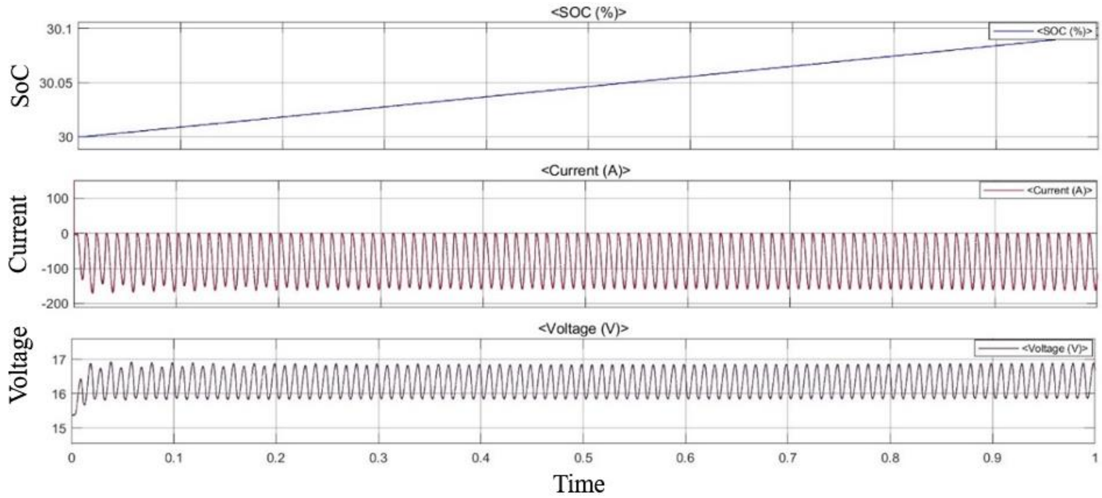
It is evident that the battery rating affects the charging time. Compared with wired scheme, wireless power transfer has limitations. Additional power conversion elements for AC is necessary for inductive transfer. Figure 10 shows the transfer of charge from battery of EV1 to that of EV2. This is possible even when the vehicles are on the go, provided they keep minimum distance between them. The SoC of EV1 falls from its initial value while that of EV2 goes up Figure 10(a). The EV1 battery is able to run the induction motor at the same time when it feeds the second vehicle.

Plot of the state of charge, voltage and current flow affirm the wireless transfer between EV1 and EV2. EV1 battery has an initial SoC of 100% and a voltage of 58 V while for EV2, they are 30% and 14 V. It's clear that EV1 SoC has drooping characteristics while EV2 SoC increases Figure 10(b). Varying the duty cycle of controls the output of the boost converter. The input and output of the boost converter are 48 V and 120 V respectively. PWM pulses from the controller operates the half bridge inverter. Simulations with batteries with different values of initial states of charge also accomplished wireless power transfer. The charging and discharging characteristics of the batteries are affected by their capacity, voltage and available charging current.

Wireless charging increases the flexibility of handling range anxiety faced by the EV owners. The do not have to wait in queue for availability of a charging port. Many vehicles can charge simultaneously or even they can charge while running also. The energy transfer efficiency is less in comparison to wired charging. The distance between the coils will also affect the energy transfer. The hardware results in Figure 11 shows that the voltage in receiver coil is higher when the transmitter and receiver coils are near to each other than they are farther away.



(a)

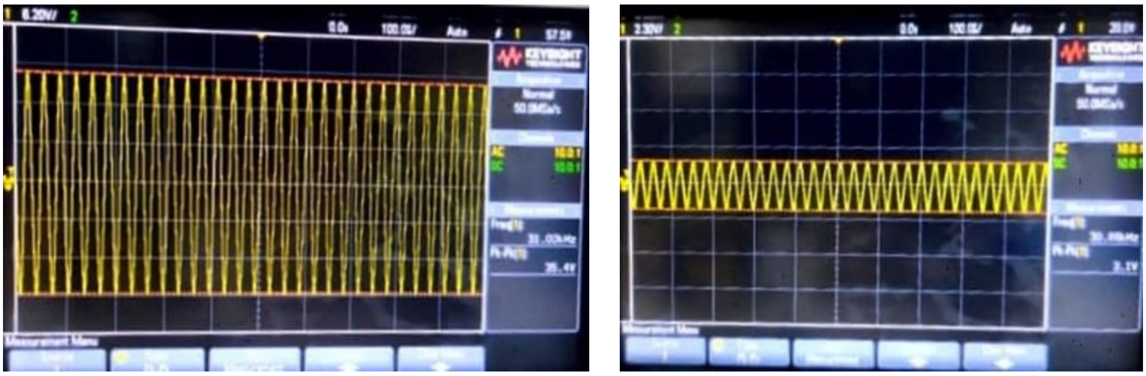


(b)

Figure 10. Battery characteristics during wireless charging (a) discharging of EV1 and (b) charging of EV2

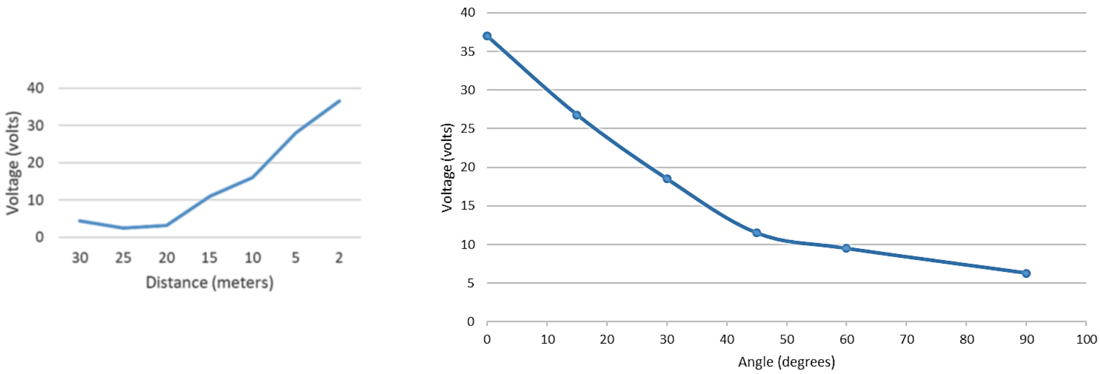
Figure 11(a) shows the voltage in the coil when the transmitter and receiver are near to each other. As the distance between them increase, the voltage magnitude decreases Figure 11(b). The distance between the coils will affect the wireless transfer. The orientation of the coils with respect to each other also affects the transfer rate.

Figure 12 shows the change in the magnitude of voltage received by the receiver coil when the distance between the coils is minimum (less than 5 cm) and is at a maximum of 30 cm. Hence, proximity of the coils influences the energy transfer rate. The orientation of the coils is another physical factor that can affect the inductive power transfer. Reading for different values of angle shows variation in the induced voltage. The graph of receiver voltage and distance is shown in Figure 12(a) and the effect of angle between the coils is depicted in Figure 12(b).



(a) (b)

Figure 11. Voltage waveform in the receiver coil, when the distance between transmitter and receiver coil is (a) minimum and (b) maximum



(a) (b)

Figure 12. Receiver voltage variation with distance and angle (a) voltage variation with distance and (b) voltage variation with angle

4. CONCLUSION

Electric vehicles have become the center of attraction across not only the society but also the research community, as fossil fuels need replacement due to the scarcity and environmental pollution. The battery capacity and drive cycles affect the range of the vehicles. Cost and range anxiety limit the popularity of the EVs. Charging time and charging facilities also affect the EV performance. When charging stations and ports are far away, EVs can share their charge. The user is relieved of the range anxiety if V2V charging is possible. This paper compares two charging schemes between vehicles; wired and wireless charging of EVs. The first method is simple and one needs to carry a compatible V2V charger along with the vehicle. The scheme in this paper analyses the available charge and allows the charge transfer. A controller must be available to estimate the SoC of both the vehicles and allocate charge for the other vehicle without affecting the reach-home charge of the donor vehicle.

This paper presented a fuzzy logic controller for determining the charge transfer strategy. Second scheme is wireless and both the vehicles need to be equipped with similar hardware for the charge transfer. The method is reliable and easy to implement. Wireless method allows transfer between vehicles even when they are on the go, provided they maintain minimum proximity. The angle between the transmitter and receiver affects the power transfer, as with the distance between them. Even though the power transfer rate and energy efficiency are inferior to the wired scheme, absence of wires outside the vehicle makes it a flexible charging option. MATLAB simulations prove the effectiveness of the schemes and hardware implementation validate the strategies.

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