

A COMPREHENSIVE REVIEW OF TORQUE VECTORING CONTROL STRATEGIES FOR DISTRIBUTED DRIVE ELECTRIC VEHICLES

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ABSTRACT

With the evolution of electric vehicle (EV) technology, advanced control strategies like torque vectoring have become critical for enhancing stability, handling, and energy efficiency. Unlike conventional internal combustion engine vehicles, EVs with distributed drive architectures enable individual wheel control, paving the way for sophisticated dynamic control techniques. This paper presents a comprehensive review of 19 recent studies focused on torque vectoring strategies in EVs. The methods are categorized based on control theory (e.g., model predictive control, H_∞ control), vehicle architecture (e.g., in-wheel, front/rear drive), and implementation objectives (e.g., yaw control, energy efficiency, fault tolerance). We analyze the strengths, limitations, and future potential of each approach and propose directions for further research.

KEYWORDS:- Electric Vehicles (EVs), Torque Vectoring (TV), Vehicle Dynamics, In-Wheel Motors, Direct Torque Control (DTC), Model Predictive Control (MPC), Robust Control, Yaw Moment Control.

I. INTRODUCTION

Electric vehicles (EVs) are redefining modern transportation by offering sustainable mobility, high efficiency, and flexible drivetrain architectures. One of the key advantages of EVs, especially those with multiple motors or in-wheel drives, is the ability to independently

control the torque delivered to each wheel. This enables torque vectoring, a technique used to manipulate the yaw moment and lateral forces of the vehicle to improve cornering stability, acceleration, and driver comfort. Unlike traditional vehicles that rely on braking-based stability controls, EVs can achieve torque vectoring through electronic motor control, enabling smoother and more efficient operation. Various control strategies have been developed to achieve this, ranging from classical PID-based yaw control to advanced Model Predictive Control (MPC), Direct Torque Control (DTC), H_∞ control, and AI-based systems. This review examines 19 recent papers that address torque vectoring from multiple dimensions, including high-performance driving, real-time adaptability, energy efficiency, and actuator constraints. Each approach is evaluated for its objectives, methodology, experimental setup, and potential for real-world implementation.

II. Literature Survey

In recent years, torque vectoring has gained significant traction as a control strategy for electric vehicles (EVs) owing to its potential to improve handling, safety, and efficiency. Knauder et al. [1] introduced one of the first integrated torque vectoring platforms—E-Vectoorc—which incorporated yaw control, wheel slip regulation, and energy coordination in a four-motor electric Range Rover Evoque. This project emphasized the importance of independent torque control for each wheel in achieving superior vehicle dynamics. Building on this, Mangia et al. [2] presented a control framework allowing drivers to choose between multiple driving modes such as "energy-efficient" or "high-performance", demonstrating how torque vectoring can be tailored to diverse objectives. Their architecture bridged the gap between handling requirements and battery conservation.

A more theoretical perspective was explored by Asperti et al. [3], who reviewed and compared classical, robust, and predictive torque vectoring strategies. They highlighted the trade-offs between simplicity, computational demands, and robustness to uncertainties like tire-road interactions and sensor noise. Meanwhile, Kobayashi et al. [4] applied torque vectoring in motorsport, integrating braking and drive torque strategies for yaw control on racing circuits. Their results confirmed substantial benefits in cornering performance, although the approach required high-fidelity tire models.

In terms of control techniques, Chantoufi et al. [6] proposed a hybrid approach combining Direct Torque Control (DTC) with backstepping nonlinear control for doubly-fed induction machines (DFIM). This method achieved low-ripple torque and high-speed stability, which are essential in practical EV applications. Ryu et al. [7] focused on robustness, introducing a

dual-loop structure comprising a Model Predictive Control (MPC) based outer loop and a disturbance observer inner loop for in-wheel motor vehicles. Their structure maintained desired cornering stiffness while compensating for model uncertainties.

Simplified control was achieved by Zhang et al. [8], who removed the weighting factor from traditional MPC, reducing its computational complexity without sacrificing precision in dual three-phase PMSM control. Kang et al. [9] further contributed to MPC-based designs by proposing a Fast Iterative MPC (FI-MPC) framework for distributed drive EVs, balancing accuracy and solving time using rule-based iteration criteria. Lu et al. [10] adopted H_∞ loop-shaping to improve control robustness in the presence of drivetrain and tire parameter variations, demonstrating superior performance over conventional PI controllers in experimental settings.

Beyond these, several studies focused on DTC improvements. For instance, BLDC motor control using dual inverter-fed open-end windings by [14] showed reduced torque ripple and EMI through improved switching schemes. Deadbeat Flux Vector Control (DBFC), introduced in [15], enabled seamless torque-speed transitions without abrupt switching, enhancing drivability under high dynamic loads.

Practical implementations also included front/rear torque vectoring using dual-motor systems. As shown in [18], such systems can adjust vehicle yaw moment during turning or acceleration by allocating torque asymmetrically between axles. Meanwhile, optimization-based control allocation approaches such as those explored in [16] found that minimizing tire slip outperformed energy-efficiency-oriented objectives in delivering improved handling dynamics. Power management was also considered in [17], where a dual inverter-fed open-end winding induction motor system simultaneously balanced battery state-of-charge (SoC) and torque requirements, enhancing energy uniformity across storage units.

Vector control methods for high-speed switched reluctance motors (SRM), as investigated in [19], showed promise in achieving robust high-speed operation (up to 20,000 RPM) with reduced vibration. Although targeted at high-performance applications, this work supports the growing trend of combining electromagnetic control with torque vectoring for optimized output. Collectively, these studies establish torque vectoring not only as a mechanism for handling enhancement but as a multi-objective strategy supporting vehicle safety, agility, and powertrain efficiency.

III. Methodological Analysis

The reviewed studies span a diverse range of control strategies, each offering distinct benefits depending on the application and hardware constraints. Model-based techniques such as Model Predictive Control (MPC) and H_∞ control [7, 9, 10] provide high accuracy, stability, and real-time adaptability, especially in scenarios with dynamic external conditions. MPC frameworks excel in managing constraints like actuator saturation and tire force limits while achieving trajectory tracking. However, their primary limitation lies in their high computational demand, which restricts their use in low-cost onboard systems without real-time optimization accelerators.

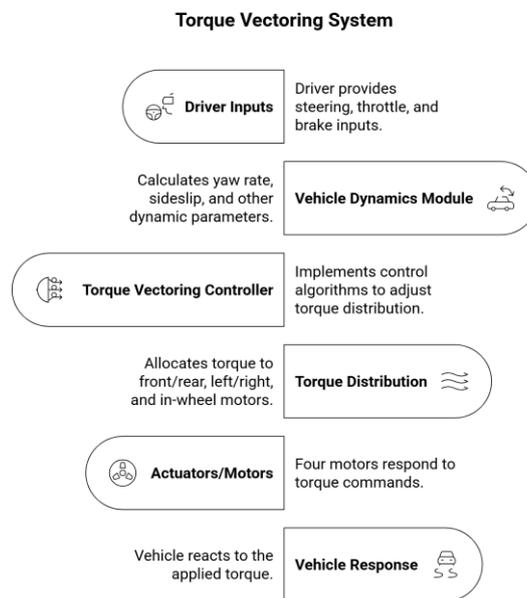


Fig. Torque Vectoring System.

The block diagram represents the complete flow of torque vectoring in an EV. It begins with driver commands, followed by vehicle state estimation, which provides yaw rate and slip angles. The control algorithm layer includes the different methods discussed in your review — MPC, DTC, robust/ H_∞ control, optimization, etc. The output is processed through torque allocation, then delivered to individual wheel motors. Finally, the vehicle response is fed back into the control loop.

Nonlinear and hybrid control methods including backstepping-DTC and disturbance observer-based schemes [6, 7] offer more robustness against model uncertainties and external disturbances. These methods are particularly useful in environments where tire-road friction and vehicle parameters vary unpredictably. In contrast, heuristic control approaches such as lookup table (LUT)-based controllers [12] and hysteresis-based DTC [13] offer a lightweight

and fast implementation with good torque response under nominal conditions, though they require fine-tuning and cannot adapt to changing dynamics without reprogramming.

Optimization-based control allocation strategies, particularly those focused on minimizing tire slip or torque demand variation [16], enable precise wheel torque distribution while maintaining vehicle stability. Their flexibility allows for multi-objective optimization—balancing energy consumption, tire usage, and comfort metrics. While powerful, these approaches depend heavily on accurate modeling of actuator limits and system constraints, making them sensitive to physical inconsistencies.

Recent work on hardware-integrated solutions such as dual-inverter configurations and vector-controlled SRMs [14, 19] indicates a promising direction for extending torque vectoring benefits to specialized motors. These configurations not only improve electromagnetic efficiency but also reduce vibrations and improve NVH (Noise, Vibration, Harshness) characteristics—critical for passenger vehicle applications.

IV. Research Gaps and Future Scope

Despite significant progress, several research gaps persist in the domain of torque vectoring control for EVs. A critical challenge lies in achieving real-time performance with predictive and optimization-based strategies. Controllers like MPC, while offering excellent precision and constraint handling, require high computation power and may not meet real-time constraints on standard embedded systems. Future work should focus on lightweight approximations or embedded solvers tailored for automotive-grade processors.

Another limitation is the lack of integration between torque vectoring and energy management. Many strategies prioritize handling or stability without considering battery health, regenerative braking, or thermal management. Merging torque vectoring with energy-aware controllers could improve both performance and range, especially in long-haul and high-speed applications.

Additionally, current studies often assume well-known road-tire interactions, but real-world driving involves variable terrain, weather, and loading conditions. Thus, there is a need for adaptive systems that can update control parameters based on real-time sensor fusion and machine learning predictions.

Finally, front/rear and left/right torque coordination in dual-motor or quad-motor EVs deserves more attention. While some papers explore individual strategies, a unified framework addressing full-vehicle torque distribution dynamically based on driving context (e.g., urban, off-road, racing) remains an open challenge. Future systems should leverage AI

and digital twins to adaptively adjust parameters based on driving history, GPS data, and vehicle condition in real time.

Table: Research Gap.

Criteria	Existing Research Papers	Proposed Unified Multi-Objective Torque Vectoring Framework
Primary Focus	Each paper focuses on ONE specific method: Classical/Robust/MPC/H ∞ /DTC/DOBC etc. Examples: MPC-based torque vectoring [7], FI-MPC [9], H ∞ loop-shaping [10], DTC/backstepping [6], Deadbeat control [15].	A unified approach combining predictive control, robust control, DTC improvements, and optimization-based torque allocation into one architecture.
Vehicle Architecture	Studies limited to specific setups: • 4-motor EV (E-Vectoorc) [1] • Selectable modes (dual-motor) [2] • In-wheel motors [7] • Dual open-end winding IM [17] • SRM high-speed control [19]	Designed to work for all EV architectures: front/rear drive, AWD, in-wheel motors, dual-inverter systems, and SRM/PMSM based EVs.
Control Strategy	Single strategy per paper: • MPC-based controllers [7], [8], [9], [20] • H ∞ control [10] • DTC-based methods [6], [13], [14] • Deadbeat control [15] • Torque distribution optimization [16]	Integrates multiple strategies: Lightweight MPC ✓ H ∞ / Robust control ✓ Low-ripple DTC ✓ Optimization-based torque allocation ✓ AI-ready framework
Objective	Focused mainly on yaw moment control and handling improvement [1], [4], [16], [18].	Addresses multiple objectives simultaneously: stability, yaw control, energy optimization, actuator protection, road-adaptive performance.
Energy Management	Very few consider energy: • Power-sharing control [17] • Energy-aware MPC [20] Most others ignore battery/SoC effects.	Integrated energy-aware torque vectoring module: battery load balancing, regenerative braking optimization, torque loss minimization.
Robustness to Uncertainties	Some papers include robustness (H ∞ [10], DOBC [7], backstepping-DTC [6]).	Combines disturbance estimation + constraint handling + adaptive gain tuning for high

Criteria	Existing Research Papers	Proposed Unified Multi-Objective Torque Vectoring Framework
		robustness across varying terrains.
Real-Time Feasibility	<ul style="list-style-type: none"> • MPC papers report heavy computation [7], [8], [9]. • DTC papers suffer from torque ripple [13], [14]. 	Uses reduced-complexity MPC, priority-based torque allocation, and low-ripple switching for real-time implementation.
Torque Allocation Layer	<ul style="list-style-type: none"> • Some include torque distribution (De Novellis et al. [16], Ruiz Diez et al. [18]). • Others ignore allocation. 	Full front/rear and left/right torque allocator with constraints on tire forces, battery current, and motor limits.
Adaptability to Road Changes	Most assume fixed road friction and ideal tire model.	Introduces adaptive parameter estimation + sensor fusion for dynamic road/tire variation.
Scalability & Modularity	Limited to individual EV platforms; not scalable across architectures.	Scalable unified design for any motor type or drive architecture.
AI / Digital Twin	None integrate ML or digital-twin prediction.	Future-ready architecture allowing AI-based torque prediction & digital twin integration.

Proposed system distinguishes itself from existing research by integrating the strengths of multiple torque vectoring strategies presented in prior works [1]–[20]. While the literature provides powerful yet isolated solutions—such as MPC-based cornering control [7], FI-MPC for faster computation [9], H_∞ -based robustness [10], improved DTC methods [6], [13], [14], and optimized wheel torque distribution [16], [18]—these are limited to single-objective or single-architecture implementations. In contrast, the proposed unified system combines predictive, robust, and energy-aware control philosophies with real-time torque allocation, making it applicable across in-wheel, dual-motor, and four-motor EV platforms. This multi-objective approach addresses key research gaps in adaptability, energy management, and computational feasibility not fully covered in previous studies.

V. CONCLUSION

Torque vectoring in EVs is a multi-disciplinary control challenge that integrates dynamics, power electronics, and software engineering. Model-based and optimization-driven controllers have proven effective in simulation and lab-scale testing, while hardware-friendly methods ensure real-time feasibility. The future of torque vectoring lies in adaptive, AI-powered, energy-aware systems that operate across diverse terrains, user preferences, and traffic conditions.

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