

# **Benchmarking System Architectures and Topologies for DC-to-DC Converters, the Heart of Off-Board Chargers**

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## **1 Introduction**

Electrical vehicles (EVs) pose a host of questions, challenges and problems for people seeking to put this breed of car on the road. OEMs' engineers have one set of issues to tackle, and infrastructure planners quite another, while policymakers are busy assembling the puzzle pieces of renewable energy, EVs and the smart grid. If we consider EVs in isolation, which is easily done on paper but difficult in the real world, the biggest issues are charging time and infrastructure availability. These challenges will have to be mastered, for EVs are the future of transportation: As many as 120 million EVs could be up and running by 2030 [1], and the more EVs are on the road, the greater the collective fleet's appetite for energy. Today charging energy demand amounts to around 20 billion kilowatt-hours, with forecasts calling for it to rise to 100 billion kilowatt-hours by 2025 and 280 billion kilowatt-hours by 2030 [1]. This is a tall order to fill – 2030 is just ten years down the road. More efficient EV chargers could help meet rising energy demands and deliver more power, faster. This article investigates various system architectures and topologies. It trains the spotlight on the DC-DC converters that are the heart of off-board chargers.

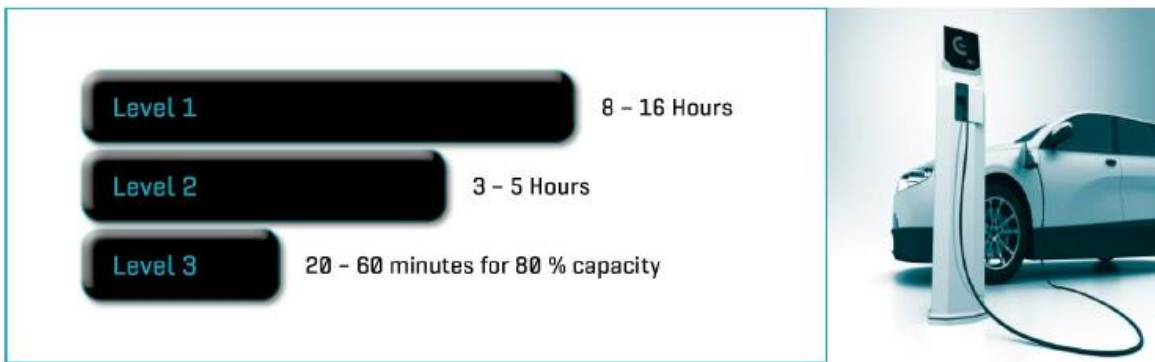
## **2 System architectures**

There are two main scenarios to ponder, public charging and home charging. Demand for each option varies by region. In view of China's infrastructural constraints and densely populated cities, public charging is likely to be the far more frequent application in that country. In much of the USA, in contrast, home charging will dominate because so people live in single-family houses. Then there is the nature of the charging device to contemplate – is it to be a slow charger, a fast charger or a high-power charger?

Charging Type	Level	Charger location	Current	Power
Slow chargers	Level 1	On-Board	AC	<3.7 kW
Slow chargers	Level 2	On-Board	AC	<3.7 kW and <22 kW
Fast chargers	Level 3	On-Board	AC(3~phase)	>22 kW and <43.5 kW
Fast chargers	Level 3	Off-Board	DC	>50 kW and <200 kW
High power chargers	Level 3	Off-Board	DC	Currently > 200 kW

Figure 1: EV charger power levels

Batteries' charging periods range are from 20 minutes to 20 hours, depending on the output power of the electrical vehicle charger (EVC). Take, for example, an EV with 27.2 kWh net battery capacity. A 3-kW residential charger replenishes this battery's capacity from 0% to 80% in nine hours. A DC-DC off-board fast charger (Level 3) does this in less than 45 minutes.



Figure

2: Average EV charging time

Three main system architectures were on the market at the time of writing. A quick review of each follows.

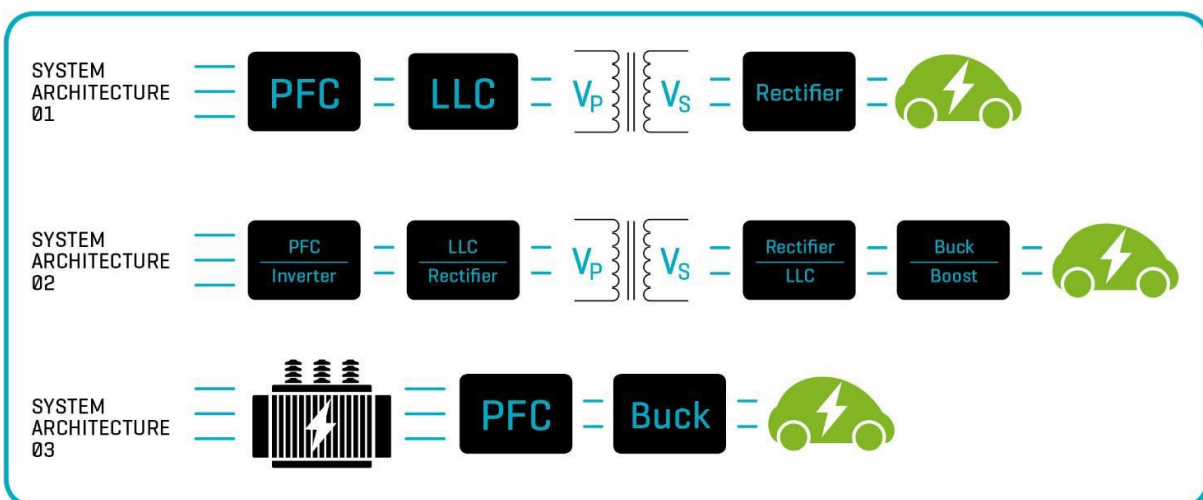


Figure 3: System architectures

## **2.1 System architecture 1**

This is the state-of-the-art system architecture for up to 200 kW. Composed of several units, it is modular. The power level and type of power unit varies by regions. In China, for example, power units for 20 kW. Most are based on telecom power supplies with discrete components that still satisfy today's expectations for efficiency and reliability. Europe presents an entirely different picture, where even 20 kW power units are based on power modules to meet reliability and efficiency expectations and reduce manufacturing time. Much the same can be said of the USA.

## **2.2 System architecture 2**

This is a bidirectional vehicle-to-grid (V2G) system. It is designed mainly for residential applications where the EV serves as the storage unit. V2G is one of the key elements in smart-home applications and the smart grid. Again, it is just not feasible to consider EVs and EV chargers in isolation without factoring renewable energy and smart-grid penetration into the equation. This is why system architecture 2 is gaining ground in applications ranging up to 22 kW and higher. Take, for example, a home-charging scenario where an American mother charges her compact EV at home, overnight. In this case, her car can actually serve as a buffer or energy storage unit for the household. This type of charger will make inroads into home-charging applications as the smart grid gains ground and renewable energy becomes a bigger factor in the energy mix.

## **2.3 System architecture 3**

This latest design aims to serve the higher power (>200 kW) market. A medium-voltage transformer furnishes power directly to the system. There is a good reason why this has to be a medium-voltage transformer: A highway-side charging station with ten chargers working at 350 kW each draws 3.5 MW from the grid. The power ought to be sourced from medium-voltage lines to meet this kind of demand. There are two ways of doing this. For one, we can use a conventional 50-Hz transformer to step the voltage down to 400 V (L-L) and then convert AC to DC. For the other, we can use power electronic transformer (PET) to generate medium-voltage, medium-frequency power with the power being converted within the transformer. Used for years in traction applications, PET will be vital to the smart grid.

DC-to-DC conversion is the heart of the system in all architectures. To date, the transformer has converted DC to DC to provide galvanic isolation between the car and mains power. The most frequently used topology is LLC. This is a zero-voltage-switching (ZVS) technique that serves to reduce switching losses, increase efficiency and energy density, and mitigate EMI

issues. The next section briefly explains LLC topology and examines the results of an effort to benchmark component technologies' cost and efficiency.

### 3 LLC Benchmark

A resonant LLC converter has advantages such as high efficiency, low EMI and increased power density. However, selecting the right component for the given application does require more effort.

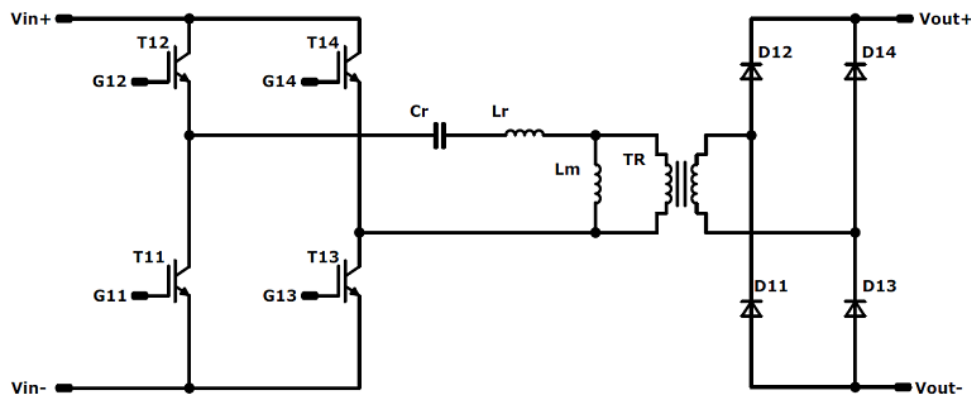


Figure 4: Full-bridge LLC converter with a full-bridge rectifier

The benchmark discussed in this paper is based on a full-bridge LLC converter

DC-DC conversion gain = turn ratio of transformers \* resonant tank gain \* switching bridge gain where the gain of the full-bridge LLC is **1** [2].

A summary of the resonant LLC converter's design parameters follows [2]:

- 1) Quality factor (**Q**)
- 2) Reflected load resistance
- 3) Resonant frequency
- 4) Ratio of primary inductance to resonant inductance (**k**)

The resonant LLC converter discussed in this paper was benchmarked using various component technologies at different resonant frequencies to rate efficiency and costs. The transformer's conversion ratio is 1 and the maximum gain of the resonant tank is limited to 1.4. The  $L_r$ ,  $C_r$  and  $L_m$  values depend on the transformer's conversion ratio, the resonant frequency and the LLC's designated power rating.

Several configurations with various component technologies are available. The double H-bridge consists of two cascaded H-bridges with 650 V components. The second configuration is an H-bridge with 1200 V components. The double H-bridge topology enables us to use 650 V components where the voltage at the PFC's output is divided in two and routed to each H-bridge [3].

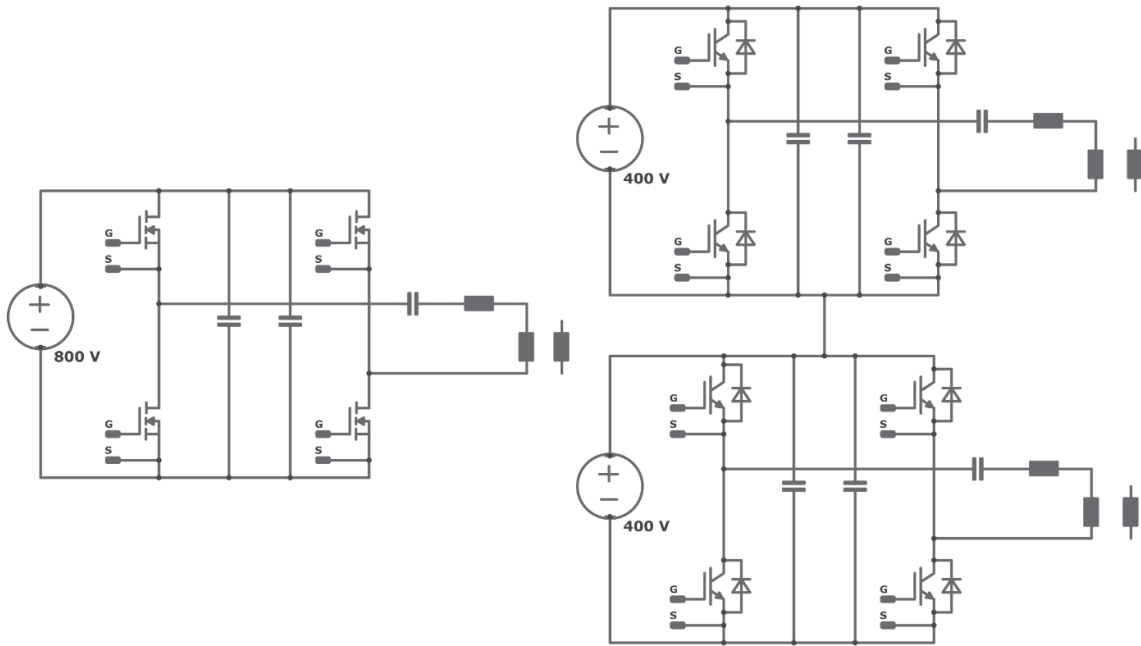


Figure 5: H-bridge topologies

### Application conditions:

Chip set	650V Fast IGBT - 100A		Chip set	650V Si-MOSFET - 20mOhm
Topology	H-Bridge		Topology	H-Bridge
Power	12.5 kW		Power	12.5 kW
V <sub>in</sub>	400 V		V <sub>in</sub>	400 V
V <sub>out</sub>	400 V		V <sub>out</sub>	400 V
k factor	9		k factor	9
Q factor	0.4		Q factor	0.4
Frequency range	1-120 kHz		Frequency range	1-120 kHz
Chip set	1200V Fast IGBT - 80A		Chip set	1200V SiC-MOSFET - 20mOhm
Topology	H-Bridge		Topology	H-Bridge
Power	25 kW		Power	25 kW
V <sub>in</sub>	800 V		V <sub>in</sub>	800 V
V <sub>out</sub>	800 V		V <sub>out</sub>	800 V
k factor	9		k factor	9
Q factor	0.4		Q factor	0.4
Frequency range	1-120 kHz		Frequency range	1-120 kHz

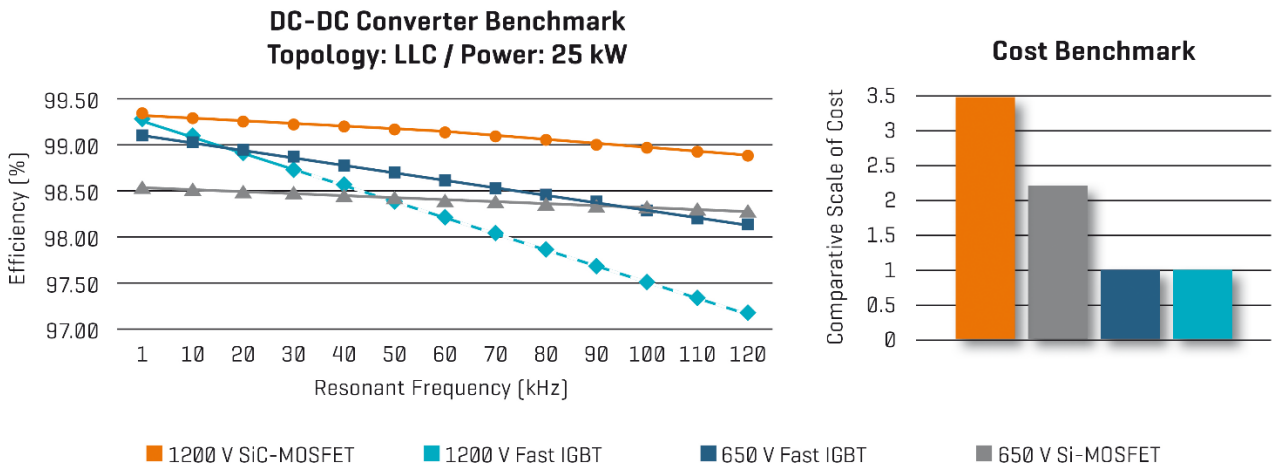


Figure 6: DC-DC converter benchmark under 25 kW full-load conditions

The 1200 V SiC-MOSFET version exhibits the greatest efficiency throughout the frequency range. The 650 V Fast IGBT and 650 V Si-MOSFET solutions in double H-bridge topology exhibit similar performance beyond 100 kHz. The 650V IGBT is more efficient at frequencies below 100 kHz. However, the Si-MOSFET solution's loss is lower than the IGBT solution's at partial loads, which is attributable to the  $R_{dson}$  steepness. On the other hand, the 1200 V Fast IGBT's performance dips drastically after 25 kHz. The cost benchmark provides a more complete picture. It clearly shows that the 1200 V SiC-MOSFET is the most expensive solution. The costs of the 650 V Fast IGBT and the 1200 V Fast IGBT are comparable and considered equal for the purpose of cost benchmarking. The Si-MOSFET, around twice as expensive as the Fast IGBT, falls midway between the two others in the cost ranking. Note that this cost benchmark takes the power module's price into account. This comparison assumes that the 1200 V SiC-MOSFET (single H-Bridge) comes in the Vincotech flow1 housing. The 650 V Fast-IGBT and 650 V Si-MOSFET are based on a double H-Bridge configuration, so they are taken to be housed in two Vincotech flow 1 housings. Although the 1200 V Fast IGBT can come in a single module, this comparison assumes it is packaged in two Vincotech flow1 housings to distribute heat across two modules. The higher losses would otherwise make it impossible to disperse the heat from a single module.

The trajectory of the efficiency curve at a partial load is a crucial issue. The graph below shows this partial load efficiency. Please note that the LLC is designed for a full load. Of course, this also determines its parameters.

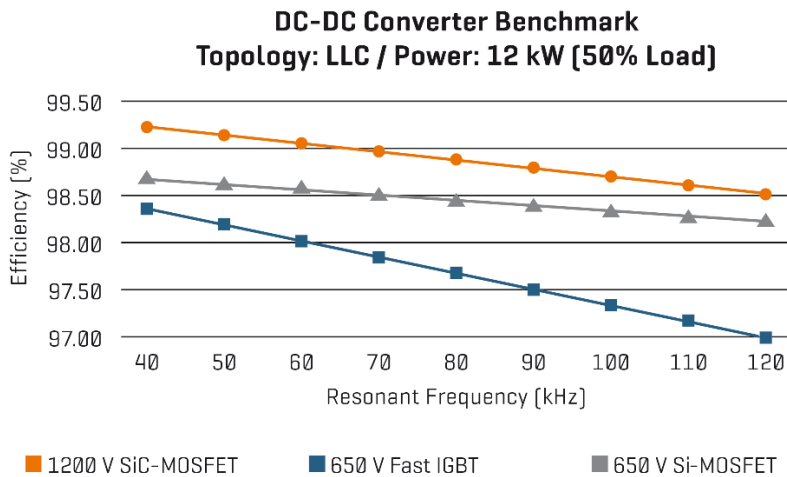


Figure 7: DC-DC converter benchmark under 12 kW partial load conditions

This benchmark for efficiency at partial load shows the 650 V Si-MOSFET outperforming the 650 V IGBT throughout the frequency range. This is explained by the lower power level – the reduced input current causes less static loss. Static losses generally outweigh switching losses in the LLC topology. Off-board DC-DC chargers supply the energy at full load to reduce charging time, which is why the comparison at full load is more meaningful. The final question to be examined in this paper is how much efficiency money can buy. We halved the 650V Si-MOSFET’s  $R_{dson}$  to investigate how this affects efficiency. The graph below provides some answers.

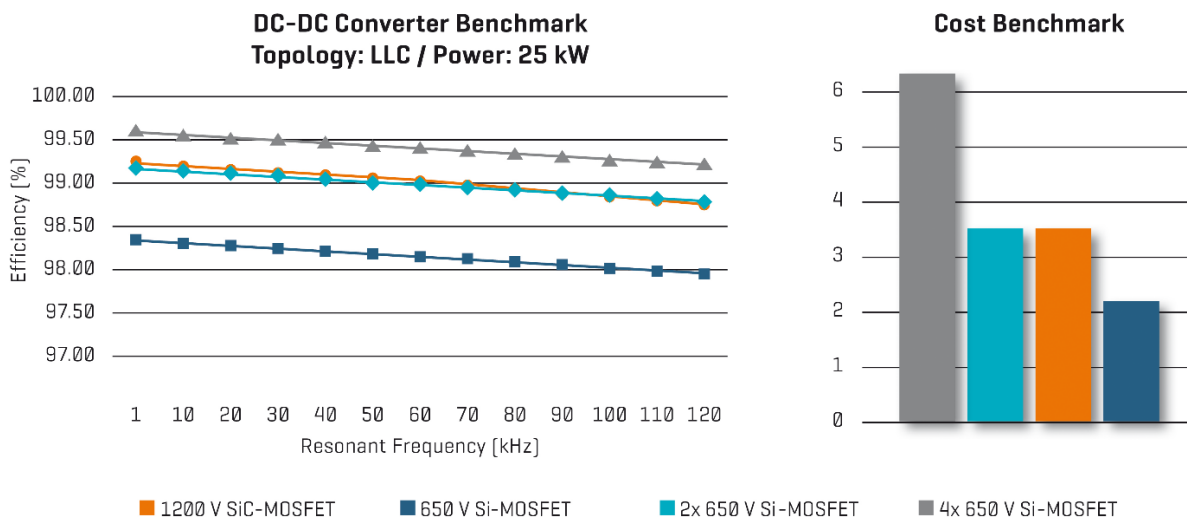


Figure 8: DC-DC converter benchmark under 25 kW full load conditions

As the above graph shows, paralleling two 650 V Si-MOSFETs reduces losses and increases efficiency. If we halve  $R_{dson}$  to 10 m $\Omega$ , the efficiency level is on par with that of 1200 V SiC-MOSFET (20 m $\Omega$ ). The next step is to reduce  $R_{dson}$  to 5 m $\Omega$ , which is done by paralleling four Si-MOSFETs (20 m $\Omega$ ). This again raises the system’s efficiency to a level beyond that of the SiC-MOSFET. As is to be expected, the modules’ price rises accordingly. Note that doubling the

650 V Fast IGBT's current rating would not increase efficiency as much as halving the Si-MOSFET's  $R_{dson}$ , which is why this option has not been explored. Conversely, doubling the Fast IGBT's current rating does indeed reduce  $R_{th}$ , which helps cut losses by bringing the junction temperature down. This, in turn, enhances component reliability and extends service life.

## 4 Conclusion

This paper briefly reviewed current EV chargers' system architectures and zoomed in for a closer inspection of the LLC topology. The EV booming market has its challenges. As power levels increase, efficiency becomes an ever more important consideration. The resonant LLC DC-DC converter is one of the most frequently used options in charger applications, but it is vital to select the right component and configuration for the application. The double-H bridge configuration with the 650 V Fast IGBT performs well in terms of both cost and efficiency. The 1200 V SiC-MOSFET and 650 V Si-MOSFET are good options if the application requires very high efficiency even at partial loads. Charging stations are a priority market for Vincotech. With its range of standard power modules and customer-specific solutions, the company offers the right solution to meet the demands of every customer's applications. To learn more, please visit our website at <https://www.vincotech.com/>

### References and Notes:

[1] Charging ahead: Electric-vehicle infrastructure demand by Hauke Engel, Russell Hensley, Stefan Knupfer, and Shivika Sahdev  
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[3]: Cost and Efficiency of Level-3 DC Fast-charging Power Modules—A Benchmark Comparison by Baran Özbakir  
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