A more efficient DC–DC converter:
Improving EV charging and more

A team from Shell Technology has been working on a novel prototype 20-kW DC–DC converter for electric vehicle (EV) charging. The converter uses the principle of partial power processing and complies with the principal charging standards. Peak efficiencies of > 99% have been obtained, which is higher than the 95–97% efficiency of current DC–DC converters used in EV charging. If this technology is successfully implemented, it could also find applications in the haulage and shipping industries, in which it could offer higher-energy-density chargers with reduced cooling requirements.

Introduction

Most EV charging systems convert AC to DC directly off the grid. The current generation of ultra-fast DC chargers are rated at over 250 kW, but even these take about 15 minutes to charge a typical battery, which is still somewhat longer than gasoline filling. However, some power distribution networks have congestion and capability restrictions that may not allow direct grid charging by multiple high-power chargers. One way round this problem is to use a battery energy storage system (BESS). This involves the placement of a large battery at the charging location. Figure 1 shows the standard configuration for a DC energy storage system used to boost charging power. AC from the grid is converted to DC, which continuously charges a local BESS. When a car arrives for charging, part of the EV battery's charge comes directly from the grid, while the majority of the required high power is supplied by the BESS battery.

A major consideration is the efficiency of the DC–DC converter. This has a large cooling requirement (tens of kilowatts) and needs to be very efficient (> 95%). The present limit in a commercially deployed system, the E.ON Drive Booster developed by Volkswagen, is 97%. In this study, the team used a novel DC–DC converter to raise this to over 99%.

Current state of the art in Shell

High technology readiness level (TRL) implementations of EV DC chargers in Shell are highlighted by systems such as:

- the recently installed 1-MW peak charger for trucks and ships at Energy Transition Campus Amsterdam (ETCA) [Ref 1]; and
- the 2 × 175-kW charger at Zaltbommel for normal passenger EVs [Ref 2].

These systems are directly AC connected, although the latter incorporates a 360-kWh Alfen battery storage system with a two-way DC–AC converter, as shown in Figure 1.

Challenges

There are currently two main restrictions on charging directly from the grid: capacity for simultaneous charging of more than one EV and high operational costs.

- Charging multiple EVs simultaneously requires extremely high peak power from the distribution grid [Ref 3]. This can impact distribution systems and cause voltage imbalances, especially in areas where a strong grid is not accessible, such as highways between cities and rural areas.
- High monthly operational costs generated by high peak demand can make EV fast charging very expensive [Ref 4]: fast charging is thus much more expensive than home charging. In a monthly billing period, apart from the

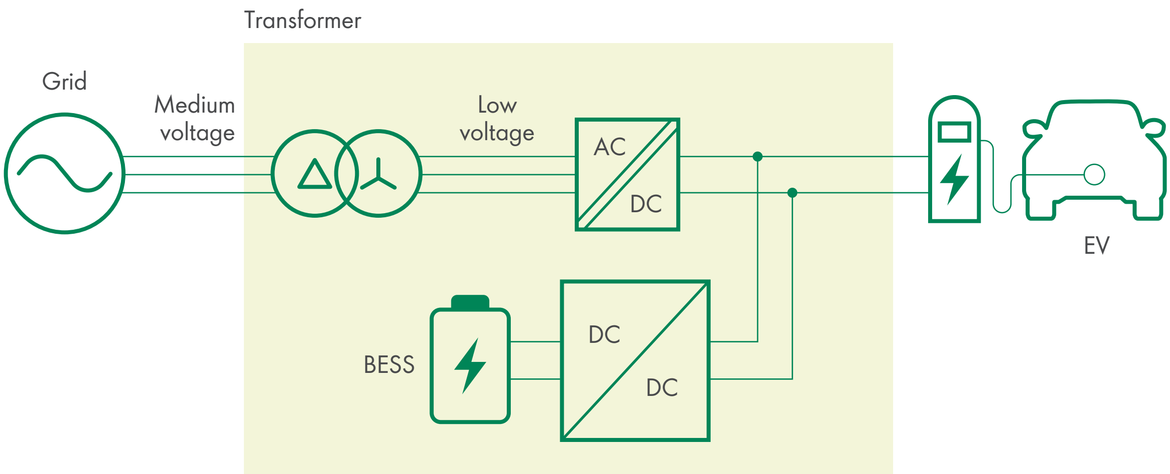


FIGURE 1
Configuration of a BESS for EV charging.

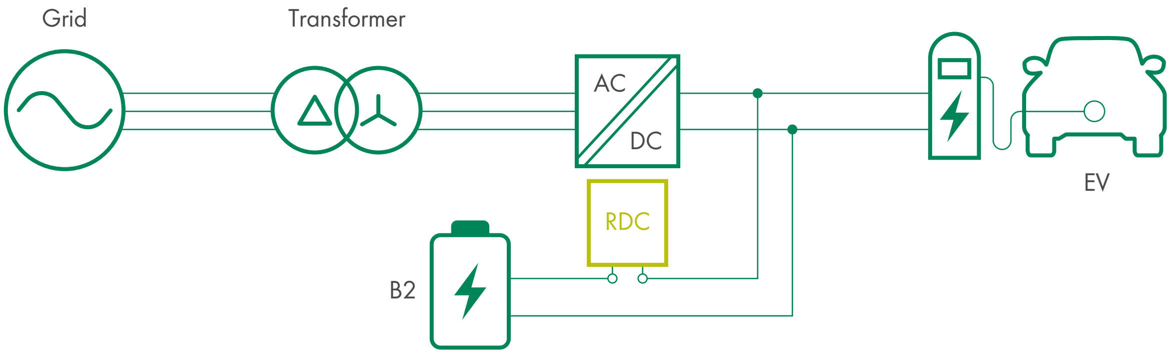


FIGURE 2
Proposed new converter.

electric energy consumption cost (\$/kWh), in many locations a peak demand fee is charged (\$/kW_{max}). This fee is based on the highest rate at which electricity is drawn during any 15- to 30-minute interval in a monthly billing period. A recent NREL report tabulates charges as varying from \$2/kW to \$90/kW [Ref 5]. This depends on the states and regions of charging sites, utility providers, tariffs, etc. Paradoxically, it tends to be higher in states where EVs are more popular, such as California, Massachusetts and New York. The fees tend to be higher along highways and countryside roads, where DC fast-charging stations are the most needed (i.e. between cities), owing to weak grid connections.

To address both challenges, highly efficient DC–DC converters are required. The team therefore set out to evaluate the options for providing this capability.

Solution

A promising option for boosting the efficiency of DC–DC converters from the current 95–97% is the use of partial power processing. This avoids overheating components and greatly reduces the costs of cooling equipment, which form a major component of the overall cost represented by high-power chargers [Ref 6].

Figure 2 shows a system based on only *partial* processing of the power using a reduced dissipation converter (RDC). The main benefit is that the power loss is reduced so less cooling is required. This enables a reduction in size. These changes lead to reduced cost. It is the design and implementation of this novel converter that is the main focus of this report.

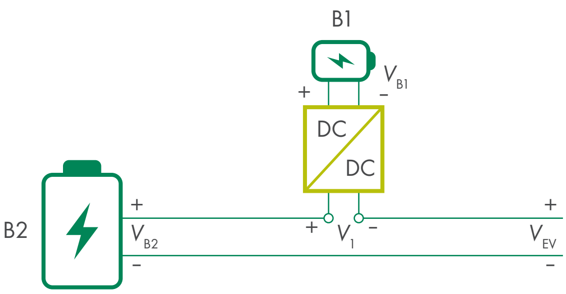


FIGURE 3
Voltage drop details across an RDC.

Principles

As to the architecture for this modified DC–DC converter, only one pole of the battery is processed, as per the configuration in Figure 2 (which is shown in more detail in Figure 3). The figure uses the symbol B2 with voltage V_{B2} for the main BESS. Typically, B2 has a larger capacity (≈200 kWh) than the EV battery (≈60–80 kWh). A second, smaller battery backing B1 with voltage V_{B1} is then introduced behind a modified buck converter switch topology [Ref 7]. This is controlled (with switching and some filtering – see later in this article) to provide a voltage V_1 to compensate for the voltage difference between the EV and the main BESS.

Benefit

Note that, by definition, $V_1 \neq V_{B1}$, as the converter controller determines the power drop for the series current in the system i_{EV}.

$$\underbrace{V_1 \cdot i_{EV}}_{P_{RDC}} + \underbrace{V_{B2} \cdot i_{EV}}_{P_{B2}} = \underbrace{V_{EV} \cdot i_{EV}}_{P_{EV}} \qquad \text{[Eq 1]}$$

As can be seen from Equation 1, the RDC only processes a small portion of total charging power (P_{RDC}), while most of the power P_{B2} flows directly from B2 to the EV. Thus, the power rating of the RDC is reduced, as is its cost. For subsequent discussion, and based on Equation 1, the efficiency is defined by

$$\eta = \frac{P_{EV}}{P_{RDC} + P_{B2}} = \frac{V_{EV} \cdot i_{EV}}{V_{B1} \cdot i_{B1} + V_{B2} \cdot i_{B2}} . \qquad \text{[Eq 2]}$$

Note that the power balance in Equation 1 contains the controlled voltage output across the RDC, whereas the efficiency term has the net input power in the denominator and thus uses the voltage across battery B1.

Design

Starting from a modified buck converter, a number of topologies were evaluated using the electronics simulation software PLECS [Ref 8]. This involved modelling a number of pulse wave modulation (PWM) controlled switches along with various low-pass inductor–capacitor (LC) filter options.

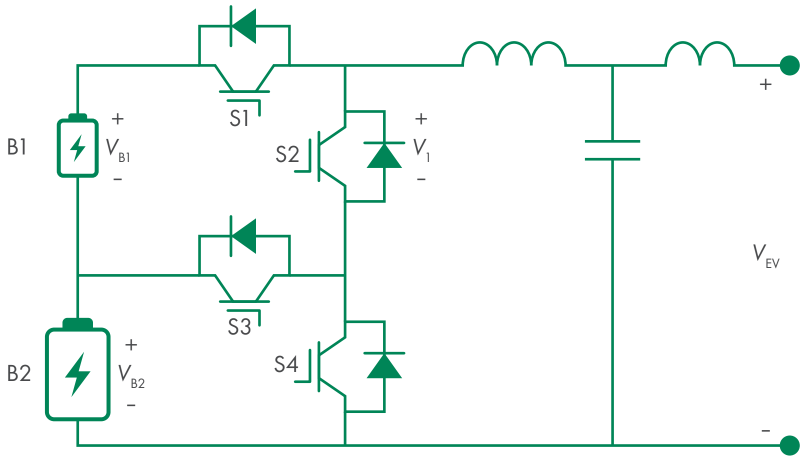


FIGURE 4
Proposed topology.

The main limitations were the battery characteristics, in particular voltage variation as a function of state of charge (SOC). The team's analysis showed that pure buck converters do not work, because of limitations on the relationship (see Figure 2) between V_{B1} and V_1. For a simple buck converter, this is given by $V_1 = DV_{B1}$, where D is the duty cycle of the switching. Thus, V_1 always has the same polarity as V_{B1}. According to Equation 1, $V_1 = V_{EV} - V_{B2}$. However, if the EV is overdischarged, then $V_{EV} < V_{B2}$ and the polarity of V_1 needs to invert. The buck topology cannot provide the required negative output voltage.

A full-bridge converter was also studied [Ref 4], but it had a similar problem: B1 extracted power from B2. Such power circulation reduces converter efficiency and can reduce the lifespan of the BESS. Furthermore, the full bridge topology lacks grounding and sufficient galvanic isolation. (Galvanic isolation is required for compliance with standards and to prevent faults being transferred between EVs.)

From a number of designs aiming to solve the restrictions discussed above [Ref 9], the topology of Figure 4 emerged. S1 to S4 are switches, assumed for now to be metal oxide silicon field effect transistors (MOSFET). The proposed topology works in two different modes:

- Mode 1: $V_{EV} > V_{B2}$. This corresponds to the SOC range of the EV battery, such that 5% < SOC(EV) < 100%, which covers the normal charging range of 20–80% SOC. Most of the charging power flows directly from B2 to the EV. S1 and S2 only process partial power from B1.
- Mode 2: $V_{EV} < V_{B2}$, which we include for completeness. It corresponds to SOC(EV) < 5%. In order to cover this rare event, S1 is turned off so B1 is cut off. S2 is permanently on. B2 charges the EV and the circuit is equivalent to a single buck converter.

Component specification

There are three stages to component selection: inputs, converter loss model for optimisation and component selection including filter design.

1. The inputs to the hardware design are the standards and the derived input specifications on current and voltage ripples shown in Table 1. The EV battery was based on the Tesla Model Y. B1 and B2 for the BESS were based on lithium iron phosphate cells. ▸▸▸

TABLE 1
Ripple limits from different charging standards.

Source (standard/manufacturer)	**Current ripple** (peak-peak, %)	**Voltage ripple** (peak-peak, V)
CCS	5	0.4
Tesla Supercharger	2	Not found
CHAdeMO	5	0.1
This study	5	0.4

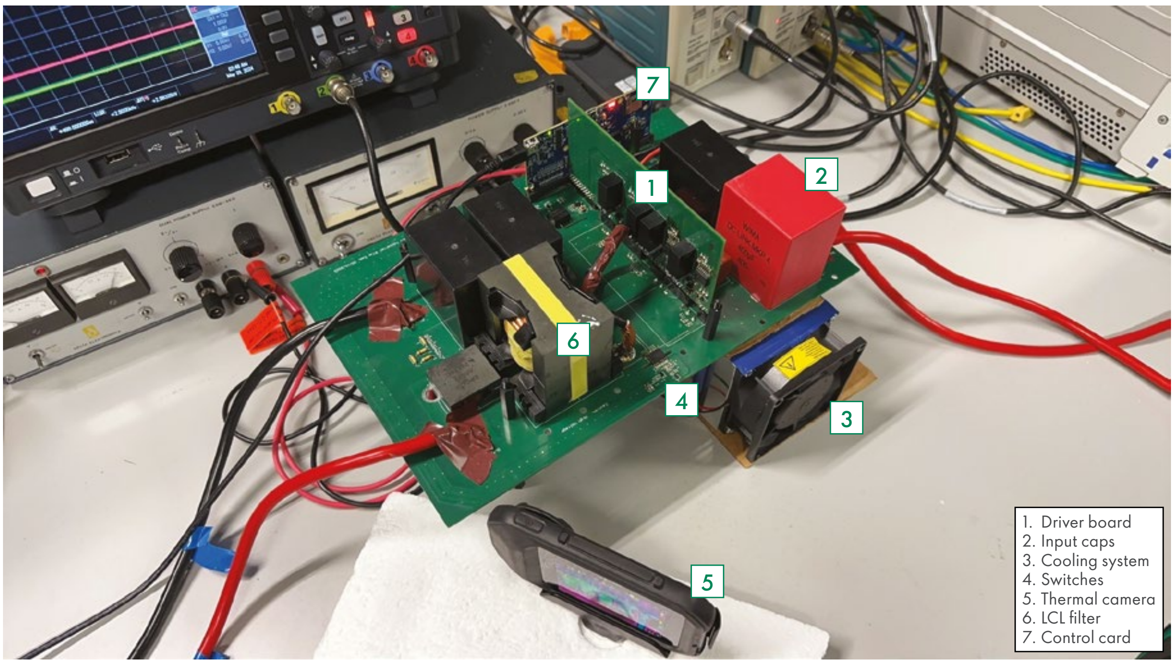


FIGURE 5
A 20-kW RDC.

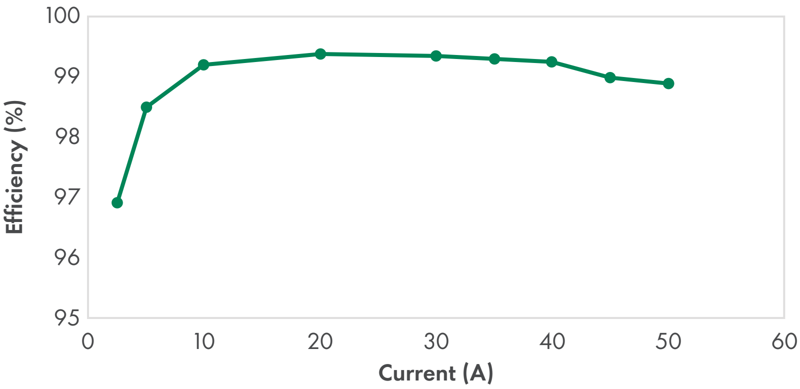


FIGURE 6

Power efficiency as a function of input current.

2. The converter loss model takes into account semiconductor and inductor losses. The values are optimised for the S1 and S2 MOSFET switching frequency (40 kHz) and current ripple, as specified in Table 1.
3. The voltage ripple standards are used for the input and output filter design. Such AC voltage fluctuations can cause EV battery degradation (such as lithium deposition on electrodes) and need to be controlled.

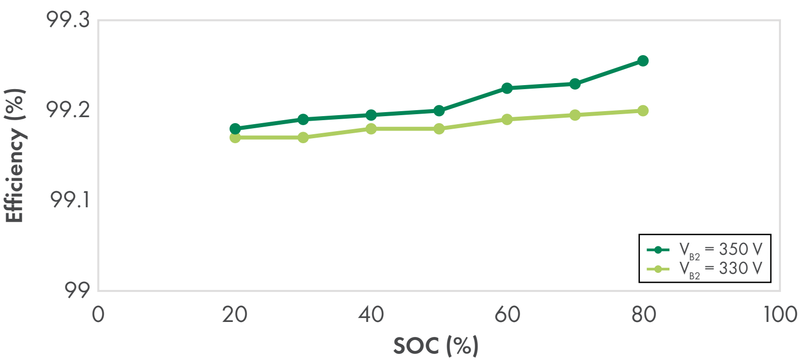
Demonstration

A 20-kW prototype was built in the laboratory at Eindhoven University of Technology and is shown in Figure 5 with principal components indicated. S1 and S2 were silicon MOSFETs and S3 and S4 were silicon carbide MOSFETs. The EV made use of a Cinergia battery emulator. The two batteries of the BESS used power supplies from Delta Elektronika. During low-power testing, switching rings of > 20 MHz were observed. These were dampened by use of a resistor–capacitor (RC) snubber circuit (see full report for more details [Ref 10]). In a subsidiary study, improved heat dissipation was introduced in order to enable 100%-rated operation without exceeding the temperature limits for the MOSFETs.

Figure 6 shows the efficiency as a function of current under open-loop control (i.e. the values are set in the controller but there is no feedback-modified control). The current of 50 A corresponds to a 100% rating with the battery emulator set to 400 V. The peak efficiency of the RDC is about 99.4% at 20 A and at full load only decreases to 98.9%. This deterioration is due to the temperature reaching 110°C.

FIGURE 7

Efficiency as a function of EV SOC at 20 A constant current charging at two different B2 voltages.



High temperature increases the on-resistance of the MOSFETs, which then have more power loss. (This is why it is important to have very high efficiencies for high-power chargers.) Note that efficiencies are above the current 95–97% efficiency ratings, and this will reduce cooling requirements. They are also considerably higher than the current systems discussed in the introduction to this article – notably the nearest competitor, the Volkswagen E. ON Drive Booster, which clocks in at 97%.

The team also carried out tests under closed-loop control with current feedback. This is how a charger works in practice for the SOC of 20–80% discussed above. For the EV battery, this corresponds to a variation of voltage from 360 to 380 V. For the B2 battery, this corresponds to a variation from 350 to 330 V. This is demonstrated in Figure 7, which shows efficiency variation for these two voltages as a function of the EV SOC. The efficiency in constant current charging mode is maintained above 99.1%. According to Equation 1, when V_{B2} is smaller, V_1 as regulated by the RDC will be larger. In this case, based on Equation 1, the processed power has increased from 200 to 1,000 W. The corresponding efficiency decrease is very small (< 0.1%). Overall, the efficiency of the RDC remains extremely high and stable for the whole normal SOC charging range.

Currently, the team is measuring further charging characteristics, such as the assessment of step current responses and other standards. They have estimated a power density of 5 kW/L, which compares well with current high-efficiency converters in the 10–20 kW/L range.

Conclusion

The team has demonstrated the principle of operation for a partial power processing DC–DC converter for EV charging. TRL is thus now > 2. Partial power processing is clearly advantageous for EV charging to compensate for grid insufficiency and also reduces dissipation in the converter. Efficiencies are > 99% and exceed the nearest competitor's. This project is now incorporated into the EU Horizon Europe programme E2GO, of which Shell is a consortium member.

The E2GO project is a consortium with three academic partners (TU Eindhoven, the Netherlands; the University of Minho, Portugal; and Aalborg University, Denmark) and six industrial partners (Shell and Delta Electronics in Poland, Heliox and KEMA in the Netherlands, Efacec in Portugal and Infineon in Austria). The full title of the project is "Cost-reduction of EV fast-charging station to enable large-scale electrification of mobility". Funding from the EU Horizon Europe programme Marie Curie fellowship scheme is to develop nine doctoral candidates.

This project involves developing novel DC–DC converters for incorporation into an EV charger for use when a (stationary) BESS is locally available. The emphasis in this project is on enabling high-power charging for cars (> 350 kW), trucks (> 1 MW) and ships (> 5 MW) while reducing energy losses and dissipation (e.g. in cooling requirements).

Future work will include:

- Evaluating a scaled-up version of a single board (e.g. 100 kW) with an associated replacement of current MOSFET switching with an insulated-gate bipolar transistor (IGBT) or integrated gate-commutated thyristor (IGCT) for high-power applications. This would have to be compared, for example, with a module containing five of the designs established in this report.
- This study used a very specific battery as reference. This will need to be extended to cover different batteries and their associated management systems.
- AC winding losses in the inductors were estimated to be only around 1–3% of total winding losses. They were neglected in the current study but should be further investigated for a fully optimised system for the RDC. ■

Review:

Paul Donnellan, Principal Advisor Power Technology

This content follows Shell's net carbon footprint and net-zero emissions target principles as documented here: www.shell.com/investors/disclaimer-and-cautionary-note.html.

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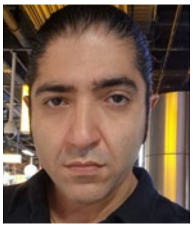

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