The proposed model comprises a CUK converter fed resonant LLC (Inductor Inductor Capacitor) converter-based charging solution for an e-bike battery pack, wherein the CC/CV (Constant Current/Constant Voltage) charging algorithm is implemented through the LLC converter. Heretofore, modifications were made in DC-DC converter topology to incorporate bridge-less topology to increase efficiency to eliminate current inrush issues and involve galvanic isolation. Moreover, bypassing the switching losses presented by a half-bridge converter. The presented topology operates a pulse-width modulated CUK converter in DCM (discontinuous conduction mode), which serves natural current shaping without an input ripple filter. The LLC converter eliminates switching losses by undergoing ZVS (zero voltage switching) and allows high-frequency operation. The closed-loop control of the trigger pulses of the CUK and LLC converters is responsible for the CC/CV charging of the battery and hence the reduced charging time. An 800 Wh CC/CV charger with a current rating of 16 A is developed to charge a 48 V, 20 Ah Li-ion battery, where the battery is expected to charge in less than 2 hours.

Keywords: Electric vehicle battery charger, DC to DC converter, Power Electronics converters Battery Charger electric vehicles.

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1. Introduction

As much promise the electric vehicle industry holds, the time taken to charge any electric vehicle has been its Achilles heel. People prefer an IC engine vehicle to its electric counterpart. A major reason being- It takes approximately two minutes to refuel an IC engine vehicle at the rate of 38 liters per minute, or about 1.3 GJ per minute- this translates to about 21.5 MW of power transfer per minute. An average electric vehicle takes around 3 to 4 hours on a fast charge to acquire as much energy which is considerably more than that taken to refuel a traditional vehicle. Evidently, there is a pressing need for faster charging and advancement in the charging technology, that is how fast our current infrastructure is capable of charging. Most of the chargers use power converters in the initial stage of the charging topology to be freely able to regulate voltages to a desired value. CUK converter presents a string of advantages when operated in DCM. It facilitates simple control loop structure and a natural current shaping without any output filter [1, 2].

CC-CV is utilized to charge Li-ion battery powered EVs, because of their higher power densities and energy densities, than other cells [3]. This algorithm works by mapping the battery voltage in CC mode and switching to CV mode once the maximum voltage level is reached [4–6]. The LLC resonant bridge converter is the preferred second-stage converter, as it is highly efficient. ZVS in LLC converter enables switch-on losses to be eliminated and switch-off losses to be minimized. The LLC converter can also be used at higher frequencies due to which the size of components is greatly reduced [2, 7], meeting both the demands of compactness and fast charging [3, 7, 8].

Thus, this paper presents an efficient charging algorithm
where the CUK converter is operated in DCM because it gives natural current shaping. This topology also replaces Half-Bridge converters with LLC resonant converter, which operates under ZVS (Zero Voltage Switching), thus reducing switching losses.

2. Proposed Charger Topology

The proposed converter is designed to charge a Li-Ion battery pack consisting of 12 cells in series and 8 cells in parallel with a capacity of 20 Ah, while the nominal and peak voltage of the said e-bike battery is 43.2 Volts and 50.4 Volts, respectively. In this configuration, the single-phase AC main is given as a supply to the diode rectifier. An input filter is connected to reduce the current and voltage ripples. The rectified DC output is given as an input to the specified DC-DC converter. The inverted DC output of the CUK converter is given to the LLC resonant converter, which produces pulsating DC output, given to a linear filter is connected to reduce the current and voltage ripples. The rectified DC output is given as an input to the specified DC-DC converter. The inverted DC output of the CUK converter is given to the LLC resonant converter, which produces pulsating DC output, given to a linear transformer. The output is given to the battery through a diode rectifier [9]. As depicted in Fig. 1(b), a closed loop system is formed to obtain the pulses needed to trigger the MOSFETs. The system takes battery current and voltage as feedback and compares it with a reference value. The comparison obtained after passing through a comparator is given to PI controllers sequentially. A square pulse is generated to trigger MOSFETs present in CUK converter and LLC resonant converter [10].

2.1. Operation of CUK Converter

A CUK converter is operated in discontinuous conduction mode (DCM) if the inductor current in \( L_1 \) is not zero. Thus, the inductor current \( I_{L2} \) is equal to the load current which is not dependent on input voltage [11, 12]. The average voltages generate the following equation as

\[ V_{in} = V_{L1} + V_{C1} + V_{L2} \]  

(1)

The average currents generate the following equation as,

\[ I_{D1} = I_{L1} - I_{L2} \]  

(2)

(i). Mode I: (0<\( t < T_d1 \)) : Initially switch \( S_1 \) is turned ON and inductor \( L_1 \) gets charged by input voltage \( V_{in} \) as shown in Fig. 2(b). The coupling capacitor \( C_1 \) is charged to source voltage \( V_{in} \), and the coupling capacitor discharges via inductor \( L_2 \). Diode is reverse biased hence open circuit [10, 13, 14]. A CUK converter operates in discontinuous conduction mode (DCM) only when inductor current through \( L_2 \) has zero value.

(ii). Mode II: (\( D_1 < t < T_2 \)) : The circuit shown in Fig. 2(c) represents that switch \( S_2 \) is OFF. Inductor \( L_1 \) discharges across coupling capacitor \( C_1 \), and charges it. Inductor \( L_2 \) changes polarity and is turned on by diode \( D_1 \). Inductor \( L_2 \) discharges across \( C_2 \) and load [10, 13, 14].

2.2. Operation of Resonant LLC Converter

The converter operates in three modes based on input voltage and load current conditions [15]: 1. \( f_s = f_r \), at frequency of resonance. 2. \( f_s > f_r \), at beyond the frequency of resonance. 3. \( f_s < f_r \), at under the frequency of resonance.

2.3. Operation of Control System

The voltage is taken as feedback in the first stage which is compared with a reference. The error generated is given to the voltage controller, which consists of a PI controller tuned in order to achieve a specific error. The error generated from the voltage controller is compared with the battery current. The error generated from the adder is given to a current controller which has a PI controller. The output is compared with a sawtooth wave and a square pulse is obtained [2-4, 7, 8, 11]. The obtained square pulse operates the two switches present in the resonant LLC converter, alternatively [5]. The square pulse obtained is compared with a reference frequency which is the ideal value. The error is passed through a frequency controller and saturator to ramp up the incoming pulse. This output is compared to a reference value, which is the ideal voltage level. In the final stage, this output is passed through a PI controller and voltage limiter to confine the output within safe limits. This is compared with a carrier frequency wave and a second square pulse is generated. This square pulse is used to operate the CUK converter [2, 4, 7].

2.4. Charging of Battery in CC-CV

Maintaining the CC mode current requires that the charge voltage should, together with the cell voltage, increase to exceed the battery back EMF. In CV mode charge voltage is kept at the same level, christened as “float level” [6]. As the point of minimal current is closed upon, charging cuts off, which indicates that charging is completed [16, 17]. Equation mentioned, might give a reasonably approximated duration for the time taken to fully charge a battery utilizing the prescribed CC/CV charging methodology [4].

Charging Time = \[ 1.3 \times \frac{(\text{Battery capacity in Ah})}{(\text{CC mode charging current})} \]  

(3)

3. Power Loss Analysis

3.1. Loss Analysis of CUK Converter

In CUK converter stage, the losses obtained are generally due to switching losses \( P_{MOSFET} \), diode conduction losses \( P_{Diode} \) and inductor losses \( P_{Inductor} \) [6]. The power loss
in switching devices or MOSFET is considered as switching losses. This is calculated below,

\[ P_{MOSFET} = I_{OUT}^2 \times R_{DS(on)} \times D \]  

Where \( I_{OUT} \) is the output current of CUK converter, \( R_{DS(on)} \) is drain-to-source channel resistance during ON condition, and \( D \) denotes duty cycle.

\[ P_{MOSFET} = 20^2 \times (5 \times 10^{-3}) \times 0.66 = 1.32W \]

The diode conduction losses is given by the below equation, where \( V_F \) is the forward voltage drop of diode.

\[ P_{Diode} = V_F \times I_{OUT} \times (1 - D) \]

\[ = 0.7 \times 20 \times (1 - 0.66) = 4.76W \]

The DC resistance (DCR) of the inductor is considered,
hence, its loss is measured as,

\[ P_{\text{Inductor}} = I_{\text{OUT}}^2 \times DCR = 20^2 \times (420 \times 10^{-3}) \]
\[ = 168 \text{W} \]  

Since, CUK converter contains two inductors, \( P_{\text{Inductor}} = 2 \times 168 = 336 \text{W} \) The total power loss in CUK converter stage is denoted as \( P_{\text{total}} \), which is the sum total of equation 4, 5 and 6.

\[ P_{\text{Conduction}} = P_{\text{MOSFET}} + P_{\text{Diode}} + P_{\text{Inductor}} = P_{\text{total}} \]
\[ = 1.32 + 4.76 + 336 = 342.08 \text{W} \]  

\[ P_{\text{OUT}} = 8200 \text{W} \]

\[ \text{Efficiency} = \frac{P_{\text{OUT}}}{P_{\text{OUT}} + P_{\text{total}}} = \frac{8200}{8200 + 342.08} \times 100 \]
\[ = 95.99\% \]

Hence, the efficiency of the first stage of the topology is calculated to be 95.99%,

\[ i_s = I_{\text{OFF}} = 15 \text{A} \]  

\[ V_{DS} = \frac{V_i (\omega t)^2}{(\omega t_r)^2} \]
Parameters

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Experimental Value</th>
</tr>
</thead>
<tbody>
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<td>SEPIC Converter</td>
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</tr>
<tr>
<td>1</td>
<td>Input Voltage</td>
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</tr>
<tr>
<td>2</td>
<td>Output Voltage</td>
<td>420 V DC</td>
</tr>
<tr>
<td>3</td>
<td>Inductor, ( L_1 )</td>
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</tr>
<tr>
<td>4</td>
<td>Inductor, ( L_2 )</td>
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<td>5</td>
<td>Capacitor, ( C_1 )</td>
<td>0.526 ( \mu )F</td>
</tr>
<tr>
<td>6</td>
<td>Capacitor, ( C_2 )</td>
<td>0.117 ( \mu )F</td>
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<td>LLC Resonant Converter</td>
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<td>Turns Ratio of LLC Transformer</td>
<td>4.117</td>
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<td>2</td>
<td>Resonant Capacitor, ( C_r )</td>
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</tr>
<tr>
<td>3</td>
<td>Resonant Inductor, ( L_r )</td>
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</tr>
<tr>
<td>4</td>
<td>Magnetising Inductor, ( L_m )</td>
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<tr>
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<td>1</td>
<td>Nominal Voltage</td>
<td>44.4 V</td>
</tr>
<tr>
<td>2</td>
<td>Nominal Capacit</td>
<td>25 Ah</td>
</tr>
<tr>
<td>3</td>
<td>Peak Voltage</td>
<td>50.4 V</td>
</tr>
<tr>
<td>4</td>
<td>Constant Charging Current</td>
<td>16 A</td>
</tr>
</tbody>
</table>

(a) Battery Characteristic - Before and After Charging.

(b) Transient Characteristics during Battery Charging.

Fig. 11. Experimental result.

Power loss during the rise-time of the current flowing through the switch (\( i_s \)) is calculated as,

\[
P_{t_r} = \frac{1}{2\pi} \int_0^{2\pi} i_s V_{DS}(\omega t) T_s = \frac{V_l I_{OFF} T_s}{3 T_s} = \frac{400 \times 15 \times (1 \times 10^{-6})}{3 \times (0.25 \times 10^{-6})} = 80W
\]

(11)

The current before turn-off period during fall-time of the switch and drain to source voltage is given by,

\[
i_s = I_{OFF}(1 - \frac{\omega t}{\omega t_f})
\]

(12)

\[
V_{DS} = V_I
\]

(13)

Power loss during the fall-time of the current flowing through the switch (\( i_s \)) is calculated as,

\[
P_{t_f} = \frac{1}{2\pi} \int_0^{2\pi} i_s V_{DS}(\omega t) T_s = \frac{V_l I_{OFF} T_f}{2 T_s} = \frac{400 \times 15 \times (1 \times 10^{-6})}{2 \times (0.25 \times 10^{-6})} = 192W
\]

(14)

Total switching loss of LLC converter is sum total of equations 11 and 14,

\[
P_{t_{-off}} = P_{t_r} + P_{t_f} = \frac{V_l I_{OFF}}{T_s} (\frac{T_r}{3} + \frac{T_f}{2}) = 80 + 192 = 272W
\]

(15)

Losses due to drain-to-source resistance of the switch is given by,

\[
P_{RDS_{(on)}} = \frac{I_{OFF}^2 R_{DS_{(on)}} t_{on}}{T_s} = (14)^2 \times (1 \times 10^{-3}) \times (1.6 \times 10^{-6}) = 0.1255W
\]

(16)

RMS value of diode current is taken as,

\[
I_{D_{rms_{(on)}}} = \frac{1}{2\pi} \int_0^{2\pi} i_{D_{DS}}(\omega t) d(\omega t) = \frac{\pi I_o}{4} = \frac{\pi \times 12}{4} = 9.42A
\]

(17)

Power losses due to internal resistance (\( R_F \)) of diode is calculated as,

\[
P_{RF} = R_F I_{D_{rms}}^2 = (1 \times 10^{-3}) \times 9.424^2 = 0.08W
\]

(18)

Current flowing through the diode (\( I_D \)), is justified as,

\[
I_D = \frac{1}{2\pi} \int_0^{2\pi} i_{D_{DS}}(\omega t) d(\omega t) = \frac{I_o}{2} = \frac{12}{2} = 6A
\]

(19)

The turn-on power loss is shown as,

\[
P_{V_{T_{(on)}}} = V_T I_o = \frac{0.8 \times 12}{2} = 4.8W
\]

(20)

Combining equations 17 and 18 with 20, to obtain total power loss in diode,

\[
P_D = \frac{V_T I_o}{2} + \frac{\pi^2 I_o^2 R_F}{16} = 4.8 + \frac{\pi^2 \times (10^3)^2 \times 10^{-3}}{16}
\]

(21)
Power loss due to resistance of the resonant inductor \( (P_{Lr}) \) is calculated as,
\[
P_{Lr} = \frac{L_r I_p^2}{2T_S} = \frac{(29.6 \times 10^{-6}) \times 14^2}{2 \times (2.5 \times 10^{-5})} = 116 \text{ W}
\] (22)

Hence, the efficiency of the second stage of the topology is calculated to be 69.24 %.
\[
P_{\text{OUT}} = \text{885.12 W}
\]
\[
P_{\text{total}} = 272 + 0.1255 + 4.888 + 151 = 428.143 \text{ W}
\]
\[
\text{Efficiency} = \frac{P_{\text{OUT}}}{P_{\text{OUT}} + P_{\text{total}}} = \frac{885.12}{885.12 + 428.143} \times 100 = 67.38\%
\] (23)

Overall system efficiency becomes 81.69 %.

### 4. Simulation Results

The DC input taken from the PV grid will be boosted via DC-DC converter stage and is thus given as LLC input. The resonant converter generates a sinusoidal voltage output which is given as input to a linear transformer. A full-wave bridge rectifier is used to rectify the AC output, which is filtered by an output filter and is used to charge the battery pack. The values of the components are mentioned in the table 1.

#### 4.1. Input Current and Voltage Characteristics of CUK Converter and Resonant LLC Converter

The input voltage and current are received after rectification from an AC voltage source. A single-phase 230 V AC supply is supplied to the rectifier which rectifies it into 207 V DC. The respective waveforms are shown in Fig. 5(a) and Fig. 5(b). The resonant LLC converter takes the non-inverted output from the CUK converter and converts into pulsating DC. The CUK converter gives an average output voltage of 420 V. The input current and voltage to LLC converter is shown in Fig. 5(c) and Fig. 5(d).

#### 4.2. Switching pulses of CUK and LLC Converter

In the cascaded loop, the first pulse is given to Switch \( S_2 \), \( S_2 \) and \( S_3 \) work alternatively or at a phase difference of 180°. Thus, with the help of a NOT gate this pulse is given to Switch \( S_3 \) as well. The second pulse obtained is given to Switch \( S_1 \), which is present in the SEPIC converter. The pulses for LLC and CUK are shown in Fig. 6.

#### 4.3. Battery Output Characteristics

The nominal voltage is observed as 45.6 V at 100 % SoC and the fully charged voltage is noted to be 50.4 V. The current in CC mode is observed to be 16 A which decays as the SoC level crossed 70 %. The voltage, current, and SoC waveforms are shown in Fig. 7.

#### Table 2. SoC versus Charging Current and Charging Voltage.

<table>
<thead>
<tr>
<th>SoC</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-15.67</td>
<td>32.50</td>
</tr>
<tr>
<td>30</td>
<td>-15.67</td>
<td>36.04</td>
</tr>
<tr>
<td>40</td>
<td>-15.67</td>
<td>40.29</td>
</tr>
<tr>
<td>50</td>
<td>-15.67</td>
<td>44.47</td>
</tr>
<tr>
<td>60</td>
<td>-15.70</td>
<td>47.58</td>
</tr>
<tr>
<td>70</td>
<td>-15.67</td>
<td>49.71</td>
</tr>
<tr>
<td>80</td>
<td>-11.49</td>
<td>49.75</td>
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<td>90</td>
<td>-8.22</td>
<td>49.85</td>
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<tr>
<td>95</td>
<td>-3.70</td>
<td>50.20</td>
</tr>
<tr>
<td>98</td>
<td>-1.60</td>
<td>50.30</td>
</tr>
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</table>

#### Table 3. Component Values used in Hardware.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Inductor, ( L_1 )</td>
<td>100 mH</td>
</tr>
<tr>
<td>2.</td>
<td>Inductor, ( L_2 )</td>
<td>100 mH</td>
</tr>
<tr>
<td>3.</td>
<td>Capacitor, ( C_1 )</td>
<td>2.2 ( \mu )F</td>
</tr>
<tr>
<td>4.</td>
<td>Capacitor, ( C_2 )</td>
<td>4.7 ( \mu )F</td>
</tr>
<tr>
<td>5.</td>
<td>SEMIKRON IGBT Module</td>
<td>150 V, 30 A</td>
</tr>
<tr>
<td></td>
<td><strong>LLC Resonant Converter</strong></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Resonant Capacitor, ( C_r )</td>
<td>47 nF</td>
</tr>
<tr>
<td>3.</td>
<td>Resonant Inductor, ( L_r )</td>
<td>9 ( \mu )H</td>
</tr>
<tr>
<td>4.</td>
<td>Magnetising Inductor, ( L_m )</td>
<td>56 ( \mu )H</td>
</tr>
<tr>
<td>5.</td>
<td>SEMIKRON IGBT Module</td>
<td>150 V, 30 A</td>
</tr>
</tbody>
</table>

The SoC-current and SoC-voltage characteristics are in conformity with the expected waveforms (see Fig. 8). The Table 2 clearly shows the progression of current and voltage values from 20 % SoC to 98 % SoC. The constant current can be seen to be diminishing from 15.67 A to 1.6A. Here, CC mode switches to CV mode at 70 % SoC, as the battery approaches end of cycle. While, the voltage can be seen rising, until 70 % SoC and gaining a constant level, in the CV mode. The CC-CV charging facilitates an efficient charging approach where, in CC mode, a high charging current provides fast charging till the voltage reaches a safe threshold, and in CV mode, the current trickles down and charges slowly until the battery is fully charged. This mode avoids the over-charging due to high current, thus, ensuring charge safety.
4.4. Charging Current Variation at Different Switching Frequencies

As can be observed, a charging current of 15 A at 40 kHz switching frequency is obtained, which is the maximum current that the battery pack can sustain. The observations have been plotted in Fig. 9a and Fig. 9b. The CUK converter was tested with multiple switching frequencies varying from 10 kHz to 40 kHz. Subsequently, a charging current of 16 A is obtained at a frequency of 40 kHz against 16.5 A, 16 A and 17 A at 10 kHz, 20 kHz and 30 kHz respectively. Likewise, the LLC tank circuit was provided an input of switching frequencies ranging from 10 kHz to 40 kHz. A satisfactory and desired charging current of 16 A was obtained at 40 kHz.

5. Experimental Verification

5.1. Hardware Component

The components used in hardware verification and their parameter values are listed in Table 3.

5.2. RT-GUI FPGA Controller

The used Spartan-6 FPGA module provides real time user configurable bridge between a host processor and a custom graphical user interface. The closed loop charge controller is realised using the Spartan-6 FPGA module on real time basis using the logic gates, comparators and other pre-set functions available via the Graphical User Interface. The square-wave gate pulses at which the semiconductor switches of CUK and LLC converters are triggered are obtained.

5.3. Battery Stacking

As mentioned, the cells of choice are SAMSUNG cylindrical 18650 NCA chemistry cells. With an objective to construct a 48 V, 20 Ah battery pack, following calculation was made to determine the stack configuration. Hence, to achieve a pack voltage of 48 V, the number of cells in series is 12. A nominal pack voltage of 43.2 V and a peak voltage of 50.4 are obtained

\[
\text{Number of cells in series} = \frac{\text{desired pack voltage}}{\text{unit cell voltage}} = \frac{48}{4.2} = 11.4 \quad (24)
\]

Hence, to achieve a pack capacity of 10 Ah, the number of cells in parallel is 4 [9]. The pack appears as shown in Fig. 10.

\[
\text{Number of cells in parallel} = \frac{\text{desired pack capacity}}{\text{unit cell capacity}} = \frac{20}{2.5} = 8 \quad (25)
\]

5.4. Hardware Results

The output waveforms are recorded which depict various characteristics of battery in varied conditions. Output response of the battery before and during charging follows the characteristics as shown in Fig. 11a. The battery charging profile during charging shows average charging voltage, while before charging, the voltage level of battery was relatively low. Constant current is used to charge the battery. The output current of CUK and LLC converter holds a constant value with negligible ripples. Fig. 11b represents the battery transient response, which signifies the charging characteristics of the battery, while the SoC is 90 % and above (approaching to the full charge state). It can be observed that the battery charging current is decreasing, while the charging voltage is almost standing constant and further increasing.

6. Conclusion

In this study, a 800 Wh charger for a 48 V, 20 Ah E-bike battery was designed and simulated. The topology was realized using the CUK Converter operating in DCM of its input inductor, which in turn supplies the Resonant LLC Converter. The LLC Converter undergoes ZVS and eliminates turn-on losses and reduces the turn-off losses. Further, the charger utilizes the CC/CV methodology to charge the battery stack, and this takes place via the closed loop controller designed using an inner current and outer voltage loop. The battery stack has been designed using Li-ion NCA cells, and can be charged by the designed system within 2 hours. Charging time was not compared experimentally, but commercial standards were considered to reach a goal of sub-2 hours of charging time. Companies offering similar capacity battery packs charge it in about 2 to 3 hours. So, to provide a faster means of charging we aimed to charge our 960 Wh pack within 2 hours. For comparison, Bosch E-bike systems fast charging occurs at 6A current and takes 3 hours to reach 100 % SoC. While Hero Lectro takes 3 hours to charge its 216 Wh battery pack.

7. Acknowledgement

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References

[1] Bhim Singh and Vashist Bist. Improved power quality bridgeless Cuk converter fed brushless DC motor


