Introduction to Power Electronics for Electric Vehicles

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OBJECTIVE

This study provides an overview of electric vehicle (EV) technology and battery charging with emphases on the following topics:

1. Electric Vehicles
2. Charging: conductive and inductive charging; high-power or rapid charging; on-board vs. off-board charging, integral charging, power electronics

As the material can be very wide and deep, this report presents an overview of the topics for the non-power-electronics specialist.

I. ELECTRIC VEHICLES

In recent years, there has been a significant interest in the development of electric vehicles. Announcements occur regularly on proposed new product introductions into the automotive marketplace. The projections for the grid impact of electric vehicles range from conventional hybrid with no grid impact to plug-in hybrid and full EV with significant impact on grid storage with long-term possibilities of spinning reserve. A sampling of electric vehicles is shown in Fig. 1.

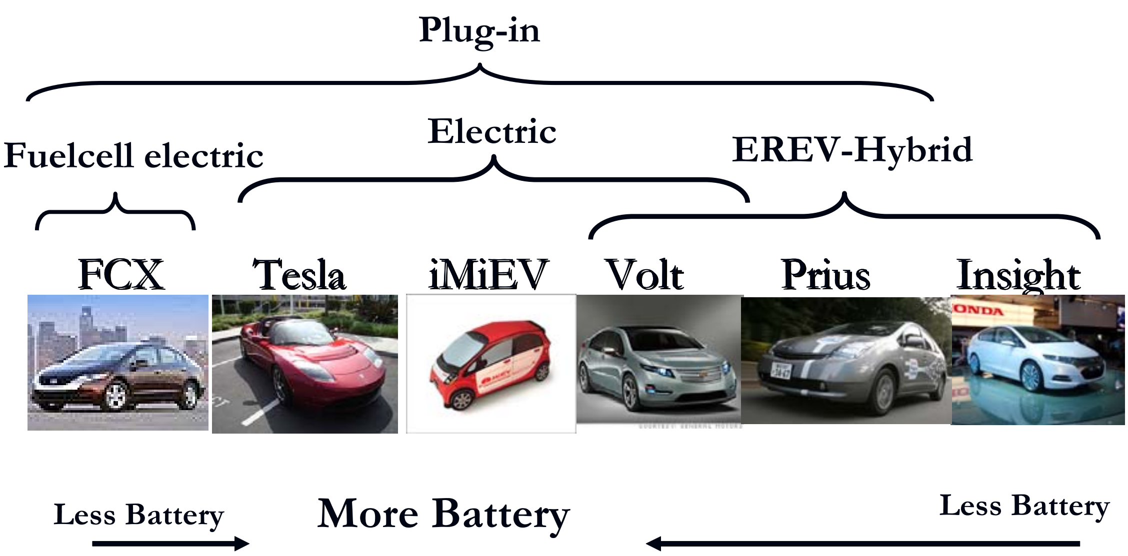

Fig. 1. EV Vehicle map

Electric vehicles can range from the hybrid-electric vehicle (HEV) technologies currently on the market such as the Toyota Prius and Honda Insight to the proposed production battery electric vehicles such as the Mitsubishi vehicle iMiEV and the Tesla products. Futuristic hydrogen-based fuelcell electric vehicles are on the far end of the EV spectrum and are generally neglected in this study due to the longer term development plans. All these vehicles use varying amounts of battery storage, electrical propulsion and grid interface. An EV functional diagram and EV classifications are shown in Fig. 2 and Fig. 3, respectively.

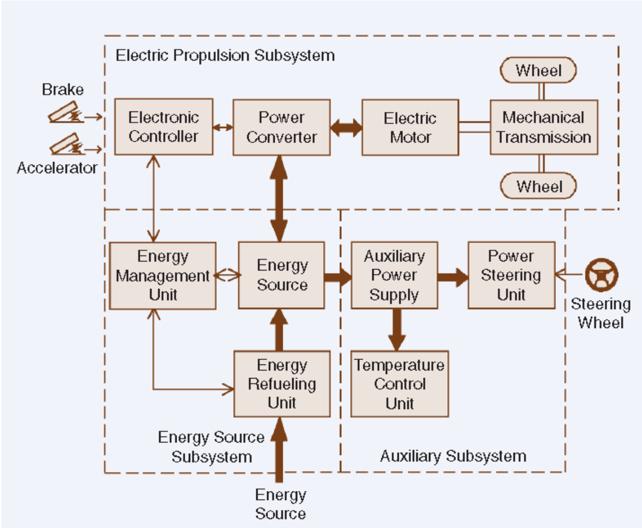

Fig. 2. EV's functional diagram [11]

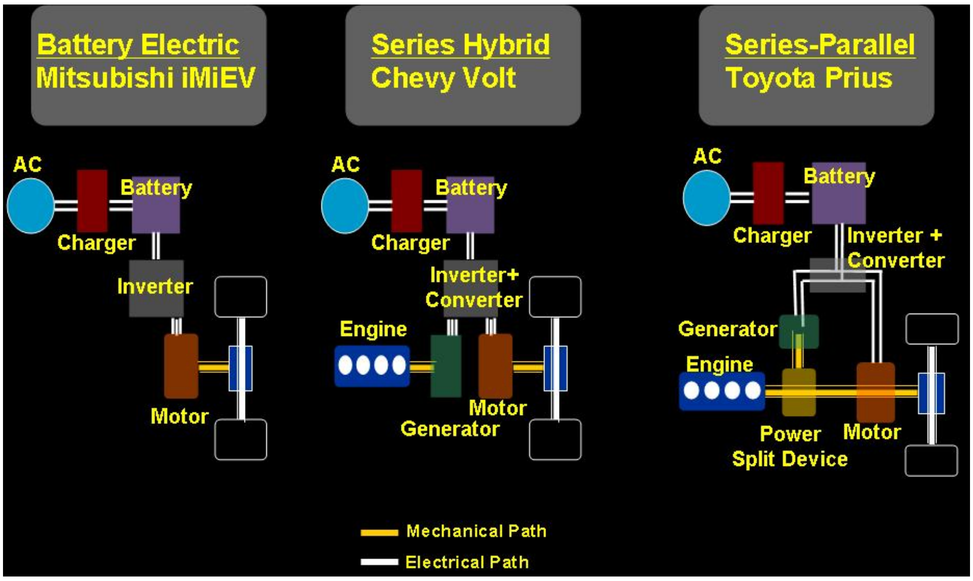

Fig. 3. Classes of (H)EVs

Presently, the production hybrids such as the Toyota Prius cannot be recharged from the electrical grid, but the next-generation Prius is proposed to have a plug-in capability. The Chevy Volt is classified by General Motors as a range-extended electric vehicle and will feature an on-board two-stage charger for the Li-ion battery pack. The Volt is a series hybrid and additionally features an internal-combustion engine to act as a generator to extend the vehicle range [7]. The battery electric vehicles from Tesla and Mitsubishi are plug-in although there are significant differences between the charging technologies as discussed later.

The use of electrical power for propulsion has been known since 1828 when the first electric vehicle model was built by the inventor of the electric motor, Anyos Jedlik. Later, in 1834 another vehicle model operating on a short circular electrified track was built by Thomas Davenport. Improvements in battery technology lead to the development of the first electric cars in the 1880s. At the turn of the century, more electric cars were sold than their internal combustion engine (ICE) counterpart as ICE vehicles were seen as unreliable, dirty and difficult to start. This all was to change with the invention of the electric starter by Kettering at Cadillac and within a short number of years, ICE vehicles dominated and electric vehicles were relegated to niche low-volume applications.

There have been various attempts to revive EV technology in the past century, the most publicized being the General Motors EV1 in the 1990s. The GM EV1 was introduced in 1996 as a high-performance, two-seater sports car, with a drag co-efficient of 0.19 and other efficiency-oriented technologies such as high pressure tires and an aluminium frame [2].

The EV1 project ended in the scrapping of the fleet in 2004, the events of which were well documented in the Hollywood documentary *Who Killed the Electric Car?*

As the authors are very familiar with the GM EV1, we will briefly review the EV technologies for comparison with more recent vehicles. Vehicle information is presented in Table I. The EV1 electric drive train featured a 100 kW squirrel-cage induction motor (SCIM) powered by a 600 V insulated-gate bipolar transistor (IGBT) inverter. Generally electric vehicles use either squirrel-cage induction motors (SCIM) or permanent magnet ac (PMAC) motors for propulsion, although some lower power, less sophisticated vehicles may use dc drives. The trend in recent years for EVs, and other technologies such as wind turbines, is to use PMAC machines. However, concern about the availability of rare-earth magnets from China is leading to renewed interest in SCIMs and other machines. Interestingly, the prototype GM vehicle was known as the Impact and it featured a charging system using the main induction motor as the charging inductor. This system was known as integral charging and will be discussed later. Tesla and AC Propulsion use integral charging and so also have the SCIM as the main propulsion motor. Renault-Nissan are also considering this option.

As with most drives systems, there is no competition for the insulated-gate bipolar transistors (IGBT) as the main power semiconductor, although the metal oxide semiconductor field-effect transistor (MOSFET) is very competitive with the IGBT for the transformer-isolated dc-dc stage of the charger. Generally, in power electronics above 1 kW, the IGBT is the device of choice. The IGBT is making advances into traditional power systems. The new Ireland-Wales interconnect will feature the ABB HVDC-light system. This system uses strings of IGBTs in parallel and series to replace the traditional thyristor and increase the switching frequency. The MOSFET and IGBT will be discussed in greater detail later in the course.

The T-shaped battery pack in the first EV1 featured lead-acid technology and the range proved to be limited, realistically in the 50 to 80 mile range. The 2nd generation vehicle featured a NiMH pack which improved the range 20 to 30 %.

Table I Electric Vehicles

	1996 EV1	iMiEV	2010 Volt	Tesla
				
Batteries	Lead Acid	Li Ion	Li Ion	Li Ion
EV Range	50-80 miles	60-100 miles	40 miles	220 miles
Storage	17 kWh	16 kWh	19 kWh	53 kWh
Motor	Squirrel-cage IM	Permanent Magnet	Permanent Magnet	Squirrel-cage IM
Generator	None	None	53 kW/1.4 l	None
BP Weight	1200 lb	375 lb	375 lb	990 lb
Weight	2970 lb	2400 lb	3520 lb	2690 lb
Horse power	130	64	150	248
0 – 60 mph	8.5 s	>15 s	9 s	3.9 s
Charging	230 V, 30 A Inductive	200 V, 15 A Conductive	230 V, 16 A Conductive	Integrated Conductive

II. Charging Technologies

There are a wide variety of charging technologies available for EVs. Choices and decisions must be made by the various manufacturers and infrastructure providers with respect to the following areas: conductive and inductive, high-power or rapid charging, and on-board vs. off-board chargers.

The proliferation of utility-connected power electronic converters has spurred the demand for products which limit the total harmonic distortion (THD) and maximize the power factor of the currents sourced from the utility. Power-factor-corrected (PFC) utility interfaces are of prime importance in the EV industry because the EV battery charger must minimize line distortion and maximize the real power available from the utility outlet. Most EV battery chargers feature a two-stage converter featuring a PFC boost ac-dc pre-regulator and a high-frequency transformer-isolated dc-dc.

EV chargers are similar in operation but have some key differences with battery chargers used in other applications, such as mobile phones and laptop computers. The basic functions of a low-power battery charger are shown in Fig. 4. They can be summarized as follows:

- AC-DC rectifier: As can be seen in Fig. 5, the diode bridge rectifies, or makes positive, the input AC voltage v_{AC} and current i_{AC} when they are in the negative half cycle. Thus, the output of the diode rectifier is always positive as seen in the waveforms at the rectifier output AC voltage $|v_{AC}|$ and current i_{AC}.
- DC Capacitor: The DC capacitor is charged to the peak AC voltage when the rectifier output AC voltage $|v_{AC}|$ exceeds the capacitor voltage. This only happens during a portion of the cycle and there is a surge of current from the AC input through the diodes and into the capacitor. This is why the current waveforms have a sharp pulsed waveform. This waveshape has significant harmonic distortion and a very poor power factor. Thus, simple diode rectifier-capacitor frontends are only permitted in low power applications.
- DC-DC Converter: The DC-DC converter converts the high-voltage on the DC capacitor (typically around 300 V) to a safe lower voltage for input to the laptop or mobile phone for use in charging. The simplest and most cost-effective DC-DC is the switch-mode Flyback converter, which switches at a high frequency and has the transformer isolation essential for safety.

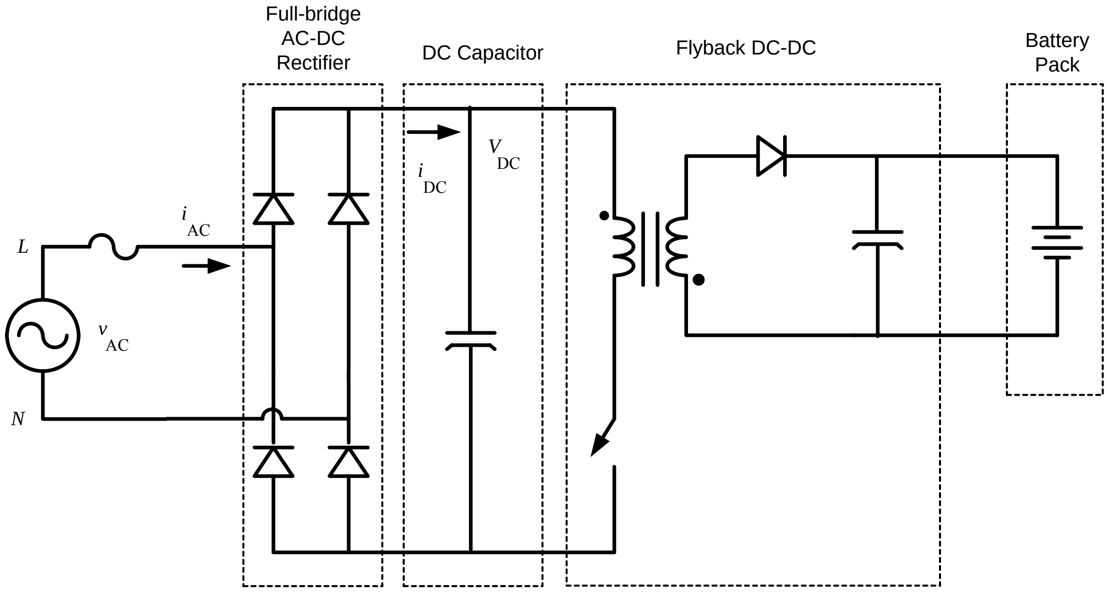

Fig. 4 Low-power charger

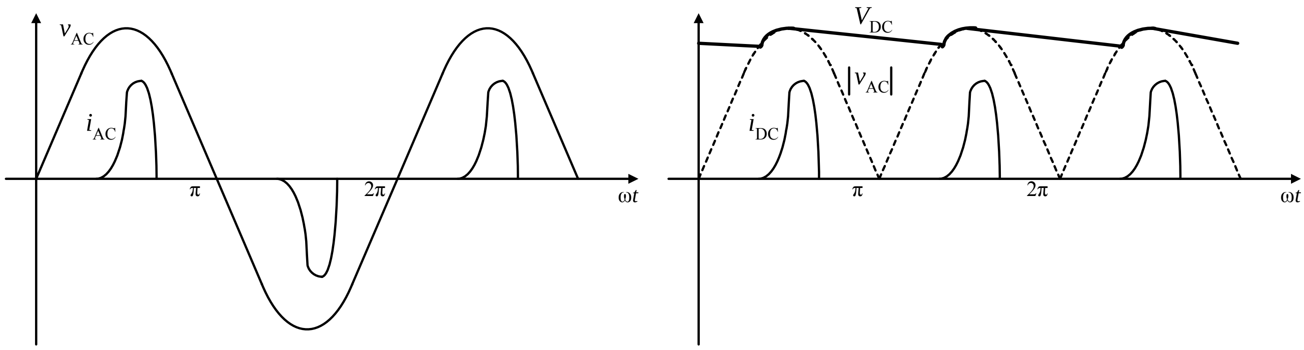

Fig. 5. Rectifier-capacitor waveforms

For high-power applications, the above AC current waveforms are unacceptable and the simple capacitive filter is buffered with another switch-mode power converter, known as the boost converter. The boost converter will act to maintain the input current waveform identical with the input voltage waveform and so eliminate any harmonic distortion and improve the power factor to unity. The power-factor corrected converter is shown in Fig. 6, and the waveforms are presented in Fig. 7. A basic requirement for the boost converter is that the output DC voltage must be greater than the peak of the input AC voltage.

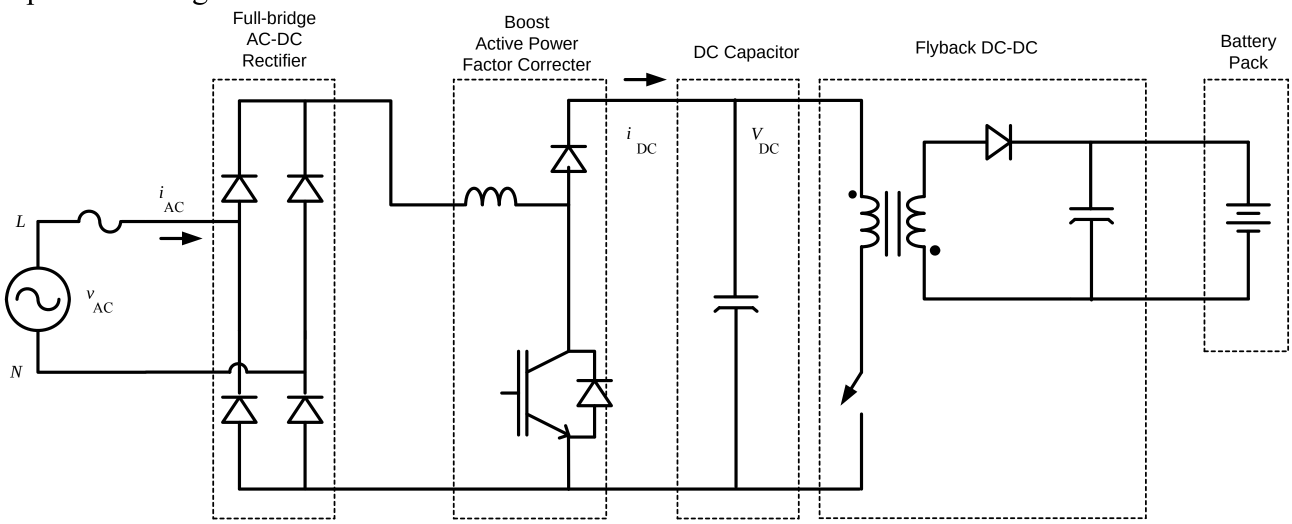

Fig. 6 High-power charger

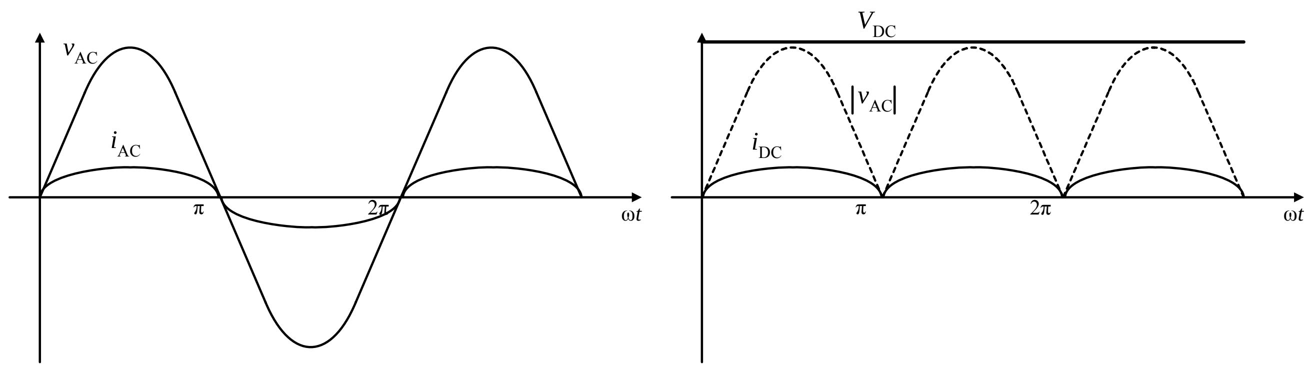

Fig. 7. Power-factor-corrected waveforms

A more detailed overview of the EV battery charging system is shown in Fig. 8. This charging system is representative of the on-vehicle conductive systems. The circuit has a number of different functions as follows:

- RCCB: A ground-fault interrupt circuit (GFCI) must be provided to prevent shock to consumers due to earth currents. The residual current circuit breaker (RCCB) detects an imbalance in the line and neutral currents, usually between about 5 to 20 mA, and triggers a circuit breaker to take the charger off line and so prevent fatalities.
- EMI Filter: switching power electronics can generate significant radiated and conducted noise or electromagnetic interference. A high-current filter with common-mode and differential-mode stages is required to meet legal emission standards in the USA (FCC) and the EU (VDE).
- Rectifier: a simple diode bridge rectifies the 50 Hz ac.
- Boost PFC: a boost converter, typically switching at 10 to 50 kHz, chops up the low-frequency rectified power and boosts it to a voltage level of about 375 to 400 Vdc, a value higher than the peak ac value.
- An electrolytic capacitor is usually used for bulk storage to filter the 50 Hz component.
- DC-HFAC Chopper: A full-bridge or H-bridge converter is used to chop the nominal 400 V dc link voltage into a high-frequency pulse stream going from -400 V to +400 V at 10 to 500 kHz.

- Transformer: The high-frequency pulse stream is galvanically isolated for safety by the transformer. The pulse stream must be high frequency in order to minimize the size and weight of the transformer.
- Rectifier-Filter: The output of the transformer secondaries are rectified and filtered to create dc current to charge the battery.

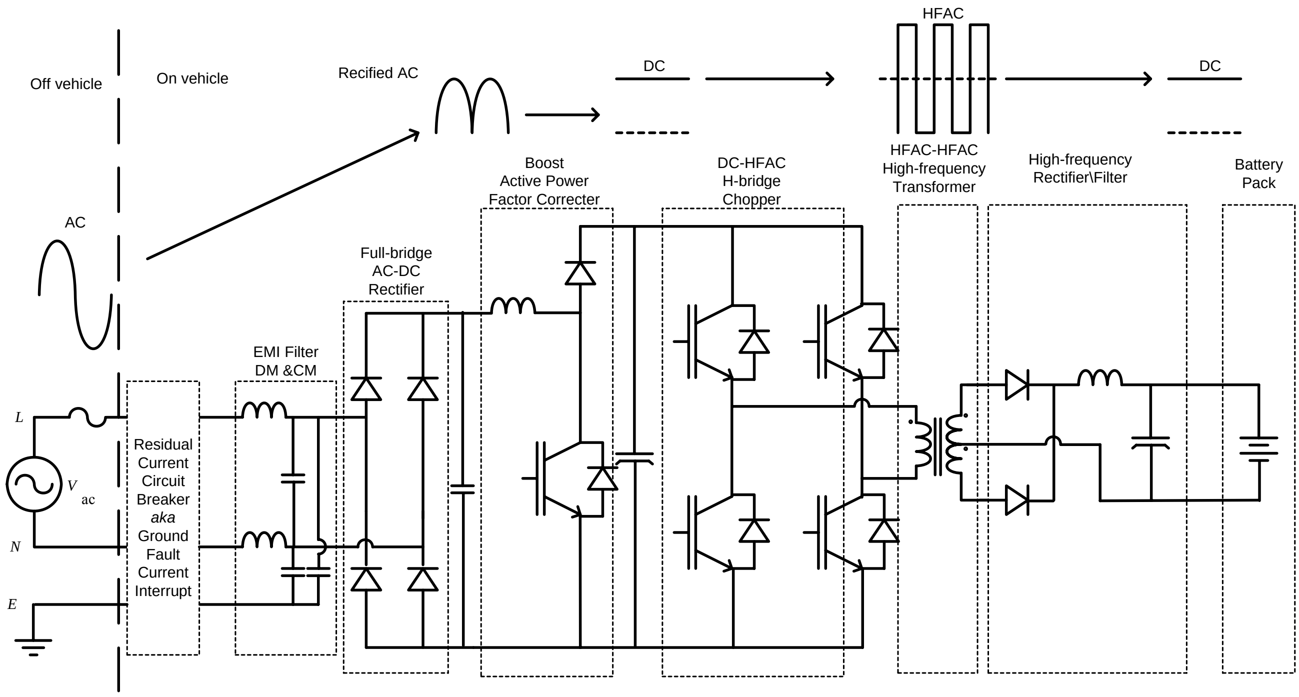

Fig. 8. Conductive battery charging system

As a brief aside, modern power electronics is based on switch-mode converters rather than the very inefficient linear converter. The basic building blocks for switch-mode power electronic converter are shown in Fig. 9, and are discussed as follows.

- Boost converter: the boost or step-up converter converts power from a lower voltage to a higher voltage. In the mobile phone the boost converter boosts the battery voltage from 3.3 V to 15 V to run the display. Boost converters are the standard technology for active power factor correctors as the rectified ac input voltage varies from 0 V to √2 x 230 V or 325 V. The high-voltage dc link must be greater than 325 V and is usually in the range of 380 to 400 V, as power converters are usually designed to accept an input ac voltage of 264 V.
  The boost converter operates as follows. The power switch Q is turned on placing the full dc input voltage V_{LV} across the inductor L. The current builds up in the inductor. The switch Q then is turned off and the inductor forces the power diode D to conduct, thus transforming the power from the lower voltage to the higher voltage.
- Buck converter: the buck or step-down converter converts power from a higher voltage to a lower voltage. An example is the mobile phone. The 3.3 V Li-ion battery voltage is stepped down using a buck converter to about 1.5 V to run the microprocessor.
- Half bridge: The half-bridge converter is created by simply connecting the power switches and diodes of the buck and boost converters. The half-bridge converter can move power bidirectionally from a higher voltage to a lower voltage.
- Full-bridge: Two half-bridge converters can be put together to create a full-bridge which can be used to transform dc to pulsed ac. This converter can also be used to generate single-phase ac for an uninterruptible power supply.
- Three-phase inverter: three half-bridge converters can be put together to build a three-phase inverter. Three-phase inverters are the work horses of motor drives and can also be used for active-power factor correction of three-phase supplies for G2V. As they are inherently bidirectional, they can be used for V2G.

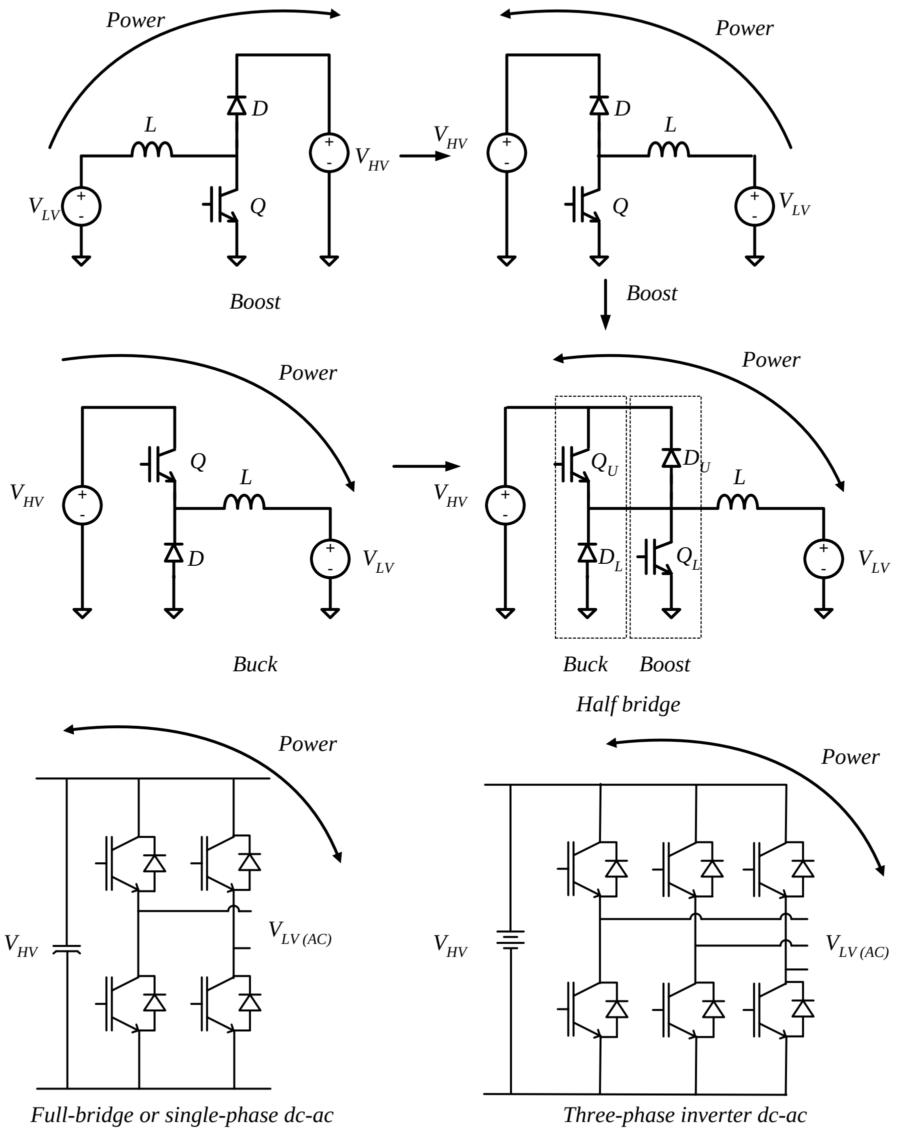

Fig. 9. Buck, boost and half-bridge converters

We generally talk about three power levels for charging: Level 1 is low power in the range of 1 to 3 kW, and generally is 230 V, 16 A in Ireland or 120 V, 15 A in the USA; Level 2 is medium power ranging from 3 to 10 kW; Level 3 is high power and is in the range of 10 kW to 160 kW.

Given that all the charging systems will use some variation on the system presented in Fig. 8, the various systems will all have comparable efficiencies. In general, overall conversion efficiencies from the power outlet to the battery should be in the low-to-mid nineties.

Most of the discussion on conductive systems has parallels with inductive systems: standardization, reliability, high power, communications, safety, user friendliness, etc. There are two proposed standards for now: SAE J-1772 for North America and IEC 62196 for Europe. Interestingly, these two standards are not compatible although an adapter may be developed. IEC 62196 has a 7 pin connection (3 power pins, neutral pin, 2 signal pins and ground). SAE J-1772 has a 5 pin connection (power and neutral, 2 signal pins and ground). The rated power is 20 kW and 43 kW for SAE J-1772 and IEC 62196, respectively.
Note that for both these standards, the connector brings ac onto the vehicle. The vehicle will contain an on-board two-stage charger for PFC boost ac-dc pre-regulation and high-frequency transformer-

isolated dc-dc conversion to charge the battery and run ancillary services. The charging systems for both these standards are as originally presented in Fig. 8.

SAE J-1772 is a proposed North American standard for a conductive connector for electric vehicles maintained by Society of Automotive Engineers. It covers the general physical, electrical, and performance requirements for the electric vehicle conductive charge system and coupler.
SAE has been making modifications to the older J-1772 November 2001 standard, moving toward a smaller (and less expensive) coupler made by Yazaki to replace the former Avcon connector. The J-1772 standard specifies a specific 5-pin plug (two power, two signal, one ground) for single-phase supply up to 80A. As shown, the Yazaki connector has two pins for ac current. This would suit North America, where split-phase 240V is the common supply. But in Europe, it's far more common to have 3-phase supplies, often of a lower current but giving a similar or higher charge power overall. Thus, the interest in the second standard discussed below.

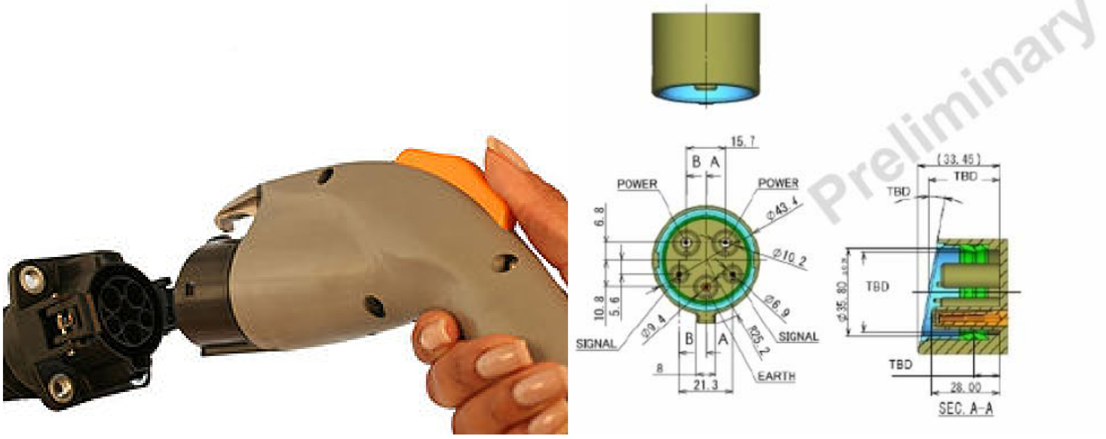

Fig. 10. SAE J-1772 Vehicle interface and vehicle inlet [12]

IEC 62196 is a proposed European standard for the electrical connector for electric vehicles which is an alternative to J-1772. Why not just use the existing IEC 60309? Well, there are a few drawbacks - the higher current versions are rather bulky and there's no provision for a pilot or data pin (to allow the cable to be de-energised when not plugged into a vehicle). As well, it would be an advantage to offer various different supplies such as 1 or 3 phase, and different current levels all through the same connector.
The new connector is made by Mennekes and was developed with requirements from RWE and Daimler. The connectors will be referenced under the IEC 62196 electric vehicle charging standard. It looks pretty similar to the SAE connector - but it has 7 contacts in total, 3 AC phases and Neutral, with a 63A rating – giving a 43kW maximum charge rate.
It appears very compact for the power, compared to the IEC60309 type, and is not overcomplicated. The developers explain that the same connector could be used on both ends of the charging cable, and there is a locking mechanism to make charging secure.

Fig. 11. IEC 62196 Connector [13]

A possible block diagram for charging with the IEC connector is as shown in Fig. 12.

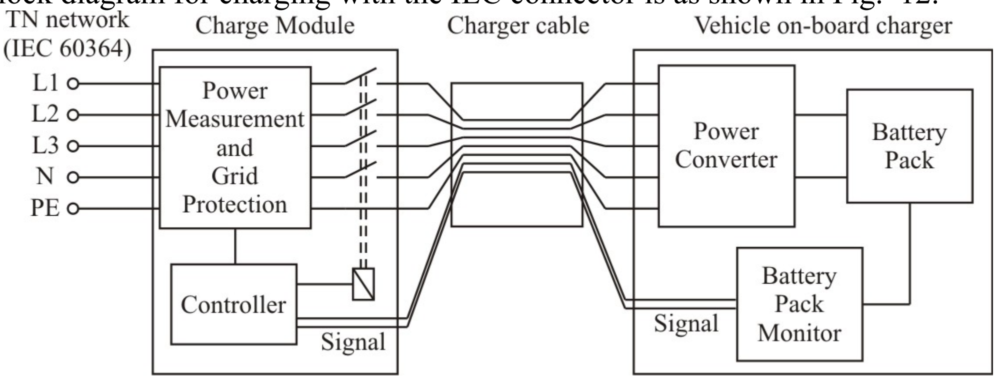

Fig. 12 IEC 62196 charging block diagram

Rapid and High-Power Charging

Rapid or high-power charging requires significant energy to be transferred from the grid to the vehicle in a matter of minutes, thus the requirement for dedicated charging stations capable to deliver power up to hundreds of kilowatts. This has serious implications for the power distribution network.

There are niche applications and definitions of rapid charging. For heavy-duty vehicles such as an electric bus, a high-power charging capability is necessary in order to charge the vehicle within a reasonable time, e.g. over night.

High-power charging is proposed for Li-ion battery packs. For instance, Reva can ship a three-phase 10 kW off-board charger which could rapidly charge the 12 kWh battery pack in about 30-60 minutes. The Mitsubishi iMiEV takes 7 hours to charge the 16 kWh batteries from a 200 V household electric outlet. There is also a 200 V 50 kW rapid charge system which enables the battery to charge 80% of power in 30 minutes.

The integral charging system developed by AC Propulsion is also high powered as discussed in the next section. Up to 20 kW is available for this on-board system known as the Integrated Reductive™ Charger.

Standardization will likely be a problem as all vehicles not using the integral charging approach will have to have a high-current dc connector on vehicle to interface with the high-power off-vehicle three-phase ac-dc charger. Significant work is required for standardization. On the other hand, the ability of the batteries to accept high power is not established and so the high-power issue can be dealt with in parallel with battery development. Battery temperature and resultant cycle lifetime are dependent on many factors including ohmic I^2R heating due to the battery conducting current. Increased current flows into the battery will result in increased heating, elevated temperatures and reduced lifetime.

A high-power charging system is shown in Fig. 13. The boost converter has been modified to feature three poles in order to provide active power factor correction and dc bus regulation for a three-phase input.

There is significant interest in providing vehicle-to-grid power transfers. A bidirectional system is shown in Fig. 14. The main difference between the converters is that the bidirectional system features a H-bridge on the secondary of the transformer. With this change, the power can flow in either direction for V2G or G2V.

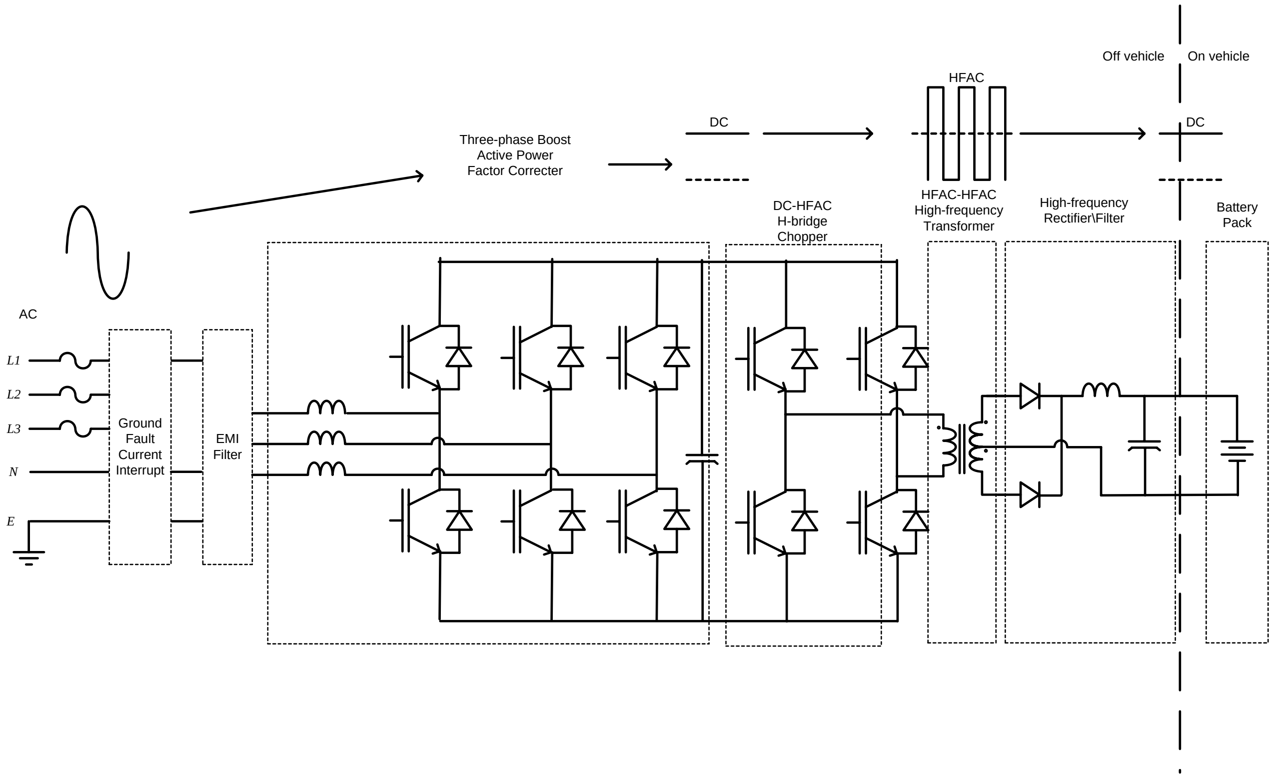

Fig. 13. High-power conductive charging system (G2V)

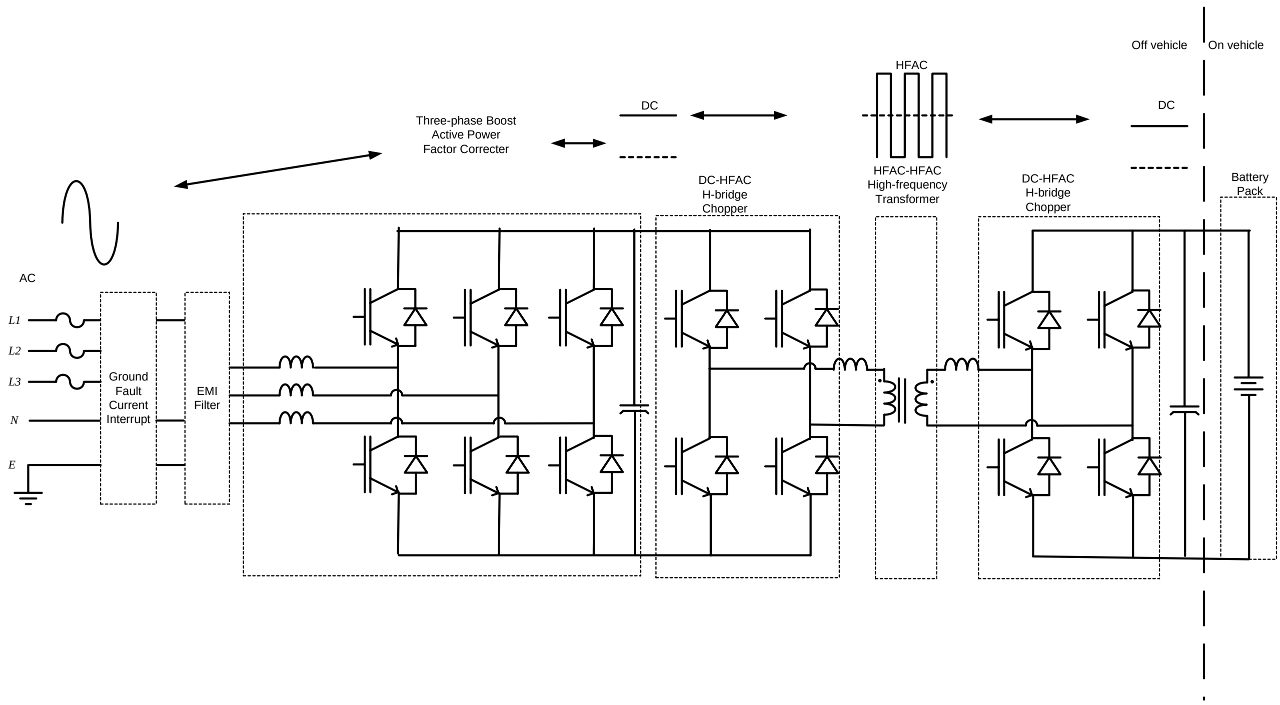

Fig. 14. High-power bidirectional conductive charging system (G2V and V2G).

Integral Charging

Carrying on from the earlier discussion, all EVs are likely to feature an on-board isolated two-stage charging system for PFC boost ac-dc pre-regulation and high-frequency transformer-isolated dc-dc conversion. Generally, the proposed systems are relatively low power, covering Level 2 charging from 3 to 10 kW. The iMiEV and Chevy Volt both feature approx. 3 kW chargers to be powered from a domestic source. This should result in a shoe-box size charger on vehicle.

An alternative approach is integral charging [10]. The integral charging system is designed to minimize on-vehicle components and reuses the on-vehicle propulsion system for charging. It simply electronically reconfigures the star-connected squirrel-cage induction motor with a neutral to a three-phase inductor for use in charging. The propulsion inverter can then be reused for charging at low or high power. This system was originally developed by Wally Ripple of Aerovironment and Alan Cocconi of AC Propulsion for use in the GM Impact, the earlier version of the GM EV1. What appears to be a related system tends to be reused on vehicles where Cocconi or AC Propulsion have a design input, such as the Tesla vehicles and the MINI E vehicles for BMW. The integral charging system is known as the Integrated Reductive™ Charger, and can also act for V2G as the charging system is bidirectional. Concerns about the technology tend to center on safety - the lack of isolation for vehicle grounding.

The following are the charger specifications for the Integrated Reductive™ Charger [5].

- Charge from any source, 100-250 VAC
- Charge rate controllable from 200W up to 20kW (with 240 V line)
- Unity power factor, sine wave current draw
- GFI outlet compatible
- Automatic mode switching (recharge mode activated when charge power is connected)
- Controlled battery discharge into power line for battery diagnostics and V2G
- UPS mode for backup power and energy transfer to other electric vehicles.

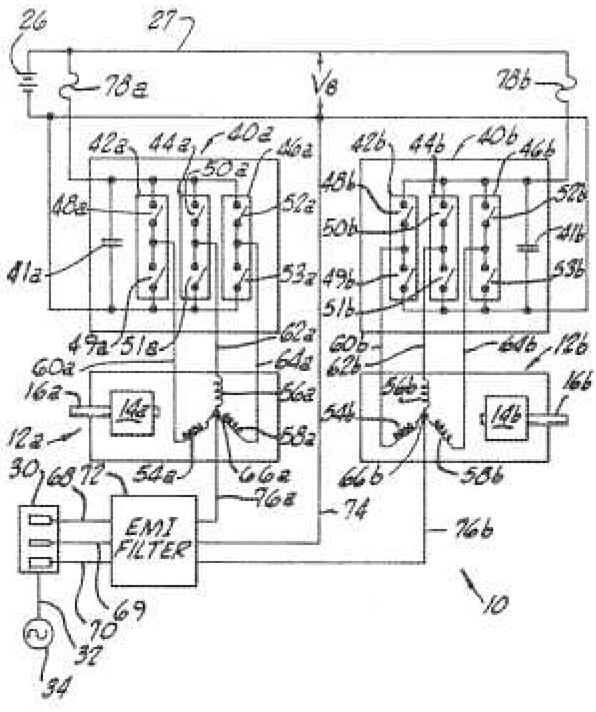

Fig. 15. GM Impact integral charger system [10]

A simplified block diagram of the power system is shown in Fig. 16. When the vehicle is moving, the three-phase inverter transfers power from the battery to the axle via the drive motor. The three-phase inverter is bidirectional and transfers power from the axle to the battery when operating in regenerative or vehicle-braking mode. The system can be reconfigured using contactors to operate as a charger. Given, the bidirectional nature of the inverter, the charger is bidirectional and can provide V2G as well as G2V.

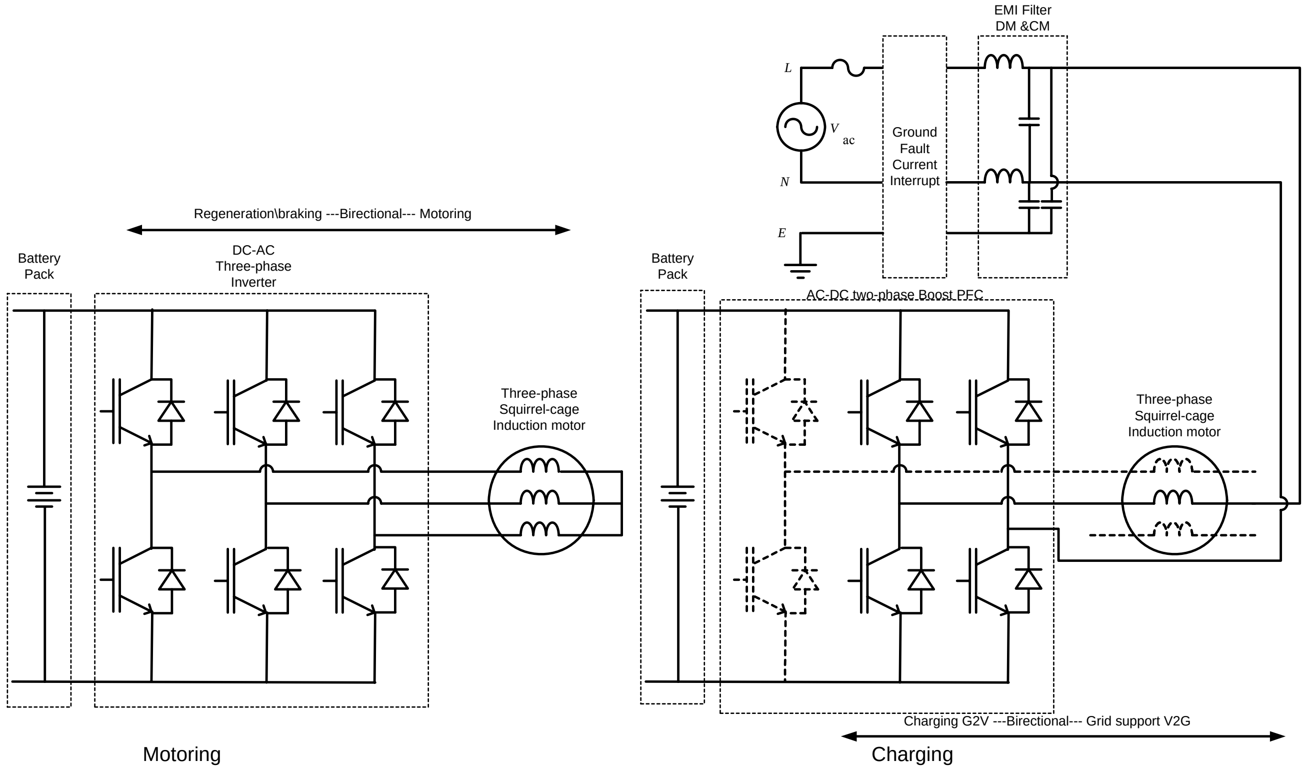

Fig. 16. Simplified diagram of bidirectional integral charging system.

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