Design of an Off-Board Charger for Level 3 Electric Vehicle Charging Stations

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***Abstract*—This paper focuses on the design and simulation of an Off-Board Charger for Electric Vehicles (EVs), which supports fast charging applications through the use of High-Level DC Power Converters. Such type of chargers - Level 3 - are increasingly being installed in public charging stations, to increase the driving range of EVs and to promote their adoption. The charger features a Bidirectional DAB converter, which offers the possibility of V2G power transfer, if an appropriate front-end converter is used. The specifications of the charger match the requirements of Electric Buses being used for public transport, while following the standards laid down by BIS [IS 17017]. The DC/DC stage - Single phase DAB - features a symmetrical structure which can be stacked to increase the power rating of the overall system.**

***Index Terms*—Level 3 Fast DC Charging, DAB converter, Off-Board Charger**

I. Introduction

Conductive charging systems have emerged as the most popular and efficient charging system for EVs. Conductive charging is broadly divided into two types: onboard charging and off-board charging. Onboard charging is mainly utilized for slow charging with all charging activity held inside the vehicle, while off-board charging offers fast charging.

The advantage offered by Off-Board charging is that it relocates the charger to the EVSE, outside of the vehicle. This reduces the weight of the vehicle and removes constraints typically present, offering increase in efficiency and performance, by the use of sophisticated thermal cooling systems and highly efficient converters which convert power directly to High Voltage DC.

In AC charging setups, the AC to DC conversion happens inside the vehicle using an onboard charger. This limits the charging speed to the capabilities of the onboard electronics. On the other hand, DC fast-charging systems handle the conversion externally — a central AC/DC converter, usually connected to a 400–480V AC bus from the MV–LV distribution transformer, supplies regulated DC power directly to the EV. These off-board converters take care of rectification, power factor correction, voltage regulation, and isolation. The AC bus architecture typically involves multiple power conversion stages and interacts with both DC sources and loads. In DC-based systems, a common DC bus is used to connect all the chargers, and isolated DC/DC converters are used at each output to provide the necessary electrical isolation and voltage control before connecting to the EV.

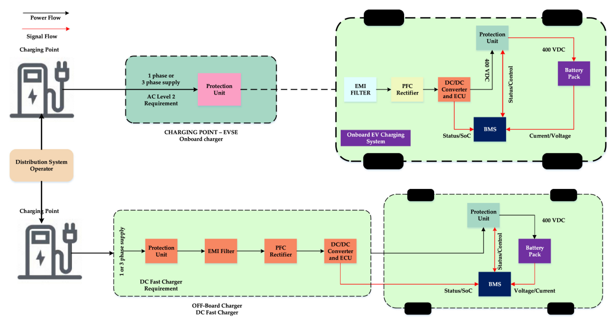

Fig. 1. Difference between On-Board and Off-Board Charging System

II. Specifications of the Charger

This section provides an overview of widely adopted charging technologies and offers a rationale for the design approach selected by the authors.

A. Levels of EV charging

Electric Vehicle (EV) charging infrastructure is categorized into three primary levels based on power delivery capabilities and charging time: Level 1, Level 2, and Level 3 (DC fast charging).

Level 1 chargers operate using standard household AC supply, typically at 120V or 220V, and utilize the vehicle's onboard charger for AC-DC conversion. This type of charging is limited by the available wall outlet voltage and current, resulting in extended charging times ranging from 10 to 12 hours for a full charge. Level 1 chargers generally employ the SAE J1772 connector and are most suitable for residential overnight charging. Installation is straightforward and relatively inexpensive, with costs typically ranging between 20,000 to 50,000, depending on local site conditions and hardware selection.

Level 2 chargers offer accelerated charging by using higher-voltage AC sources, often incorporating three-phase supply where available. Although they also depend on the vehicle's onboard charger for AC to DC conversion, the increased current capacity allows a complete charge within 4 to 6 hours. These chargers are widely used in both residential and commercial installations. While SAE J1772 is still used on the AC side, modern installations often include CCS2 or CHAdeMO connectors to support DC capability and compatibility with a wider range of EVs. Installation costs vary significantly, typically ranging from 60,000 to 5,00,000, with residential installations averaging around 1.5 to 2 lakh.

Level 3 chargers, commonly referred to as DC fast chargers, deliver high-voltage DC directly to the vehicle battery, bypassing the limitations of the onboard charger. With output voltages starting from 480V DC and above, these chargers are capable of delivering a substantial amount of energy in a short period — generally charging an EV within 30 minutes. They employ fast-charging standards such as CCS2 and CHAdeMO, and are particularly suited for public charging stations, fleet depots, and highway corridors. Due to their higher complexity, power ratings, and infrastructure requirements (including grid upgrades and transformer integration), installation costs for Level 3 chargers are significantly higher, ranging between 15 lakh to 1 crore, depending on the power level and site-specific considerations.

These chargers may use multiple lower rated modules in parallel, to increase power throughput and redundancy. The Tesla Supercharger, uses a parallel combination of 12 modules to deliver the rated power.

B. Specification Justification

The design specifications for the charger were selected based on the following considerations:

- **Level 3 DC Charging:** A Level 3 charger configuration, as outlined by BIS (IS 17017), was selected to support high-voltage, high-power applications and to enable compatibility with future-ready Vehicle-to-Grid (V2G) systems.
- **750 V Output Voltage:** A nominal output voltage of 750V was chosen to support modern electric buses, such as the Tata Starbus 4/12 EV, which operates with a battery voltage of 657V. The 750V output provides sufficient overhead for regulated fast charging while remaining within the preferred voltage ratings listed in IS 17017-2-1. V2G systems will be required to be powered by high-capacity batteries, which would be easily available in eBuses or eTrucks.
- **Charging Time and Battery Capacity Consideration:** The target vehicle's battery capacity is 400kWh. Following the common design guideline of charging at a rate equal to half the battery capacity (0.5C-rate), the system is designed to deliver 150kW, enabling a full charge within approximately 2 hours.
- **200 A Output Current:** To achieve the 150kW–200kW charging power target at 750V, an output current of approximately 200A is required. This aligns with the preferred current ratings specified in IS 17017-2-1, Section 5 (Ratings), which lists 200A as one of the standardized rated output current values.

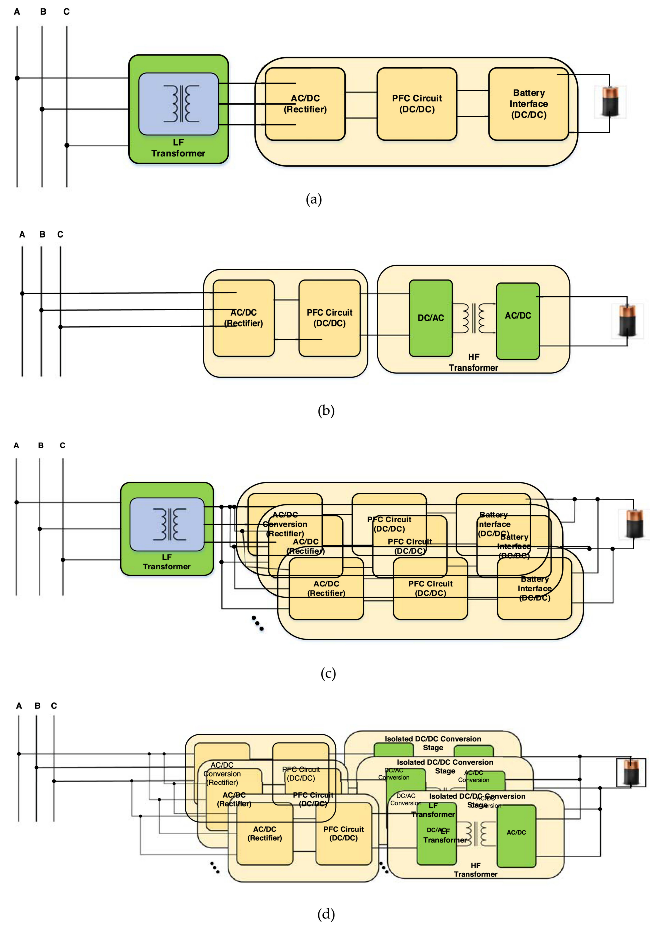

Fig. 2. Block diagram of conventional DC fast charger power conversion systems. (a) Single-module charger with a non-isolated DC/DC converter. (b) Single-module charger with an isolated DC/DC converter. (c) Multiple paralleled modules are shown in (a). (d) Multiple paralleled modules are shown in (c).

C. Final Specifications

The final specifications for the system are as follows:

- Input voltage: $400\,\mathrm{Vac} \pm 10\%$, with a current rating of $220\,\mathrm{A}$.
- Efficiency: 90% (resulting in $P_{\text{in}} = 167\,\mathrm{kW}$).
- Power factor, $pf = 0.95$.
- The system will handle a current of up to $254\,\mathrm{A}$.
- Protection factor: $+20\%$ (resulting in $305\,\mathrm{A}$).
- The AC/DC stage will output $750\,\mathrm{V}$ to the DC/DC DAB converter, which features a transformer ratio of $1:1$.
- The final converter can be configured as a stack of 10-12 parallel modules, with each module rated up to $32\,\mathrm{A}$. A prototype version with a $5\,\mathrm{A}$ rating can be built for initial testing.

Common DC fast chargers and their specifications are presented in Table 2.

TABLE I
INDIAN STANDARDS FOR EV CHARGING AS PER BIS (AS OF 01.11.2021)

Power Level & Charging Device		**Communication, Socket, and Connector**		
Type	**Standard**	**EV-EVSE Communication**	**Plug/Socket**	**Vehicle Connector**
Light EV AC	IS-17017-22-1 (7 kW)	Bluetooth Low Energy	IS-60309	As per EV manufacturer
Light EV DC	IS-17017-25 (7 kW)	CAN	Combined socket (under dev.)	IS-17017-2-6
Parkbay AC	IS-17017-1 (11–22 kW)	IS-15118 [PLC]	IS-17017-2-2	IS-17017-2-2
Parkbay DC	IS-17017-23 (11–22 kW)	IS-17017-24 [CAN], IS-15118 [PLC]	IS-17017-22-2	IS-17017-2-3
DC Fast Charging (L3)	IS-17017-23 (50–250 kW)	IS-17017-24 [CAN], IS-15118 [PLC]	—	IS-17017-2-3
eBus Charging (L4)	IS-17017-23-2 / 3-1 (250–500 kW)	IS-15118 [PLC]	—	IS-17017-2-3

TABLE II
KEY OUTPUT SPECIFICATIONS OF COMMERCIAL DC FAST CHARGERS

Model	**Power Rating**	**Output Voltage Range**	**Output Current**	**Peak Efficiency**
ABB Terra 53	50 kW	200–500 V	120 A	94%
ABB Terra HP	350 kW	50–500 V	375 A	95%
Tritium Veefil-RT	50 kW	150–920 V	125 A	92%
PHIHONG Integrated	120 kW	200–500 V / 50–500 V	240 A	93.5%
Tesla Supercharger	135 kW	200–750 V	330 A	91%
EVTEC Espresso&charge	150 kW	50–410 V / 170–500 V	300 A	83%

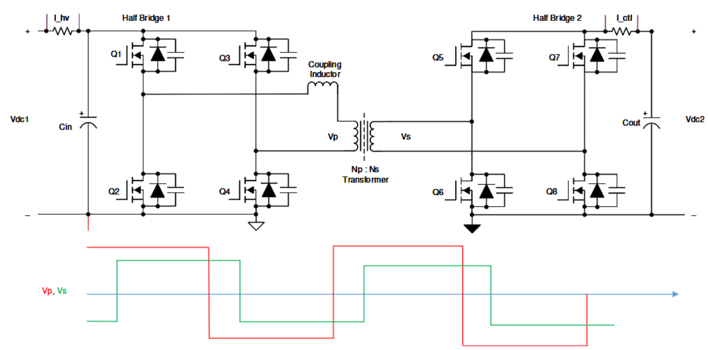

Figure 2-3. Dual-Active Bridge

Fig. 3. Schematic of a DAB converter

III. DAB (DUAL ACTIVE BRIDGE) CONVERTER SIMULATION

The DAB DC/DC converter is a galvanically isolated, highly efficient, bidirectional converter which features high power density.// LTSpice was utilized for the simulation of the DAB converter. Simulation for the converter was done on a reduced small-scale model for fast and easy simulation to observe the general characteristics.

A. Basic Components

A scaled down version of the converter with the following components was simulated.

- N-channel power MOSFETs (IRF540N) were employed as the switching elements. Each MOSFET features a threshold voltage of approximately 3.4 V and is rated for 33 A at 100 V, with an on-state resistance of 40 mΩ.
- The system operates from a 60 V voltage source, which is used to charge a 48 V battery pack.
- A switching frequency of 20 kHz is used, with a duty cycle set at 49%.
- A dead time of 200 ns is introduced between switching transitions to facilitate zero-voltage switching (ZVS).
- A high-frequency transformer is employed, with a primary (or secondary) winding inductance of approximately 600 μH, and a designed leakage inductance (or external series inductance) of 250 μH. The leakage inductance was calculated using the expression:

$$P = \frac{N V_1 V_2 \phi (pi - |\phi|)}{2\pi^2 F_s L}$$

- An output capacitor of 270 μF is used for ripple rejection, dimensioned based on the charge-voltage relation:

$$C_{\text{out}} = \frac{\Delta Q}{V_{\text{ripple}}}$$

- DC-blocking capacitors of 68 μF are included, sized using the formula:

$$C_{\text{DCBlock, min}} = \frac{100}{4\pi^2 F_s^2 L}$$

- Gate drivers supply a gate voltage of 10 V to ensure full enhancement of the MOSFETs during operation.

B. Results

Shown below in Fig. 4, 5, 6, and 7

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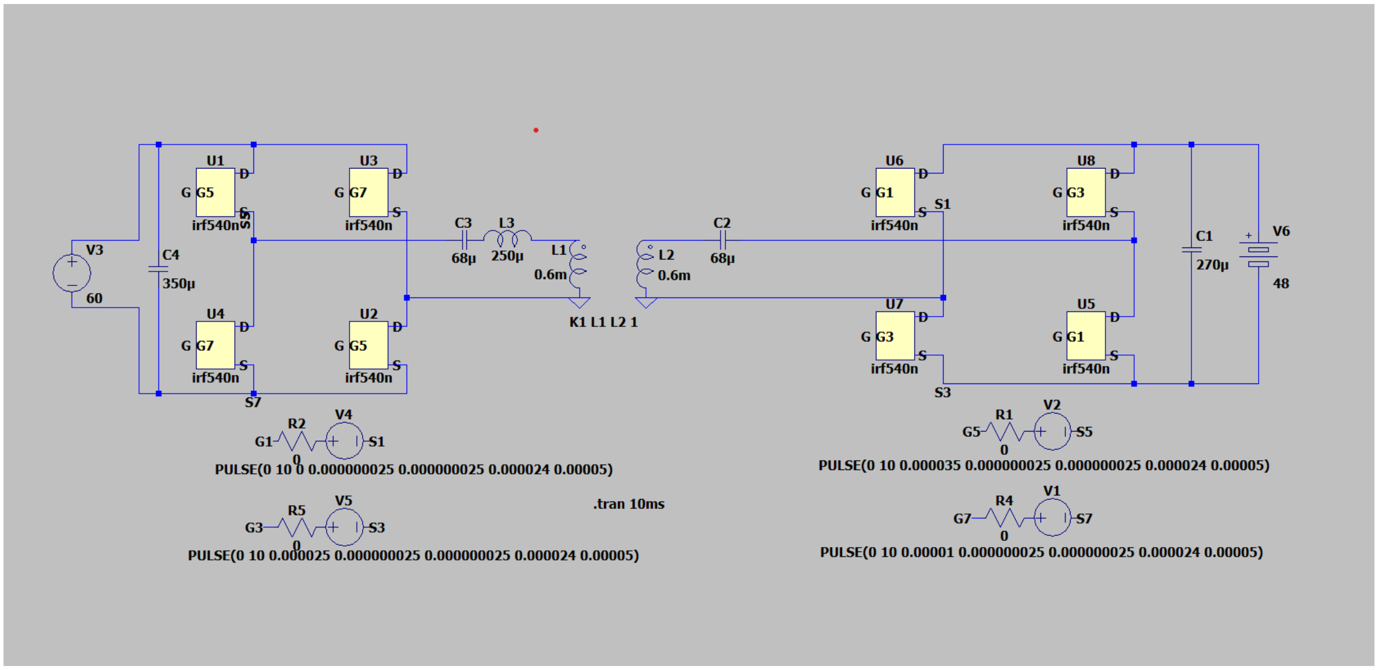

Fig. 4. Simulation Schematic

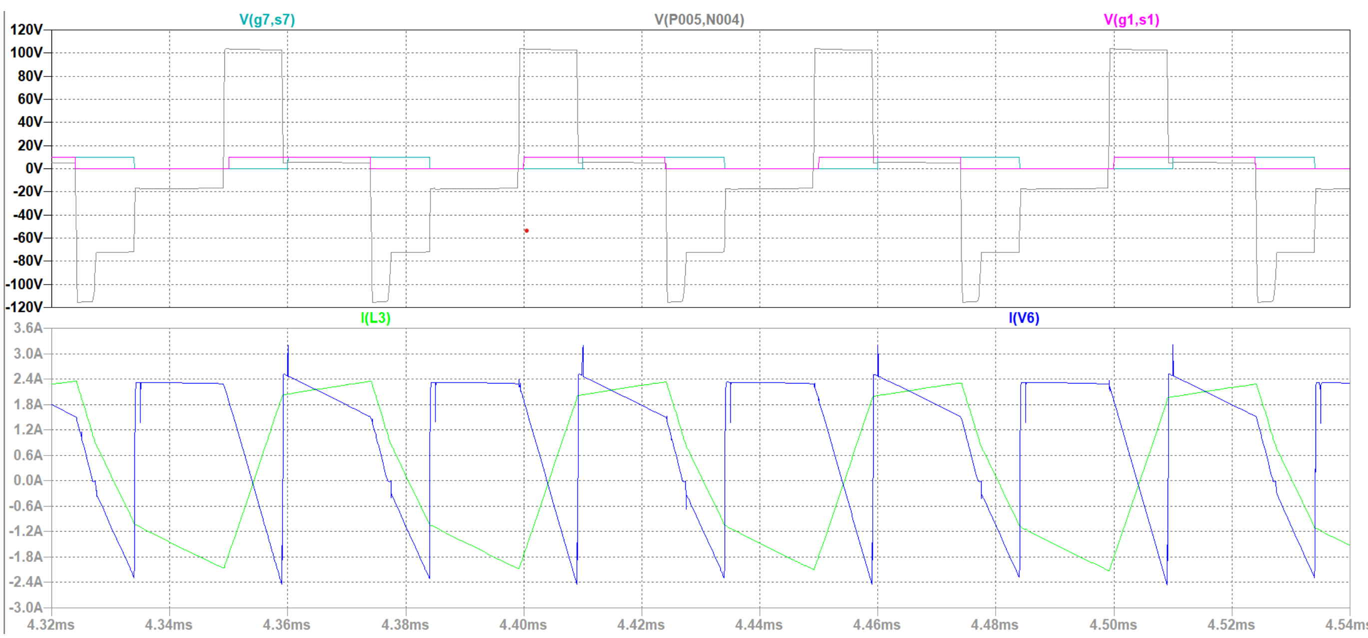

Fig. 5. Resulting Quantities with $\frac{\pi}{10}$ phase shift

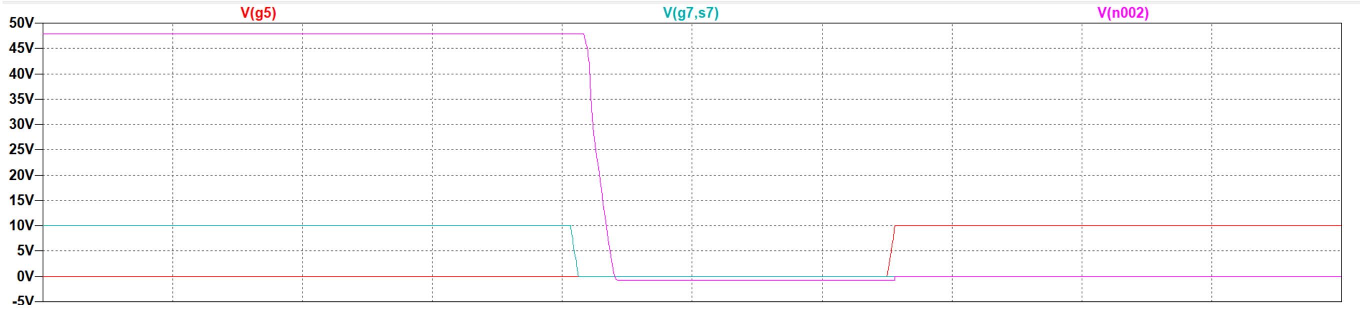

Fig. 6. Dead Time and Zero Voltage Switching

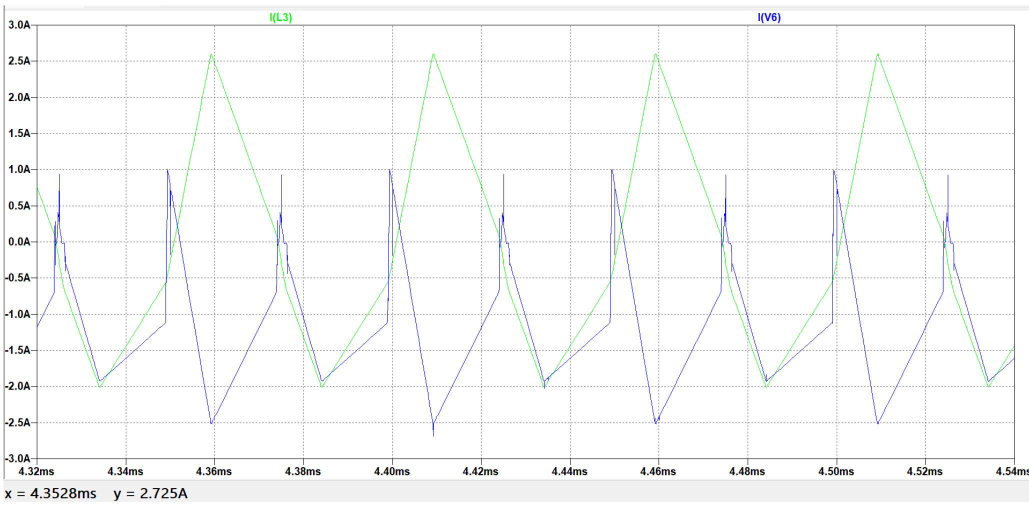

Fig. 7. Output with leading and lagging bridges interchanged

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