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Power Electronics for Electric Vehicles: A Review of Traction Inverters, Dc–Dc Converters, Charging Systems, Battery Management and Wide-Bandgap Devices

Yogesh Machhindra Dhomse[1] Samarth Shubash Dongre[2] Dhanraj Shinde[3]
Prof. A. S. Bhor[4] Prof. M. S. Nalawade[5] Dr. V. M. Dhede[6]
[1,2,3]Department Of Electronics And Telecommunication Jaihind College Of Engineering Kuran, Pune, Maharashtra, India
[4]Seminar Guide Department Of Electronics And Telecommunication Jaihind College Of Engineering Kuran, Pune, Maharashtra, India;
[5]Seminar Coordinator Department Of Electronics And Telecommunication Jaihind College Of Engineering Kuran, Pune, Maharashtra, India;
[6]Head Of Department Department Of Electronics And Telecommunication Jaihind College Of Engineering Kuran, Pune, Maharashtra, India

Abstract—Electric vehicles are replacing internal combustion vehicles in many markets, and power electronics is the technology that makes this transition possible. Every flow of energy in an electric vehicle, from the charging socket to the battery, from the battery to the traction motor, and from the high-voltage pack to the low-voltage accessories, passes through a power electronic converter. This review presents the major power electronic subsystems of a battery electric vehicle: the traction inverter that converts DC to variable-frequency AC, the bidirectional and auxiliary DC–DC converters, the onboard AC–DC charger and the off-board DC fast charger, together with the battery management system that supervises the pack. Motor control by pulse width modulation and field-oriented control is explained. The role of wide-bandgap semiconductors, silicon carbide and gallium nitride, in raising efficiency, switching frequency and power density is discussed and compared with silicon devices. Thermal management, electromagnetic compatibility and functional safety are reviewed as system-level design concerns. A complete power-flow architecture of an electric vehicle is presented, and representative studies are compared. Challenges and future directions, including 800 V architectures, extreme fast charging, integrated chargers and vehicle-to-grid operation, are identified.

Index Terms—Electric vehicle, power electronics, traction inverter, DC–DC converter, onboard charger, DC fast charging, battery management system, silicon carbide, gallium nitride, field-oriented control.

I. INTRODUCTION

Road transport is a major user of oil and a significant source of air pollution and greenhouse gas emissions. Electric vehicles (EVs), which use an electric motor supplied from a rechargeable battery, eliminate tailpipe emissions and convert stored energy to motion far more efficiently than internal combustion engines. Global sales of electric cars have grown rapidly in recent years, supported by falling battery costs and government policy [1].

Chan described the state of the art of electric, hybrid and fuel-cell vehicles and identified the electric propulsion system, comprising motor, power converter and controller, as the heart of an EV [2]. Emadi, Lee and Rajashekara explained that power electronics and motor drives determine the performance, efficiency and cost of electric and hybrid vehicles [3]. Unlike a conventional vehicle, where a mechanical drivetrain transfers engine power to the wheels, an EV relies on converters to control energy flow in every operating mode: driving, regenerative braking, charging and powering accessories.

This review explains these converters and their control. Its contributions are:

- A description of the power electronic subsystems of an EV and their functions.
- A review of converter topologies, motor control and charging systems with representative studies.
- A discussion of wide-bandgap semiconductors, thermal management and safety.
- A power-flow architecture of an EV, a comparison of technologies and a summary of challenges.

Section II describes the EV powertrain, Section III reviews the traction inverter and motor control, Section IV reviews DC–DC converters, Section V covers charging systems, Section VI covers the battery management system, Section VII discusses wide-bandgap devices and system concerns,

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Section VIII presents the architecture and comparison, Section IX discusses challenges, and Section X concludes.

II. EV POWERTRAIN OVERVIEW

A battery electric vehicle contains a high-voltage battery pack, typically between about 300 V and 800 V, a traction inverter and motor, a DC–DC converter supplying the 12 V accessory system, an onboard charger, and a battery management system (BMS). Hybrid vehicles add an engine and generator, and some designs include a bidirectional DC–DC converter between battery and inverter to boost the DC-link voltage [3]. Bilgin *et al.* argued that electrified transportation requires co-design of these components to achieve competitive cost and performance [4].

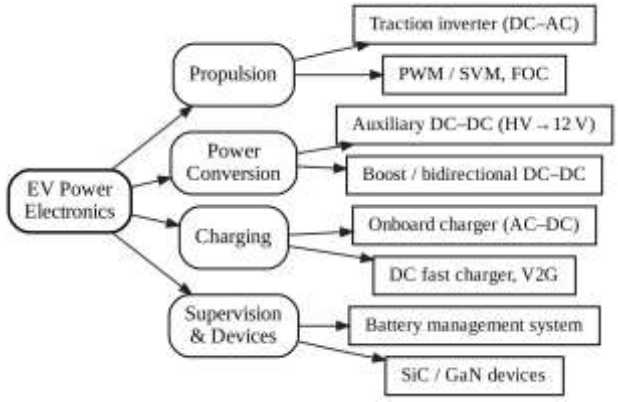


Fig. 1. Classification of power electronic subsystems in an electric vehicle.

III. TRACTION INVERTER AND MOTOR CONTROL

3.1 Inverter Topology

The traction inverter converts the DC battery voltage into three-phase AC of variable amplitude and frequency to drive the motor. The usual topology is the two-level, three-phase voltage-source inverter with six switches, implemented with insulated-gate bipolar transistors (IGBTs) or, increasingly, silicon carbide (SiC) MOSFETs [5], [6]. During regenerative braking, the same inverter operates in reverse, returning energy from the motor to the battery.

3.2 Pulse Width Modulation

The inverter synthesises a sinusoidal output by pulse width modulation (PWM). In sinusoidal PWM, a reference sine wave is compared with a high-frequency carrier to set switching instants. In the linear range, the fundamental line-to-line RMS voltage is

$$V_{LL,rms} = (\sqrt{3} / (2\sqrt{2})) \cdot m \cdot V_{dc} \approx 0.612 \cdot m \cdot V_{dc} \quad (1)$$

where m is the modulation index and V_{dc} the DC-link voltage [5]. Space vector modulation uses the DC link more effectively, extending the linear range by about 15% [6].

3.3 Field-Oriented Control

Permanent magnet synchronous motors and induction motors are controlled with field-oriented control (FOC), introduced by Blaschke [7]. FOC transforms the three-phase currents into a rotating reference frame aligned with the rotor flux, producing a direct-axis current that controls flux and a quadrature-axis current that controls torque. This decoupling allows the AC motor to be controlled like a DC motor, giving fast and precise torque response over a wide speed range [6].

IV. DC–DC CONVERTERS

4.1 Auxiliary Converter

Lights, infotainment, power steering and control units run from a 12 V (or 48 V) system. An isolated DC–DC converter steps down the high battery voltage to charge the low-voltage battery and supply these loads. Phase-shifted full-bridge and resonant LLC converters are common because they achieve soft switching and high efficiency.

4.2 Boost And Bidirectional Converters

Some vehicles use a bidirectional boost converter between the battery and inverter so that the inverter can operate at a higher, regulated DC-link voltage, improving motor performance at high speed [3]. For high-power isolated bidirectional conversion, the dual active bridge proposed by De Doncker, Divan and Kheraluwala offers soft switching and high power density [8]; it is widely used in chargers and in vehicle-to-grid systems.

4.3 Charging Systems

4.4 Charging Levels

Yilmaz and Krein reviewed charger topologies, power levels and infrastructure, classifying charging into AC Level 1 and Level 2, using the vehicle's onboard charger, and DC fast charging, in which an off-board charger supplies DC directly to the battery [9]. Table I summarises these levels.

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Level	Supply	Typical Power	Converter Location
AC Level 1	Single-phase outlet	Up to about 2 kW	Onboard charger
AC Level 2	Single- or three-phase	About 3–22 kW	Onboard charger
DC fast	Three-phase grid	About 50–350 kW	Off-board charger

TABLE I TYPICAL EV CHARGING LEVELS

4.5 Onboard Charger

An onboard charger (OBC) typically has two stages: an AC–DC power factor correction (PFC) stage that draws sinusoidal current from the grid, and an isolated DC–DC stage that regulates the charging current and voltage while providing galvanic isolation [9]. Haghbin *et al.* reviewed integrated chargers, which reuse the traction inverter and motor windings for charging to reduce cost, weight and volume [10].

4.6 Dc Fast And Extreme Fast Charging

Fast chargers convert three-phase AC to a controlled DC output at high power. Tu *et al.* reviewed extreme fast charging technologies, including medium-voltage connection with solid-state transformers, modular converter designs, and the battery and thermal limitations that constrain charging rates [11].

4.7 Vehicle-To-Grid

With bidirectional chargers, parked EVs can return energy to the grid. Kempton and Tomić analysed how vehicle-to-grid (V2G) power could stabilise the grid and support large-scale renewable energy [12].

V. BATTERY MANAGEMENT SYSTEM

The BMS monitors cell voltages, currents and temperatures, estimates state of charge (SOC) and state of health, balances cells and protects the pack from over-voltage, under-voltage, over-current and over-temperature [13]. Accurate SOC estimation is difficult because the relationship between measured quantities and SOC is non-linear and changes with temperature and ageing. Hannan *et al.* reviewed SOC estimation methods, including Coulomb counting, model-based Kalman filters and data-driven methods, and their challenges [14]. Cell balancing may be passive, dissipating excess charge in resistors, or active, transferring charge between cells with small converters.

I. VII. WIDE-BANDGAP DEVICES AND SYSTEM CONCERNS

A. *A. Silicon Carbide and Gallium Nitride*

Wide-bandgap (WBG) semiconductors have a larger energy gap and higher critical electric field than silicon. Early analysis by Shenai, Scott and Baliga identified such materials as superior for high-power electronics [15]. Millán *et al.* surveyed WBG power devices and showed that SiC and GaN allow lower conduction and switching losses, higher operating temperature and higher switching frequency [16]. SiC MOSFETs are now used in traction inverters, particularly for 800 V systems, while GaN devices suit onboard chargers and DC–DC converters at lower voltages and very high frequencies. Higher switching frequency reduces the size of magnetic components and capacitors, increasing power density.

5.1 Thermal Management

Converter losses appear as heat in semiconductors and magnetics. Liquid-cooled cold plates, double-sided cooling of power modules and integration with the vehicle's battery and motor cooling loops are used to keep junction temperatures within limits, which directly affects reliability [4].

5.2 Electromagnetic Compatibility And Safety

Fast switching produces high rates of change of voltage and current, which cause electromagnetic interference and stress motor insulation. Careful layout, filters and shielding are required. High-voltage systems also need insulation monitoring, contactors and interlocks for functional safety.

VI. ARCHITECTURE AND COMPARATIVE ANALYSIS

Fig. 2 presents the power-flow architecture of a battery electric vehicle, showing the main converters and the direction of energy flow.

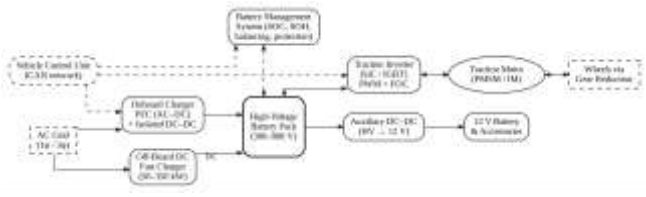


Fig. 2. Power electronic architecture of a battery electric vehicle showing charging, traction, auxiliary and control paths.

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AC energy from the grid enters through the onboard charger, or DC energy is delivered directly by an off-board fast charger. The high-voltage battery, supervised by the BMS, supplies the traction inverter, which drives the motor under FOC; during braking the flow reverses. The auxiliary DC–DC converter supplies the 12 V system. A vehicle control unit coordinates these subsystems over the vehicle network.

Table Ii Summary Of Representative Studies On Ev Power Electronics

Ref.	Subsystem	Contribution	Key Insight	Limitation
[3]	Powertrain	Power electronics and drives for EV and HEV	Converters define performance and cost	Pre-WBG era
[9]	Charging	Charger topologies, power levels, infrastructure	Standard classification of charging	Fast-evolving power levels
[10]	Integrated charger	Reuse of traction drive for charging	Lower cost and weight	Control complexity, isolation
[11]	Fast charging	Extreme fast charging overview	Grid and battery limits of fast charging	Infrastructure cost
[16]	Devices	Survey of SiC and GaN power devices	Lower losses, higher frequency	Device cost and reliability data
[14]	BMS	Review of SOC estimation methods	Model and data-driven trade-offs	Accuracy under ageing
[12]	V2G	Vehicle-to-grid power implementation	EVs as grid resources	Battery degradation concerns

Table Iii Comparison Of Si, Sic And Gan Power Devices For Ev Converters

Property	Silicon (IGBT / MOSFET)	Silicon Carbide (SiC)	Gallium Nitride (GaN)
Bandgap	About 1.1 eV	About 3.3 eV	About 3.4 eV
Typical voltage class	Up to 1700 V (IGBT)	650–1700 V	Up to about 650 V
Switching frequency	Low to medium	Medium to high	Very high
Operating temperature	Moderate	High	Moderate to high
Typical EV use	Traction inverter (legacy)	800 V traction inverter, fast charger	Onboard charger, DC–DC
Main limitation	Switching losses	Cost, gate-oxide reliability	Voltage rating, packaging

VII. CHALLENGES AND FUTURE DIRECTIONS

The industry is moving to 800 V battery architectures that halve current for the same power, reducing cable losses and enabling faster charging, but requiring higher-voltage devices and insulation [11]. Extreme fast charging is limited by battery heating and lithium plating as well as by grid connection costs. Integrated and multifunctional converters that combine charging, traction and auxiliary functions can reduce cost but complicate control [10]. Reliability of SiC devices over the vehicle lifetime, especially gate-oxide stability and short-circuit robustness, requires further study [16]. Battery state estimation must improve to make full use of pack capacity safely [14]. Bidirectional charging for vehicle-to-home and vehicle-to-grid services requires standards, communication and business models [12]. Wireless charging and in-motion charging are further directions.

VIII. CONCLUSION

Power electronics is the enabling technology of the electric vehicle. The traction inverter, controlled by PWM and field-oriented control, converts battery energy into precise motor torque and recovers energy in braking. DC–DC converters supply accessories and adapt voltage levels, onboard and off-board chargers deliver energy from the grid, and the battery management system keeps the pack safe and efficient. Wide-bandgap SiC and GaN devices are raising efficiency and

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power density. The architecture and comparisons presented here show how these subsystems work together, and the challenges identified point to continued advances in high-voltage systems, fast charging, integration and grid interaction.

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