Review design of E-Motorcycle charger topology for DC house using planar magnetics

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Abstract. Following the global trend of adopting renewable energy into the electric power system, many direct currents (DC) houses concepts are proposed. Most of the renewable energy systems are based on DC voltage sources. This paper discussed the development of a lightweight, low-profile, and built-in electric motorcycle (E-Motorcycle) charger that does not take excessive space and compatible with the DC house system. A topology comparison in high switching frequency above 1 MHz using planar magnetics is performed to select the most suitable DC-DC converter. A wide bandgap (WBG) devices are used to achieve high efficiency in high switching frequency and reduce the charger's size. Simulation results and design of the selected topology is presented.

1. Introduction

The people who live in remote and sparsely populated areas live without electricity due to the difficulty of reaching by the conventional centered generation transmission line. In this case, the distributed generation is the most suitable solution that utilizes renewable approaches since distributed generation typically uses renewable energy, which plenty of resources are in the remote and sparsely populated areas [1].

Most of the renewable power plant and house electric load are based on DC. According to [2],[3],[4],[5],[6], the concept of developing DC distribution has been researched towards its beneficial potential. Furthermore, it will be more advantageous from the aspect of conversion losses when DC generation feeds the DC bus and then directly to power the DC load, as shown in figure 1 [7]. Using a DC distribution system, a single residential house could optimally use 48-120 V DC as the DC Bus [8].

![Figure 1. Charging electric-motorcycle by (a) AC source and (b) DC source.](image-url)
EV charging energy demand can be seen by observing the percentage of kWh needed in 2020 for the top 3 EV leading regions (USA, Europe, China). Which the energy demand for an in-vehicle inverter that converts AC to DC to charge EV in 2020 is 91% in the USA, 94% in Europe, and 77% in China [9]. The DC house and DC microgrid are in line with the development of electric vehicles (EVs). It uses batteries, which also store energy in DC to power the vehicle. However, the current electricity infrastructures are based on the AC system. Therefore, the widely commercialized EV charger consists of two conversion stages: 1) front-end power factor correction converter and 2) isolated dc-dc converter, to charge the EV battery. On the other hand, when the utility is DC, only a single isolated dc-dc converter is required to charge the EV battery, which results in a smaller charger and higher conversion efficiency.

In the Asia region, the household ownership of the motorcycle is quite high [10], as shown in Table 1. Exchanging conventional motorcycle to electric motorcycle (E-Motorcycle) in these countries could have a big impact on reducing the carbon footprint. However, an E-Motorcycle could only provide low mileage due to low energy capacity designed within a small vehicle dimension for its mobility purpose.

| Vehicle | Vietnam | Indonesia | Malaysia | China | India | Thailand | Philippines |
|---------|---------|-----------|----------|-------|-------|----------|-------------|
| Motorcycle | 86%     | 85%       | 83%      | 60%   | 47%   | 87%      | 32%         |
| Car     | 2%      | 4%        | 82%      | 17%   | 6%    | 51%      | 6%          |

Generally, a longer E-Motorcycle mileage can be obtained by increasing the battery capacity, which is achieved by either adding more batteries or replacing it with better battery technology, such as Li-Ion, with a higher energy density battery cell [11]. Considering the limited space inside the E-Motorcycle, increasing the battery capacity, and including a built-in charger in the E-Motorcycle battery room will be quite challenging. Thus, designing a small and compact E-Motorcycle charger that can fit into the limited battery room is the objective of this paper. By increasing the switching frequency, the bulky passive component size, such as capacitor and magnetics, can be greatly reduced. However, the switching loss increases as the switching frequency rises. Thus, a combination of the high-efficient wide bandgap (WBG) devices and soft-switching converter topology is the solution to reduce the converter size without any adverse effect on the charger efficiency [12]. In this paper, two well-known DC-DC converter topologies for EVs, which are LLC resonant and dual active bridge (DAB) converters, are compared for DC house based E-Motorcycle charger [13][14].

2. Comparison of HBLCC & DAB Converter 120 V DC House based Electric Motorcycle Charger

The DC house has a nominal voltage of 120 V, and the E-Motorcycle nominal battery voltage is 48 V [15], which the detail specification is shown in Table 2. Note that we consider Li-ion battery rather than SLA battery because of higher power density and higher charging rate [16].

| $V_{in}$ | $V_{batt}$ | $I_{batt,max}$ | $P_{max}$ | $f_{sw}$ | Battery Technology |
|---------|------------|----------------|-----------|----------|--------------------|
| 120 V   | 48-55 V    | 10 A           | 550 W     | ≥ 1 MHz  | Li-ion             |

Li-ion battery requires a constant current (CC) and constant voltage (CV) charging method [16], which CC charging has a longer period than the CV charging. Hence, the converters are compared in two battery voltage conditions: 48 V and 55 V, with CC charging at 10 A. Table 3 shows the comparison and performance results between half-bridge LLC (HBLCC) and the DAB converter. Both topologies have similar performance in terms of the switching devices rating. The DAB uses more switching devices, resulting in higher conduction loss, but it enables the house-to-vehicle (H2V) and
vehicle-to-house (V2H) power flow. Meanwhile, HBLLC can only operate for H2V charging since it uses diodes.

The DAB secondary GaN FETs have a smaller voltage rating than HBLLC secondary diodes, which enable DAB to use switching devices with a smaller footprint. Although both converters’ GaN FETs are turned-off with hard switching conditions, the GaN FETs turn-off energy is negligible [17]. On the other hand, turn-on loss of GaN FETs is a big factor for the charger efficiency, which eliminated because both converters can operate with ZVS turn-on for whole operating conditions. Therefore, based on the performance comparison between DAB and HBLLC given in Table 3, the DAB converter is preferable due to the extra functionality of bidirectional power flow.

### Table 3. Topology Comparison

| Topology          | HBLLC Resonant | Dual Active Bridge |
|-------------------|----------------|------------------|
| Circuit diagram   | ![HBLLC Circuit Diagram](https://example.com/hbllc.png) | ![DAB Circuit Diagram](https://example.com/dab.png) |
| Turn-ratio        | 1:1            | 2:1              |
| Converter control | Frequency modulation | Phase shift modulation |
| Switching frequency | 1.125-1.3 MHz  | 1 MHz            |
| # Switching devices | 2 GaN FETs 2 Diodes | 8 GaN FETs       |
| Powerflow characteristic | H2V     | H2V & V2H        |
| $V_{bat}$ Condition | 55V  | 48V  | 55V  | 48V  |
| Voltage           | $V_{S1,S2} = 120$ V | $V_{S1,S2} = 120$ V | $V_{S1,S4} = 120$ V | $V_{S1,S4} = 86.4$ V |
|                   | $V_{D1,D2} = 110$ V | $V_{D1,D2} = 100$ V | $V_{S5,S8} = 55$ V  | $V_{S5,S8} = 34.9$ V |
|                   | $I_{S1,S2} = 8.1$ A (rms) | $I_{S1,S2} = 8.1$ A (rms) | $I_{S1,S4} = 4.1$ A (rms) | $I_{S1,S4} = 4.1$ A (rms) |
|                   | $I_{D1,D2} = 5$ A         | $I_{D1,D2} = 5$ A         | $I_{S5,S8} = 10.6$ A (rms) | $I_{S5,S8} = 10$ A (rms) |
| Switching device  | Voltage           | Current           | Voltage           | Current |
|                   | $I_{S1,S2} = 10$ A       | $I_{S1,S2} = 14.5$ A  | $I_{S1,S4} = 7$ A  | $I_{S5,S8} = 8$ A |
|                   | $I_{D1,D2} = 7$ A        | $I_{D1,D2} = 12.5$ A  | $I_{S5,S8} = 21$ A | $I_{S5,S8} = 17$ A |
| ZVS turn on       | ✓                | ✓                | ✓                | ✓                |

3. Magnetic Design and Converter Estimated Size

This chapter discusses the magnetics design since it is the converter's biggest component, which greatly affects the power density. The design flowchart for the PCB integrated transformer and inductor are given in Figures 2 and 3, respectively [18]. The minimum number of turns is considered in this paper.

![Figure 2. Transformer design flowchart](https://example.com/transformer-flowchart.png)

![Figure 3. Inductor design flowchart](https://example.com/inductor-flowchart.png)
The ML91S core material from Hitachi Metals is chosen for both magnetics because it has the lowest core-loss density at high switching frequency [19]. Both magnetics are designed using two layers PCB to reduce the production cost. The formula to calculate the core cross-section area $A_c$ and winding size $W$ for both magnetic components are given in (1)-(3). As shown in Table 4, the inductor size of HBLLC is smaller than DAB due to lower inductance value. The transformer is designed based on the worst-case volt-second and winding current of both topologies. The volt-second of the DAB converter is higher than the HBLLC converter, affecting the size of the transformer $A_c$. However, due to the DAB converter use two primary turns, the DAB transformer $A_c$ is similar to HBLLC transformer $A_c$. Nevertheless, the transformer size of DAB is bigger than HBLLC because DAB requires a larger footprint to accommodate the total transformer winding area, as shown in Table 5.

\[
A_{c,ind} = \frac{L \cdot \text{airgap}}{\mu_0 \cdot \mu_r}
\]

\[
A_{c,trans} = \frac{\text{Volt} \cdot \text{sec}}{2B_{\text{max}} \cdot N_p}
\]

\[
W = \frac{I_{\text{rms}}}{\text{layer}} \cdot \text{Current Density} \cdot \text{PCB Copper Height}
\]

### Table 4. E-Motorcycle charger inductor design comparison

| Topology          | HBLLC Resonant | Dual Active Bridge |
|-------------------|----------------|-------------------|
| Inductance        | 500 nH         | 2,210 nH          |
| $I_L$             | 11.5 A         | 5.7 A             |
| $W_{\text{ind}}$  | 2.07 mm        | 1.03 mm           |
| $A_c$             | 160 mm²        | 309.4 mm²         |

### Table 5. E-Motorcycle charger transformer design comparison

| Topology          | HBLLC Resonant | Dual Active Bridge |
|-------------------|----------------|-------------------|
| $I_{\text{pri}} / I_{\text{sec}}$ | 11.2 A/11.1 A | 6.1 A/15.4 A      |
| $W_{\text{pri}} / W_{\text{sec}}$ | 4.03 mm/4.03 mm | 4.39 mm/5.55 mm |
| Volt-sec          | 24.8 V·µs      | 55 V·µs           |
| $A_c$             | 248 mm²        | 275 mm²           |
| $L_m$             | 3.7 μH         | 5 μH              |

3D view
The comparison of the estimated E-Motorcycle charger size between HBLLC and DAB are shown in Table 6. As shown in Table 6, the size of the magnetic components occupies more than 84% of the total charger size. Due to the larger magnetic components size of DAB compared with HBLLC, the DAB-based charger is larger than the HBLLC-based. Although the contribution of the switching device and capacitor to the total charger size is minimal, the DAB switching devices and capacitors require a 16.8% larger footprint than HBLLC. When the DAB is manufactured with the related control, gate driver, and EMI filter circuitry, the DAB-based charger size is much larger than HBLLC. Therefore, despite the lack of V2H functionality, the HBLLC-based charger is preferred for a small and compact built-in E-Motor charger.

**Table 6. Estimated E-Motorcycle charger size comparison**

| Topology          | HBLLC Resonant | Dual Active Bridge |
|-------------------|----------------|-------------------|
| Switching devices | ![Diagram](image1) | ![Diagram](image2) |
| Capacitors        | ![Diagram](image3) | ![Diagram](image4) |
| Top View          | ![Diagram](image5) | ![Diagram](image6) |
| Top-half 3D view  | ![Diagram](image7) | ![Diagram](image8) |
| Converter Volume  | 24,116.4 mm³   | 59,480.6 mm³      |
| Top view w/ winding | ![Diagram](image9) | ![Diagram](image10) |

**4. Conclusions**

The issue of remote and sparsely populated people has given ideas to implement a distributed generation electrification, which mainly uses renewable energy with DC output. DC House is one of the solutions to take advantage of the efficiency in supplying DC loads using DC electricity. The development of DC houses could be aligned with low-cost electric vehicles, such as E-Motorcycle. In this paper, two topologies, HBLLC and DAB with GaN FETs, are compared to design a small, compact, high frequency, and soft-switching E-Motorcycle charger.

The results show that HBLLC uses fewer components, which lead to less manufacturing cost. Both performance of HBLLC and DAB successfully achieve ZVS with the \( I_{rms} \) value relatively similar. In the matter of volume, HBLLC is 24,116.4 mm³, while DAB is 59,480.6 mm³. Magnetic components in
both topologies occupy more than 84% of the charger size. The design showed that DAB is twice bigger than HBLLC, which means that DAB power density is less than HBLLC. Therefore, the HBLLC-based E-Motorcycle charger is chosen to be developed in future work.

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