Cost and Efficiency of Level-3 DC Fast-charging Power Modules—A Benchmark Comparison

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1 Abstract

The market for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) is heating up with environmental concerns, consumer demand, new laws, and government incentives all adding fuel to the fire.

Of course, it will take a lot more charging stations to keep all those EVs and PHEVs on the road. In this paper, we briefly review EV chargers' power Levels 1, 2 and 3, take a big-picture look at the charger market, and then zoom in for a closer inspection of Level-3 DC fast-charging solutions. A comparison of the latest architectures and topologies follows before we draw our conclusions in closing.

2 Introduction

Most people charge their EVs at residential locations simply because Level 1 charging with household power is just so convenient. Level 2 is the higher-power option—experts expect it will eventually become the preferred method for public and private use. This type of device is an on-the-go solution. It can be installed practically anywhere for charging on the fly. Level 1 and Level 2 chargers draw on single-phase supplies. Level 3 is the game-changer for EVs because it will mitigate range anxiety, putting to rest the fear that the vehicle will run out of juice on the road. Level 3 chargers connected to three-phase power supplies are going up like gas stations once did, with operators deploying them in shopping areas, theaters, hotels and the like. Fig.1 provides a quick run-down of charging levels.

	Level	Location	Current	Power
	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 (three-phase)	>22 kW and <43.5 kW
Fast chargers	Level 3	Off-board	DC	Currently <200 kW

Figure 1: EV charger power levels

Batteries' charging periods range 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.

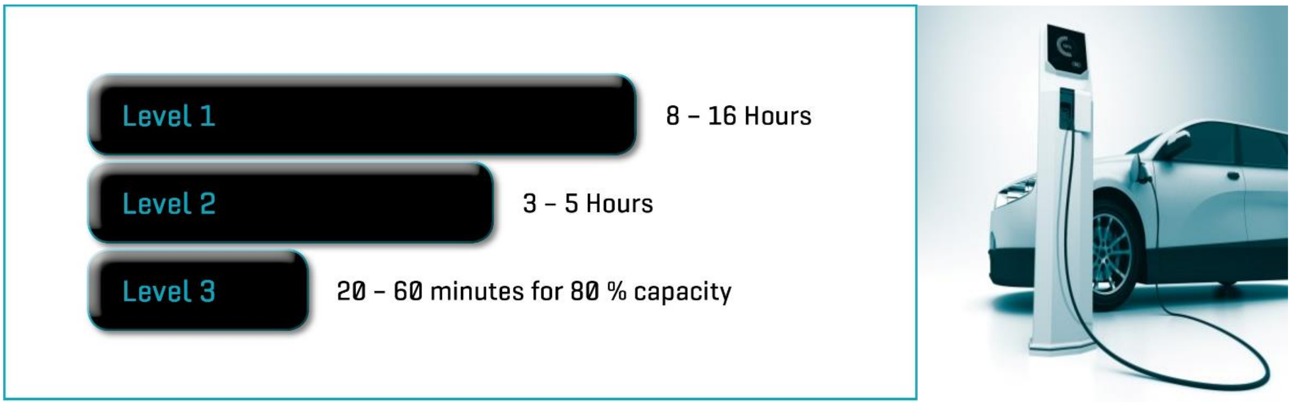

Figure 2: Average EV charging time

3 A Look at the Market

Publicly accessible charging stations are being deployed faster than EV makers are selling their cars. The number of charging outlets spiked in 2016, rising by 72% while the global EV fleet grew by roughly 60%. This upsurge suggests that a tipping point has been reached with more and more markets adopting EVs. Again, the fast off-board DC charger is the ticket to electric mobility. The market figures tell the story of the off-board charger's potential. On-board EVCs accounted for a far larger share of global revenue in 2015, but the scales are tipping towards off-board chargers. According to projections for 2020, theirs will be the far bigger slice of the revenue pie. What is more, the forecast calls for a 23% compound annual growth rate (CAGR) between 2015 and 2020. Fig. 3 depicts global revenue share for 2015 and the predicted share in 2020.

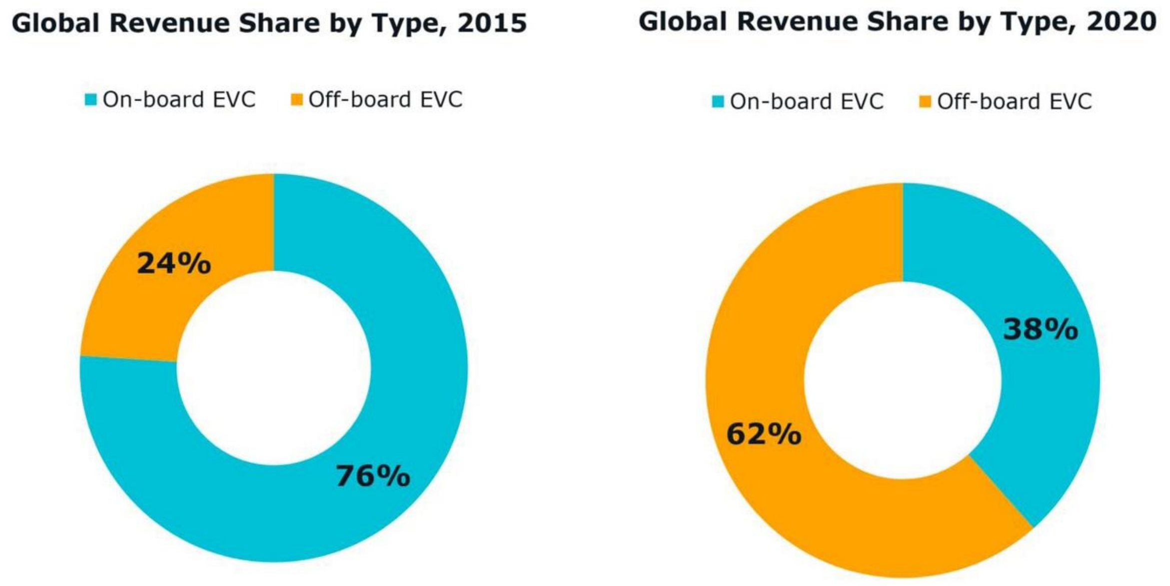

Figure 3: Global revenue share by type

Source: QY research (March 2016)

4 System Architectures and Topologies

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

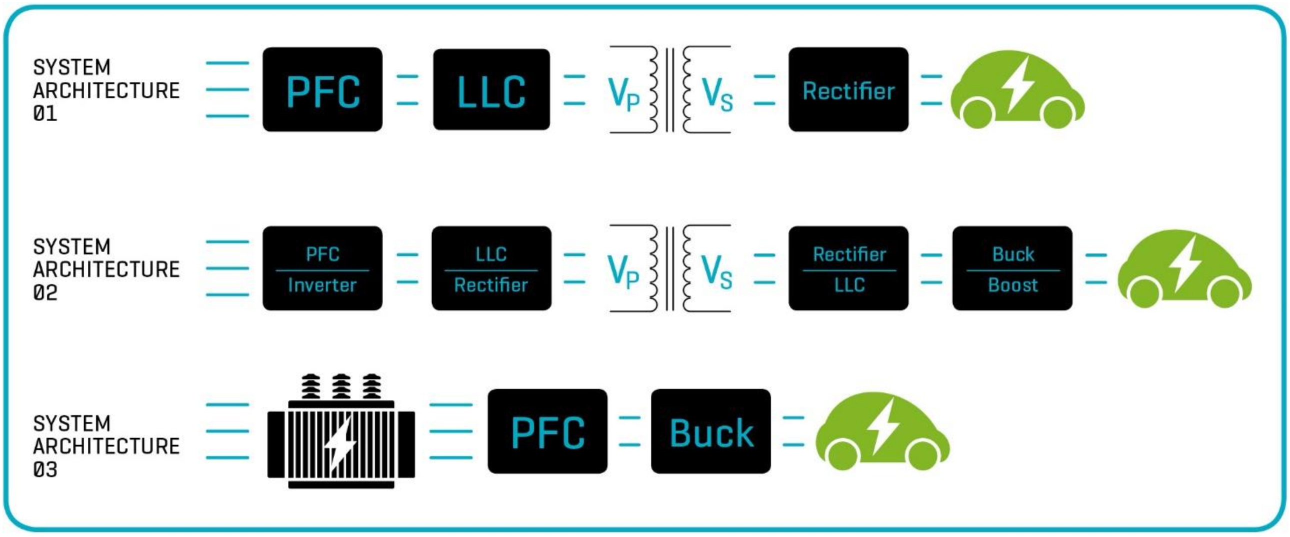

Figure 4: System architectures

System Architecture 1

This is the state-of-the-art system architecture for up to 200 kW. Composed of several units, it is a modular system.

System Architecture 2

This is a bidirectional Vehicle-to-Grid (V2G) system. It is mainly designed for residential applications where the EV serves as the storage unit. V2G is one of the key elements of smart-home applications and the smart grid.

System Architecture 3

This is the latest design aimed to serve the higher power (>500 kW) market. A medium-voltage transformer furnishes power directly to the system. It does not use any resonant topology as the medium-voltage transformer provides the galvanic isolation from the grid.

5 Three-phase PFC Topologies

Three-phase PFC is an appealing solution for engineers seeking high power density and high efficiency. It is common practice to combine three single-phase modules in an AC system, thereby achieving the required output power level with three-phase PFC. This section briefly explains the prevailing three-phase PFC topologies, and benchmarks these in the context of an EV charger's application conditions.

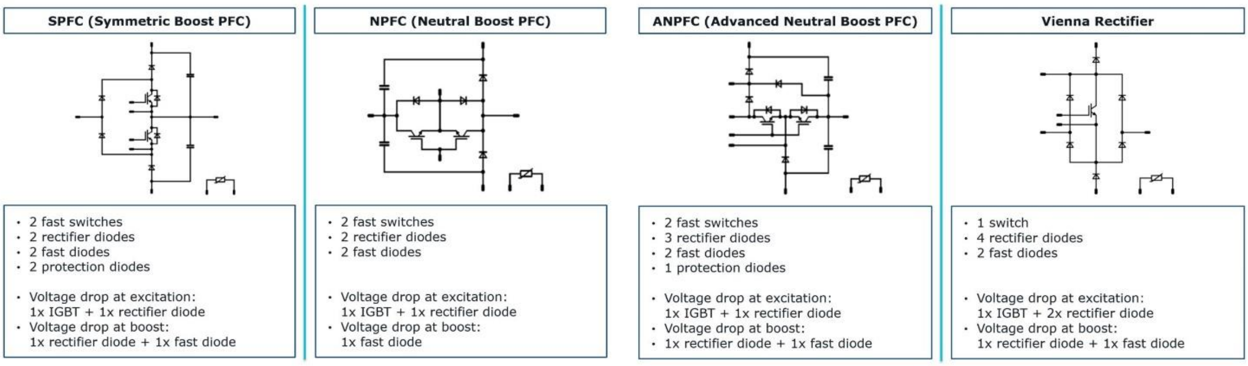

Figure 5: Three-phase PFC topologies

We benchmarked costs and efficiency to illuminate the topologies' strengths and weaknesses. Switching frequencies are higher (>40 kHz) in PFC modules for charger applications, so for this comparison we considered IGBTs in switches and SiC diodes at the positions where reverse-recovery losses occur. Fig. 6 shows the benchmarked efficiencies and costs on a comparative scale. Note that SPFC and ANPFC topologies' efficiencies are nearly the same given the same component technologies. However, ANPFC requires just one gate-driver, which reduces the overall system's cost.

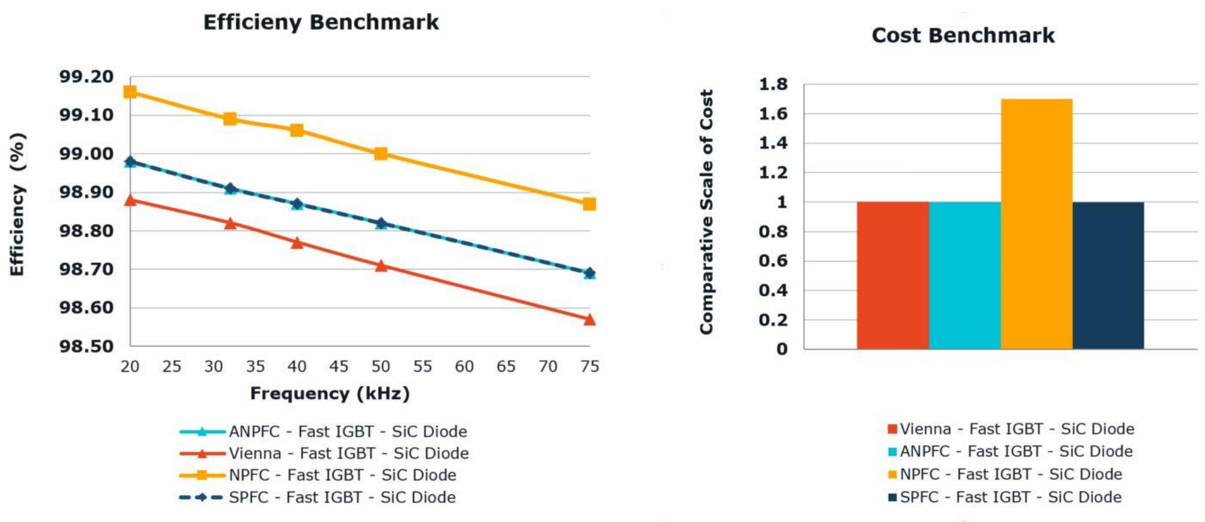

Figure 6: Benchmarked efficiencies and costs on a comparative scale

6 LLC Topologies

The resonant topology in an EV charger application serves two purposes—to provide the galvanic isolation and convert DC to DC. The industry uses several resonant (soft-switching) topologies. This paper's comparison is based on LLC, the state-of-the-art resonant topology for charger applications. LLC is a soft-switching topology. Every design's parameters are unique, so finding the right module for the application is more of challenge than for hard-switching topologies. 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 PFC's output is divided in two and routed to each H-bridge.

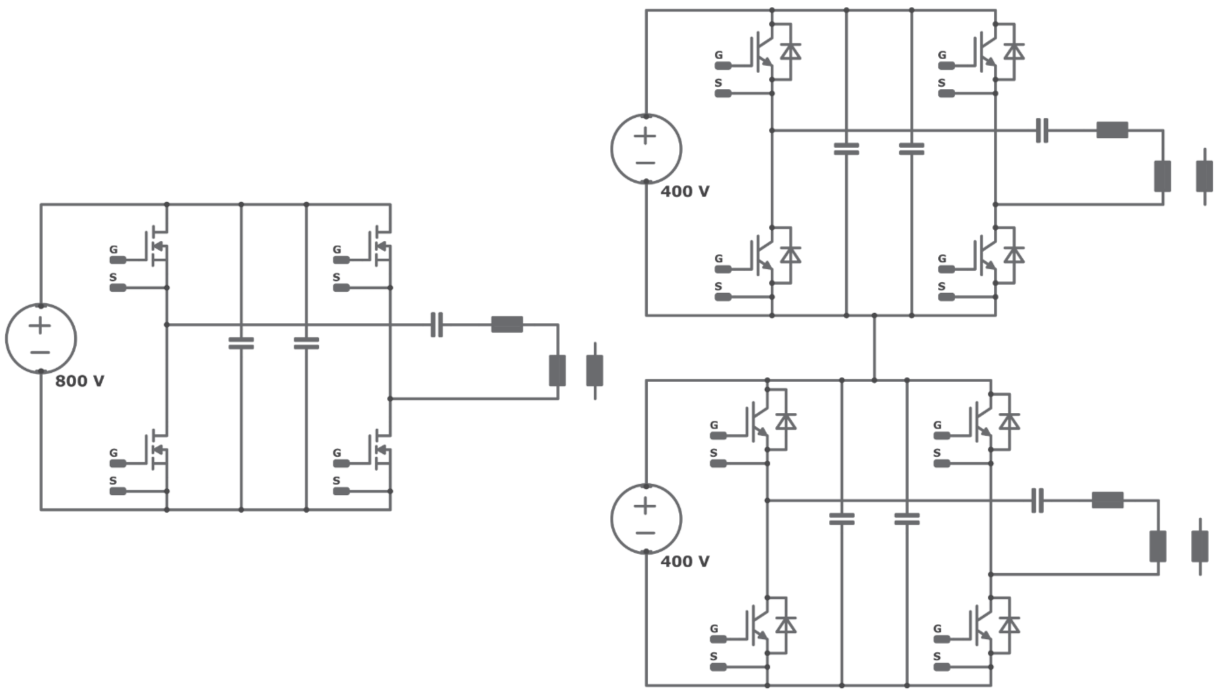

Figure 7: H-bridge topologies

We benchmarked and compared costs and efficiencies to gain deeper insight into these topologies' benefits and drawbacks.

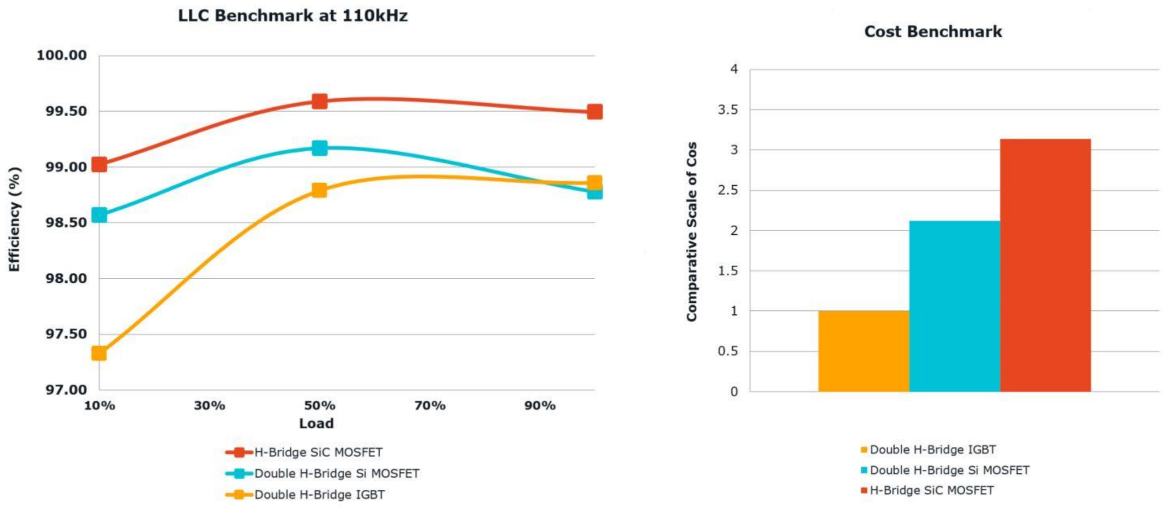

Figure 8: Benchmarked efficiencies and costs on a comparative scale

The SiC-MOSFET version exhibits the greatest efficiency across the entire load range. The performance of IGBT and Si-MOSFET solutions in the double H-bridge topology is comparable at 100% load. 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. The upshot of all this is that the SiC-MOSFET is the go-to solution for high efficiency in all load situations. Si-MOSFET is a compromise between cost and efficiency. And the cost-effective solution is IGBT-based. Another alternative to the SiC-MOSFET solution is to over-size components. For example, IGBTs and Si-MOSFETs may be oversized by installing parallel chips in the module; this increases efficiency throughout the load range. Oversizing drives costs up, but this option may still be cheaper than the SiC-MOSFET solution. Oversizing also enhances reliability because the junction temperature drops.

7 Conclusion

In this paper, we briefly reviewed EV chargers' power Levels 1, 2 and 3, took a big-picture look at the charger market, and then zoomed in for a closer inspection of Level 3 DC fast-charging solutions. This market is booming, with a 72% rise in the number of publicly accessible chargers and a 60% increase in EVs in 2016. Level 3 system architecture will gain traction in the near future as EVs' battery capacity increases. None of the other three-phase PFC topologies can match ANPFC's price–performance ratio. On the other hand, LLC topologies figure prominently in Level 1 and 2 system architectures, where the winner in the price-performance stakes is an IGBT with a double H-bridge. The upshot: One size does not fit all. Charging stations are a priority market for Vincotech. We offer the right solution to meet the demands of each customer's applications—either with our standard power modules or our customer-specific solutions. To learn more, please visit our website at www.vincotech.com