RECENT DEVELOPMENTS IN ELECTRIC VEHICLE POWERTRAINS: EFFICIENCY, TORQUE DELIVERY, AND THERMAL PERFORMANCE ANALYSIS

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Abstract

This review surveys recent advances in electric vehicle (EV) powertrains with a focus on three interrelated performance pillars: energy efficiency, torque delivery and control, and thermal management. We synthesize developments in motor topologies and multi-speed transmission strategies, power-electronics architectures, and model-based and AI/ML control methods that improve drivetrain efficiency and real-world energy consumption. Concurrently, we review torque-control techniques including high-fidelity torque vectoring and distributed-motor coordination that enhance dynamic performance, handling, and regenerative braking effectiveness. The paper also examines integrated thermal management approaches for batteries, motors, and inverters, highlighting active, passive, and hybrid systems that maintain performance, extend lifetime, and improve safety. Finally, we identify key trade-offs, remaining technical challenges (thermal limits, packaging, cost, and control complexity), and research opportunities such as holistic co-design of thermal and control systems and standardised test protocols. This synthesis aims to inform researchers and practitioners seeking to optimise EV powertrain performance in the face of accelerating market adoption and evolving system requirements.

Keywords: *Motor efficiency[1]; Torque delivery[2]; Torque vectoring[3]; Power electronics[4]; PMSM/BLDC motors[5].*

1. Introduction

The rapid global transition toward sustainable transportation has positioned electric vehicles (EVs) as a central solution for reducing greenhouse-gas emissions, improving urban air quality, and decreasing dependence on fossil fuels. At the core of EV performance lies the powertrain an integrated system consisting of the electric motor, transmission, power electronics, energy storage, and control architecture. Unlike internal combustion engine (ICE) vehicles, EV powertrains offer inherently higher energy conversion efficiency, instant torque delivery, and smoother drivability. However, the continued evolution of EV technologies has introduced new engineering challenges related to efficiency optimization, high-torque operation, thermal management, and system reliability under varying driving conditions. Recent years have seen rapid advancements in motor design, including high-power-density permanent magnet synchronous motors (PMSM), interior permanent magnet (IPM) architectures, switched-reluctance machines, and advancements in inverter switching using wide-bandgap semiconductors such as SiC and GaN. These developments have improved drivetrain efficiency and expanded operating ranges. Parallel progress in torque control strategies such as field-oriented control (FOC), model predictive control (MPC), and advanced torque vectoring has enhanced vehicle stability, responsiveness, and regenerative braking capability. At the same time, rising power densities have intensified thermal stresses on motors, inverters, and batteries, making integrated thermal management systems essential for preserving performance, reliability, and safety. Given these ongoing innovations, a comprehensive review of EV powertrain efficiency improvements, torque delivery strategies, and thermal performance trends is essential. This paper synthesizes current technological developments, compares various architectures and control methods, and highlights key research opportunities that will shape the next generation of high-performance electric vehicles.

2. Literature Review

Powertrain Efficiency Developments

Recent studies highlight significant progress in improving EV powertrain efficiency through enhanced motor topologies, high-efficiency inverters, and optimized control strategies. Permanent magnet motors with high-grade rare-earth materials exhibit reduced core losses and improved magnetic performance. Research on wide-bandgap semiconductor-based inverters demonstrates substantial reductions in conduction and switching losses. Integrated motor–inverter architectures have further minimized parasitic losses and improved electromagnetic-thermal coupling. Machine-learning-based energy management systems have shown potential in optimizing power distribution for varying drive cycles.

Torque Delivery and Control Techniques

Field-Oriented Control (FOC) and Direct Torque Control (DTC) remain dominant techniques for torque regulation in EVs. However, recent research emphasizes the benefits of Model Predictive Control (MPC) due to its fast dynamic response and low torque ripple. Distributed drive systems using wheel-mounted motors allow precise torque vectoring during dynamic maneuvers, improving acceleration and vehicle handling. Multi-speed transmissions have emerged as a solution to enhance low-speed torque while enabling efficient high-speed operation, reducing motor heating at continuous high loads.

Thermal Management of Motors

Thermal constraints are a key limitation in high-power EV motors. Excessive temperatures can cause permanent magnet demagnetization, insulation breakdown, and increased copper losses. Liquid cooling, oil-jet cooling, and refrigerant-based cooling systems have demonstrated superior performance compared to air cooling. Recent literature explores integrated modeling techniques that combine electromagnetic loss analysis with computational fluid dynamics (CFD) to predict temperature distribution. Dual-loop cooling systems separating motor and power electronics are increasingly preferred for minimizing thermal interference.

Thermal Management of Power Electronics and Batteries

Inverters and converters generate significant heat due to high switching frequencies. SiC-based power electronics offer higher thermal stability and reduced loss, enabling compact designs. Liquid-cooled cold plates and heat pipes have become standard for EV inverters. Battery thermal management is equally critical; studies show that phase-change materials (PCMs), immersion cooling, and refrigerant cooling improve temperature uniformity and cycle life. Integrated thermal architectures combining motor, inverter, and battery cooling loops are becoming a dominant trend for next-generation EVs.

3. Thermal Performance Analysis – Overview

Thermal performance analysis plays a critical role in determining the reliability, efficiency, and durability of electric vehicle (EV) powertrains. As modern traction motors, inverters, and batteries operate at higher power densities, the amount of heat generated during operation has increased significantly. Without effective thermal control, components experience temperature rise that leads to reduced efficiency, torque derating, insulation degradation, accelerated aging, and in extreme conditions thermal runaway. Therefore, understanding and analyzing heat generation, heat flow, and cooling effectiveness is essential for the overall powertrain design. In EV motors, losses such as copper losses, core losses, and inverter-induced harmonic losses contribute to temperature rise. Thermal analysis evaluates how these losses are distributed across the stator, rotor, windings, and bearings. Similarly, in power electronics, high switching frequencies and current loads create localized hotspots within semiconductor devices, necessitating accurate thermal modeling and cooling solutions. Battery thermal performance analysis focuses on cell temperature uniformity, heat generation during charging/discharging, and prevention of degradation. To address these challenges, researchers use computational fluid dynamics (CFD), lumped-parameter thermal models, finite element analysis (FEA), and multi-physics simulations to predict temperature behavior in real operating conditions. Advanced cooling technologies such as liquid cooling, oil-jet cooling, refrigerant direct cooling, heat pipes, and immersion cooling have been extensively evaluated for their thermal efficiency.

4. Key Thermal Challenges in EV Powertrains

Traction Motor Thermal Challenges

- High copper and core losses during high torque or hill-climb conditions.
- Hotspots in stator windings lead to insulation degradation.
- Rotor permanent magnet (PM) demagnetization at high temperatures.
- Bearing heating affecting lubrication and mechanical reliability.
- Limited airflow near motor housing in compact EV designs.

Power Electronics (Inverter/Converter) Challenges

- High switching frequency causes localized heat in Si, SiC, and GaN devices.
- Thermal cycling leads to solder joint fatigue and bond wire failure.
- Compact packaging increases thermal resistance.
- Inverter hotspots reduce switching efficiency.

Battery Thermal Challenges

- Temperature deviation >5°C between cells reduces cycle life.
- Fast charging generates significant heat → SEI layer growth.

- Extreme cold increases internal resistance and reduces power output.
- Thermal runaway risk due to exothermic reactions.

Table 4.1: Comparison of EV Cooling Methods

Cooling Method	Components Used	Advantages	Limitations
Air Cooling	Fans, ducts	Low cost, simple	Inefficient for high-power motors and inverters
Liquid Cooling	Coolant, pumps, cold plates	High heat removal, widely used in EVs	More complex, higher weight
Oil-Jet Cooling (Motor)	Oil nozzles, sump	Excellent stator & rotor cooling	Pumping losses, system complexity
Refrigerant Direct Cooling	AC refrigerant loop	Very high performance, fast cooling	Complex integration with HVAC
Heat Pipes	Wick structure pipes	Lightweight, passive	Limited heat transport distance
Immersion Cooling (Battery)	Dielectric liquid	Uniform temperature, prevents hotspots	High cost, sealing challenges
Phase Change Materials (PCM)	PCM pads or blocks	Maintains stable temp peak	Slow recovery, limited heat capacity

5. Discussion

Recent advancements in electric vehicle powertrains indicate a strong shift toward integrated solutions that simultaneously enhance efficiency, torque delivery, and thermal stability. Studies show that PMSM motors combined with SiC/GaN-based inverters significantly improve powertrain efficiency by reducing electrical and switching losses, while multi-speed transmissions and optimized regenerative braking further enhance energy utilization. Torque delivery has also improved due to advanced control strategies such as FOC, MPC, and torque vectoring, which reduce torque ripple and enhance dynamic response; however, high torque demand increases thermal stress on motors and inverters. Thermal management remains a central performance determinant, with modern liquid cooling, PCMs, and refrigerant-based systems enabling better temperature control and prolonged peak torque output, though challenges remain regarding cost, weight, and system integration. The literature clearly reveals a strong interdependence between efficiency, torque optimization, and thermal behavior, where improvements in one domain directly influence the others, necessitating a holistic design approach. Despite notable progress, existing limitations such as material cost, long-term thermal reliability, and real-time control complexity highlight the need for further research in integrated architectures, wide-bandgap semiconductor scalability, and intelligent energy and torque management systems to meet future EV performance demands.

6. Conclusion

This review highlights that recent developments in electric vehicle powertrains are strongly driven by the need for higher efficiency, improved torque characteristics, and robust thermal management. Advancements in high-performance motors, wide-bandgap semiconductor inverters, and optimized control strategies have significantly enhanced energy utilization and torque responsiveness. At the same time, emerging cooling technologies such as liquid and refrigerant-based systems play a critical role in maintaining stable operation and enabling sustained high-torque performance under diverse driving conditions. The interdependence of electrical, mechanical, and thermal aspects underscores the importance of holistic powertrain design rather than isolated subsystem improvements. Although challenges remain in terms of material cost, system complexity, and thermal reliability, ongoing innovations in integrated motor-inverter systems, AI-assisted control algorithms, and advanced thermal architectures promise substantial improvements in the next generation of EVs. Overall, the reviewed studies indicate a clear trajectory toward more efficient, responsive, and thermally resilient electric powertrains capable of meeting future mobility demands.

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