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Power electronics and energy management in modern vehicles: a review of electric propulsion, battery systems, and charging technologies

Anggit Pamungkas, Hendril Satrian Purnama
Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

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ABSTRACT

The development of electric vehicles (EVs) is transforming automotive engineering by increasing the importance of efficient electric propulsion, energy storage, and charging technologies. Power electronics provide the essential interface between batteries, traction motors, auxiliary electrical systems, and external charging infrastructure. This review examines the principal technologies supporting modern vehicle electrification, with emphasis on electric motors, traction inverters, DC–DC converters, battery systems, regenerative braking, and charging technologies. It discusses the advantages and limitations of different motor and converter configurations, battery management approaches, and energy recovery strategies. Conductive, wireless, fast, and bidirectional charging are also evaluated in relation to vehicle requirements and grid integration. The review identifies system efficiency, thermal management, battery lifetime, power quality, and charging interoperability as interconnected engineering challenges. The analysis indicates that improvements in individual components must be coordinated through integrated energy management to achieve meaningful vehicle-level performance gains. Future development should prioritize high-efficiency semiconductor devices, intelligent battery management, bidirectional power conversion, and charging infrastructure capable of supporting reliable and sustainable electric mobility.

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1. INTRODUCTION

The transition from internal combustion engine vehicles to electric and hybrid vehicles is changing the architecture of modern transportation systems. Electric propulsion can improve energy conversion efficiency, reduce local exhaust emissions, and enable the integration of renewable electricity into transportation. However, the performance of an electric vehicle (EV) depends on the coordinated operation of its motor, power converters, battery, control system, and charging infrastructure. Consequently, vehicle electrification represents an integrated electrical engineering challenge rather than simply replacing a combustion engine with an electric motor [1], [2].

Power electronics are central to this transition because they regulate electrical energy between components operating at different voltage, current, and frequency levels. Traction inverters supply controlled AC power to electric motors, while DC–DC converters regulate voltage between the battery and auxiliary or intermediate electrical buses. Battery management systems monitor storage conditions, and regenerative braking recovers part of the vehicle's kinetic energy during deceleration. Charging technologies complete this architecture by enabling energy transfer from external electrical networks to the vehicle [3], [4].

Although substantial progress has been achieved in individual EV technologies, several system-level challenges remain. Conversion losses, battery ageing, thermal limitations, charging time, and grid impacts can interact and influence the vehicle's overall efficiency and reliability. Research therefore needs to evaluate the relationships between propulsion, storage, energy recovery, and charging rather than treating them as

independent subsystems. This review synthesizes developments available up to 2021 and identifies the principal technical considerations for integrated vehicle energy management.

2. ELECTRIC PROPULSION AND TRACTION MOTOR TECHNOLOGIES

Electric propulsion converts electrical energy from the battery into mechanical power at the wheels. The traction motor must provide sufficient starting torque, acceleration capability, operating-speed range, and efficiency under varying driving conditions. Common motor technologies include brushed DC motors, induction motors, permanent magnet synchronous motors (PMSMs), and switched reluctance motors. Each technology presents different trade-offs involving efficiency, power density, cost, control complexity, and material requirements [1], [5].

PMSMs are attractive for modern EVs because they offer high torque density, good efficiency, and effective speed control. Their permanent magnets reduce rotor excitation losses, although dependence on rare-earth materials and the effects of temperature on magnetic properties remain relevant concerns. Induction motors provide a robust alternative without permanent magnets, but rotor losses can reduce efficiency under certain operating conditions. Switched reluctance motors offer a comparatively simple rotor construction, although torque ripple and acoustic noise require careful control and mechanical design [1], [5].

The selection of a traction motor should consider the complete drive system rather than motor efficiency alone. Motor characteristics influence inverter voltage and current ratings, cooling requirements, transmission design, and regenerative braking capability. The operating speed range is also important because vehicles experience frequent acceleration, deceleration, and changes in road gradient. An integrated motor and power-electronics design can therefore improve packaging, reduce conversion losses, and support more effective vehicle-level energy management [2], [6].

3. POWER ELECTRONIC CONVERTERS

3.1. Traction inverters

A traction inverter converts the battery's DC output into controlled AC power for the propulsion motor. Its switching devices regulate the motor's voltage, current, frequency, and torque response according to the vehicle controller's commands. Conventional two-level voltage-source inverters are widely used because of their relatively simple structure and established control methods. Multilevel inverter configurations provide alternative solutions for applications requiring improved voltage quality, reduced device voltage stress, or higher power capability [3], [4], [7].

Semiconductor technology strongly influences inverter efficiency and power density. Silicon insulated-gate bipolar transistors (IGBTs) have been widely adopted in automotive power converters, while silicon carbide (SiC) devices offer lower switching losses and the potential for higher switching frequencies and operating temperatures. These characteristics can reduce cooling requirements and improve power-conversion efficiency, although device cost, electromagnetic interference, and packaging remain important design considerations. The transition toward higher-voltage vehicle architectures also increases the importance of insulation coordination, switching transients, and converter reliability [1], [7], [8].

3.2. DC–DC converters

DC–DC converters regulate voltage between the high-voltage traction battery and other electrical subsystems. A typical EV may require a high-voltage bus for propulsion and a lower-voltage supply for lighting, controllers, communication equipment, and other auxiliary loads. Non-isolated converters can provide efficient voltage regulation where galvanic isolation is not required, whereas isolated topologies offer electrical separation and additional safety benefits. Bidirectional converters are particularly important when energy must flow in both directions, including hybrid energy storage and vehicle-to-grid applications [3], [9]. Converter selection involves balancing efficiency, power density, voltage gain, component count, thermal performance, and electromagnetic compatibility. Interleaved and multi-phase structures can reduce current ripple and distribute thermal stress across switching devices. Isolated topologies, including dual-active-bridge converters, can support bidirectional power transfer while providing galvanic isolation. Nevertheless, the additional components and control requirements may increase cost and implementation complexity [9].

4. BATTERY SYSTEMS AND ENERGY MANAGEMENT

4.1. Battery technologies

The battery is a major determinant of EV driving range, acceleration capability, vehicle mass, and cost. Lithium-ion batteries have become widely used because of their favorable energy density, power

capability, and cycle performance compared with many earlier rechargeable technologies. However, battery performance depends on chemistry, temperature, charging rate, discharge current, and ageing conditions. Battery selection must therefore consider not only energy capacity but also safety, durability, cost, and the intended vehicle operating profile [10], [11].

Battery management systems (BMSs) are essential for maintaining safe and reliable battery operation. Their functions commonly include cell-voltage monitoring, current measurement, temperature monitoring, state-of-charge estimation, state-of-health assessment, and cell balancing. The BMS can also limit charging or discharging when operating conditions approach predefined safety boundaries. Accurate monitoring and estimation help protect cells, improve usable battery capacity, and support more reliable vehicle energy management [10], [12].

Thermal management is closely related to battery performance and safety. Excessive temperature can accelerate degradation and increase the risk of thermal runaway, while low temperatures can reduce available power and charging capability. Air cooling, liquid cooling, phase-change materials, and hybrid thermal management approaches have been investigated for automotive battery packs. Each approach involves trade-offs involving heat-transfer capability, system complexity, mass, cost, and auxiliary energy consumption [13], [14].

4.2. Integrated energy management

Vehicle energy management coordinates propulsion demand, battery operation, auxiliary loads, and energy recovery. Its purpose is to distribute available electrical energy while maintaining acceptable vehicle performance, battery safety, and operating efficiency. In hybrid vehicles, energy management additionally determines how power is shared between the electric motor and other energy sources. The effectiveness of an energy management strategy depends on vehicle architecture, driving conditions, component efficiency maps, and the accuracy of the information available to the controller [2], [6].

Table 1 summarizes the principal powertrain and energy-management components discussed in this review. The comparison highlights that each subsystem has a distinct function but also affects the performance of other components. For example, inverter losses increase thermal demand, while battery temperature and state of charge influence the amount of power available for propulsion and regenerative braking. This interdependence supports the need for coordinated system-level design.

Table 1. Main electrical subsystems and their roles in modern EVs

Subsystem	Main function	Key performance consideration	Main engineering challenge
Traction motor	Converts electrical energy into mechanical power	Efficiency, torque density, speed range	Thermal loading and material cost
Traction inverter	Converts DC battery power into controlled AC	Conversion efficiency and power density	Switching losses and thermal management
DC–DC converter	Regulates voltage between electrical buses	Voltage gain and bidirectional capability	Efficiency, isolation, and component stress
Battery pack	Stores electrical energy	Energy density, power capability, and lifetime	Ageing and thermal safety
BMS	Monitors and protects battery operation	Estimation accuracy and cell balancing	Reliable sensing and protection
Regenerative braking	Recovers kinetic energy during deceleration	Energy recovery and braking stability	Coordination with mechanical brakes
Charging system	Transfers energy from the grid to the vehicle	Charging power and interoperability	Charging time and grid impact

5. REGENERATIVE BRAKING AND ENERGY RECOVERY

Regenerative braking converts part of the vehicle's kinetic energy into electrical energy during deceleration. In this operating mode, the traction motor acts as a generator and transfers recovered energy through the inverter toward the battery or another energy storage system. The amount of recoverable energy depends on vehicle speed, braking demand, motor capability, battery acceptance limits, and drivetrain efficiency. Regenerative braking can therefore reduce energy consumption, particularly in driving conditions involving frequent acceleration and deceleration [15].

Effective regenerative braking requires coordination between electrical and mechanical braking systems. The electrical system cannot always provide the full braking torque because battery state of charge, temperature, motor speed, and inverter current limits may restrict energy recovery. Mechanical friction brakes must therefore remain available to provide the required braking force under all operating conditions. Blended braking strategies distribute braking demand between regenerative and mechanical systems while maintaining vehicle stability and driver expectations [15], [16].

Energy recovery can be further improved through appropriate control and energy storage management. Supercapacitors and hybrid battery–supercapacitor configurations can absorb high-power transient energy while reducing peak current stress on the battery. However, additional storage components increase system mass, cost, and converter complexity. The choice between direct battery recovery and hybrid storage should consequently be based on driving-cycle characteristics and the expected benefits at vehicle level [2], [15].

6. ELECTRIC VEHICLE CHARGING TECHNOLOGIES

6.1. Conductive and fast charging

Conductive charging remains the most established method of transferring electrical energy to EV batteries. It can be implemented through onboard chargers, which convert grid AC power into regulated battery DC power, or off-board chargers, which provide controlled DC power directly to the vehicle. Charging power depends on charger ratings, battery voltage, thermal conditions, communication protocols, and the limits imposed by the battery management system. Higher charging power can reduce charging time, but it also increases demands on battery thermal management, electrical protection, and grid infrastructure [17], [18].

Fast-charging systems require careful coordination between the charging station and the vehicle. High-power charging can increase cable current, converter thermal stress, and distribution-network loading, particularly when multiple vehicles charge simultaneously. Higher-voltage vehicle architectures can reduce current for a given power level, potentially improving cable and converter design. However, these architectures require compatible batteries, insulation systems, power electronics, and charging infrastructure [8], [19].

6.2. Wireless and bidirectional charging

Wireless power transfer (WPT) provides an alternative to conventional conductive charging by transferring energy through magnetic coupling between ground-side and vehicle-side components. Inductive systems can support stationary charging and, in selected designs, dynamic charging while the vehicle is moving. Their potential advantages include reduced physical connector handling and greater charging convenience. However, coil alignment, air-gap variation, electromagnetic compatibility, system cost, and conversion efficiency remain important implementation challenges [20].

Bidirectional charging allows electrical energy to flow from the grid to the vehicle and, under suitable conditions, from the vehicle back to the grid. Vehicle-to-grid (V2G) operation can support grid services, load management, and renewable-energy integration, while vehicle-to-home applications can provide backup or flexible household energy supply. Bidirectional onboard chargers require appropriate converter topologies, control systems, protection, and communication with the grid. Battery degradation and the economic value of exported energy must also be considered when determining whether bidirectional operation is beneficial [17], [21].

Charging infrastructure is not solely a vehicle-side engineering issue. Charging stations must satisfy electrical safety, power-quality, interoperability, and installation requirements, while their location and capacity influence accessibility and grid loading. High-power charging can introduce additional demand peaks and power-quality concerns if infrastructure is not properly designed and managed. Smart charging and coordinated infrastructure planning can help align charging demand with network capacity and available electricity supply [18], [22], [23].

7. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

The main challenge in modern vehicle electrification is achieving efficient interaction among propulsion, conversion, storage, braking, and charging subsystems. Improving one component does not necessarily improve total vehicle efficiency if the change introduces additional losses or thermal demands elsewhere. For example, increasing inverter switching frequency may improve current control but also increase switching losses and electromagnetic interference. Similarly, faster charging can improve convenience while accelerating battery degradation if temperature and charging limits are not properly managed.

Future development should emphasize integrated powertrain design and intelligent energy management. Wide-bandgap semiconductor devices, higher-voltage architectures, advanced battery monitoring, and bidirectional power converters offer opportunities to improve efficiency and power density. Further research is also needed to establish consistent evaluation methods that compare energy consumption, conversion efficiency, thermal performance, battery ageing, and charging behavior under realistic driving conditions. These developments should be supported by safety assessment and grid-level analysis rather than relying exclusively on component-level performance.

8. CONCLUSION

Power electronics and energy management are fundamental to the performance of modern electric and hybrid vehicles. Traction motors provide propulsion, inverters regulate motor power, DC–DC converters manage voltage levels, and battery systems store and supply electrical energy. Regenerative braking can recover part of the vehicle's kinetic energy, while conductive, wireless, and bidirectional charging technologies provide different approaches to energy replenishment and grid interaction. The effectiveness of these technologies depends on their coordinated operation across the complete vehicle electrical architecture. The review identifies efficiency, battery lifetime, thermal safety, converter reliability, and charging infrastructure as interconnected priorities. Future EV development should therefore move beyond isolated component optimization toward integrated powertrain and energy-management strategies. Advances in semiconductor devices, battery management, regenerative braking control, and bidirectional charging can contribute to more efficient and reliable vehicles. Their practical value, however, must be demonstrated through system-level testing under realistic driving, charging, and grid conditions.

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