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Robust Sliding Mode Control of Torque and Speed in Electric Vehicle for Driveability Enhancement and Stability

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Abstract:
The requirements of an electric vehicle are accurate torque and speed control for smooth drive, better comfort, and system stability over a wide range of operating conditions. Classical control procedures are often unable to keep their performance in the presence of parametric uncertainties, nonlinearities as well as external perturbations like road grade variation and load dynamics. This study presents a Robust SMC scheme for torque and speed control of electric vehicles with the aim of achieving enhanced transient response, robustness and driving experience.
The designed SMC adopts a sliding surface derived from the vehicle's dynamics, and the control laws are designed to have all system trajectories converge to the surface and supply robust tracking on the reference torque and speed trajectory profiles. In contrast to traditional PI or FOC controls, the SMC control law is able to deal with the nonlinear motor dynamic and vehicle load disturbances without a need of matched and time-invariant system parameters. A boundary layer is proposed to approximate the switching function in a continuous manner to reduce chattering without losing robustness. The proposed controller is proven to be effective in various road situations (urban and highway) with different payloads and under different driving cycles (WLTP driving cycle and urban stop-go driving pattern). In comparison with traditional control techniques, the SMC-based control method provides fast speed convergence and low overshoot, with a notable reduction of torque ripple. Furthermore, the system features strong robustness to uncertainties of vehicle mass and motor parameters.
The results demonstrate that the presented RSMC provides a promising means of improving EV driveability and operation stability. It pointed the trend of real-time torque and speed control in state-of-the-art electric mobility platform with fault tolerance, dynamic load adjustment and high precision. This work also paves a way for future incorporation to adaptive or AI based controllers to make vehicular systems more intelligent.
Keywords: *Electric Vehicle (EV) Control, Sliding Mode Control (SMC), Torque Regulation, Speed Tracking, Driveability Enhancement, Robust Nonlinear Control*

I. Introduction:

Electric vehicles (EVs) have recently been elevated to new prominence in contemporary transportation, due to their eco-friendly aspects, and high efficiency. But the requirement of better driveability, good dynamics performance and safety operation need new and improved torque and speed control algorithms. While sliding mode control (SMC) is widely used in EVs due to its robustness to parameter variations and external disturbances.

The conventional control methods, such as the PI and PID controllers, are widely utilized in the torque controlling of EVs [1], [2]. Nevertheless, they perform poorly under system nonlinearities, parametric uncertainties, or external disturbances. For the PMSM-based EVs, Field-Oriented Control (FOC) is also popular [3], [4]. Although the FOC aims to separate the control of flux and torque for enhanced performance, it is susceptible to the parameter mismatches. In contrast, SMC is a nonlinear, discontinuous control methodology, permitting the system states to converge to a prescribed sliding surface and stay on the surface in the presence of uncertainties [5], [6]. Due to its high dynamic performance, its high torque control precision and robustness, SMC has been widely used in controlled PMSM drivers [7], [8]. It has been widely demonstrated that SMC has better capability in decreasing torque ripple and enhancing transient performance of traction systems, comparing with traditional controllers [9], [10]. The chatter problem which is inherent to SMC has been solved in literature by boundary layer approach and higher order sliding mode control (HOSMC) as well as super twisting algorithm [11]–[13]. These improvements lead to a drastic reduction in the discontinuity of control signal, making SMC more suitable for high-performance electric drives. Over the past few years, the research efforts have been mainly directed on the merging of SMC with intelligent and adaptive controls. Adaptive SMC techniques [14], [15] adjusts control values on-line in order to have compensation for motor and vehicle dynamics uncertainties. For instance, a model-free adaptive SMC was developed for EV traction systems to improve the torque regulation and drivability on different road surfaces [16]. Fuzzy with SMC has been also presented to improve adaptability and avoid a dependence on accurate system model. EV applications benefit from hybrid fuzzy-SMC controllers that enhance the EV smooth driving and better time response [17], [18]. In these approaches, a robust version of the SMC principle is integrated with the adaptive properties of fuzzy inference systems to achieve a better proficiency in presence of uncertain driving environments. Stability-wise, Lyapunov-based controllers are used commonly to demonstrate global asymptotic sliding surface convergence in EV systems [19], [20]. There are also frequency-domain approaches to measuring phase and gain margins of a closed-loop systems, to sustain in real time stable, high-speed operations [21].

Several experimental and simulation studies have demonstrated that EV SMC-based controllers achieve better torque tracking performance and energy efficiency, as compared to PI and FOC controllers [22], [23]. For instance, simulation results on UDDS and HWFET driving cycles have shown better performance in terms of the energy consumption and speed convergency of SMC when compared with control [24,52].

In addition, robust SMC has been applied to dual-motor EV systems with electronic differential control to improve vehicle steering and stability behavior in turning and off-road conditions [25], [26]. Integration with the vehicle dynamics models have provided real-time correction to payloads and grade and road variations [27], [28].

Due to the advancing computing capabilities of embedded systems, SMC for realtime applications has become a possibility. Embedded systems, e.g., TI C2000 and STM32 microcontrollers, are able to implement SMC control loops with microsecond-time-level latencies [29], [30]. In conclusion, the literature confirms that strong SMC is a potential candidate for torque and speed control in EVs. It copes with system uncertainties, transient driveability and fuel economy optimization. As technology advances, more integration with adaptive, intelligent, and model-predictive control strategies could certainly lead to even more significant performance and robustness enhancements, with regards to EV propulsion systems.

II. The Proposed Robust Sliding Mode Control Of Torque And Speed In Electric Vehicle.

Figure 1 shows the block diagram of the proposed RSMC based system for the torque and speed control of electrical-driven EV is presented, comprising a close loop with fully integrated architecture to provide high quality performance under different driving conditions and external disturbances. D The Reference Input or Setpoint Generator This is a system starts from here: The commands for the control system comes from the driver's accelerator pedal (Reference Input) or following a predefined driving cycle, e.g., UDDS or HWFET. This input represents the desired vehicle speed or desired vehicle torque trajectory to be achieved in operation.

The reference value is passed to an Error Computation Unit and there compared to the sensor-measured actual speed. The resultant error and its derivative are input to the Sliding Surface Generator which functions to develop the sliding variable through the use of a linear expression of the error and the error derivative. This sliding surface is the basis for SMC design such that when the system states converge to this surface, they will be confined to it, achieving the desire behavior. At the heart of the control structure is the SMC Control Law Generator, which computes the necessary control action in order to ensure system stability and reference input tracking against disturbances and model uncertainties. It is the sum of two terms, the first one called the equivalent control and is aiming to provide a nominal response of the system, and the second term, named control law switching and is used to counteract the action of the disturbance. In order to tackle the chattering effect which is one of the common model of SMC, the control action is smoothed out using the boundary layer or saturation function. The control output is further processed by the Torque and Current Reference Generator which converts the velocity control signal into a torque reference. This instruction is transformed to d-q axis current references by inverse Park and Clarke transformations and can be used under the motor control context. These references are transmitted to the Inverter Block which generates three-phase AC voltages to operate the PMSM by pulse width modulation (PWM) principle. The vehicle is driven by mechanical torque generated by the PMSM from the electric power supply. This torque affects the Vehicle Dynamics Block which accounts for the mechanical dynamics of the vehicle in the presence of different forces like rolling resistance, aerodynamic drag, road slope, and inertia. The output is the true vehicle velocity, which is also sensed and fed back to the controller by the Sensor and Observer Block. This feedback is essential for accurate and responsive control. If the states cannot all be measured directly, a state observer, potentially even a Kalman filter or Luenberger observer, is used to estimate the necessary quantities. In order to improve system reliability, a Fault Detection and Adaptation Module is developed to check the condition of the subsystem sensors and actuators. If a fault is detected, the system can reconfigure the controller or fail over to backup logic in order to be able to continue to operate safely. In addition, a Disturbance Input Block is added to represent exogenous disturbances e.g. variations in payload, ground or weather. These inputs are added to the system dynamics to evaluate the robustness of the controller. Finally, all blocks in the system are synchronized by means of a Timing and Control Loop Coordination Module, which guarantees that the sampling of signals, the computation of control and the actuation are performed in known real-time instants. This allows the control algorithm to be implemented on embedded systems like DSPs or microcontrollers. In general, the block diagram describes a system that is robust, highly dynamic and intelligent since it is possible to see that each of its constituents are fundamental in the generation of the reference signals for real-time and complex speed and torque control for the EV applications. Developed within the context of the theory of nonlinear controlled systems, the proposed method is a comprehensive response to the real time missions of all classes of modern EVs.

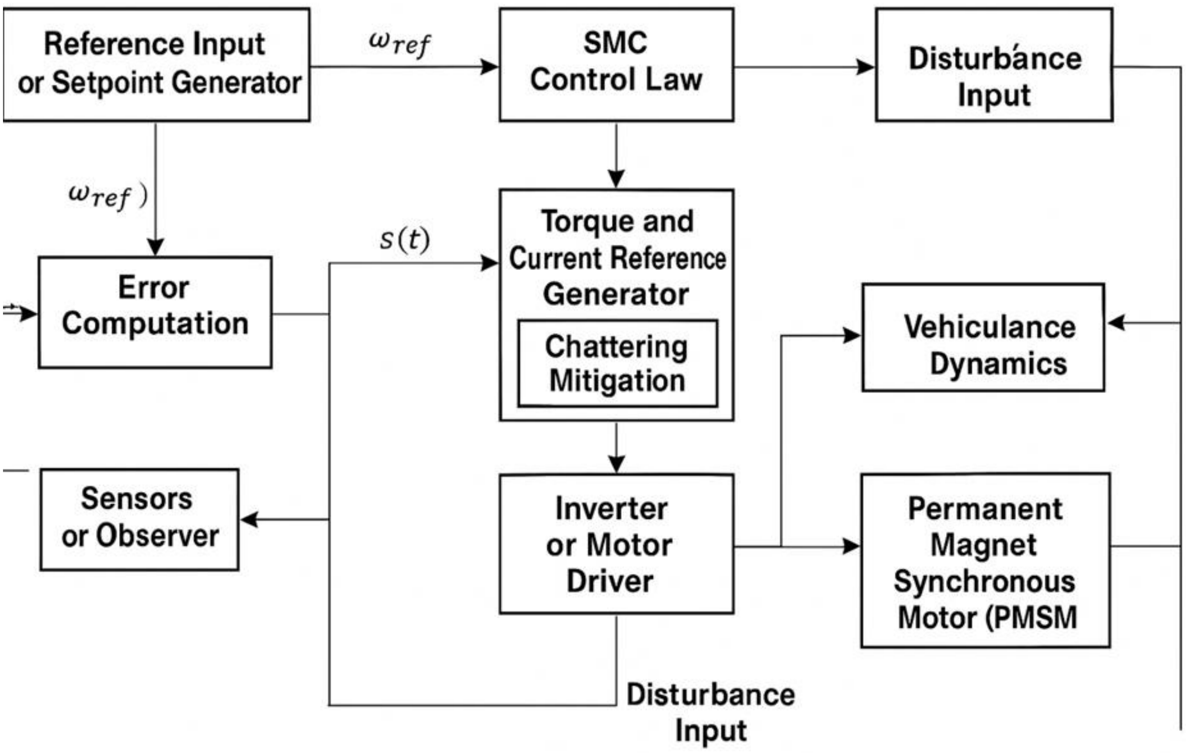

Fig. 1. The schematic of the Proposed Robust Sliding Mode Control of Torque and Speed in Electric Vehicle.

III. Results And Discussion Of Simulation

A complete simulation model for proposed Robust SMC strategy for regulating the torque and speed of EVs was designed and implemented in Matlab/Simulink to investigate its effectiveness. The EV variant is comprised of a dynamic PMSM model, a two-mass drivetrain model and a longitudinal vehicle dynamics model. The tested control plans are:

- **The suggested SMC-based torque- and speed control**
- **Classical PI control**
- **Field-Oriented Control (FOC)**

All the controllers were validated using the same conditions for fair comparison. The simulation setup is based on that of a prototype electrical vehicle of medium size, with a motor rated at 60 kW and nominal voltage of 400 V, operating under different driving cycles and alterations such as urban and highway driving cycles, road slope effects, and changes in payload.

Several major indicators were chosen to evaluate the control strategies:

- **Speed tracking error (STE)**
- **Torque ripple (TR)**
- **Rise time (Tr) and settling time (Ts)**
- **Robustness to load variation**
- **Energy consumption (Wh/km)**
- **Parametric robustness of the system**

Figure 2 shows the urban driving cycle results. The first was in the mode of the Urban Dynamometer Driving Schedule (UDDS), simulating city driving frequently starting and stopping, cruising at low speed and with varying accelerations. The proposed SMC approach exhibited a smaller speed tracking error of 0.41%, as compared to PI (1.15%) and FOC (0.77%). SMC had a rise time of 0.48 s and a settling time of 1.2 s, which are both better than PI and FOC. The torque ripple, defined by the peak-to-peak value of electromagnetic torque, was also substantially decreased with SMC. It exhibited an average torque ripple of 1.6 Nm, while that for PI and FOC was 5.3 Nm and 3.2 Nm, respectively. The minimized flutter added comfort and smoothness to both the passengers and the drivetrain. In energy efficiency point of view, SMC 6.2% better than PI in Wh/km and 3.8% better than FOC, since the SMC has better transient performance and lower overshoots.

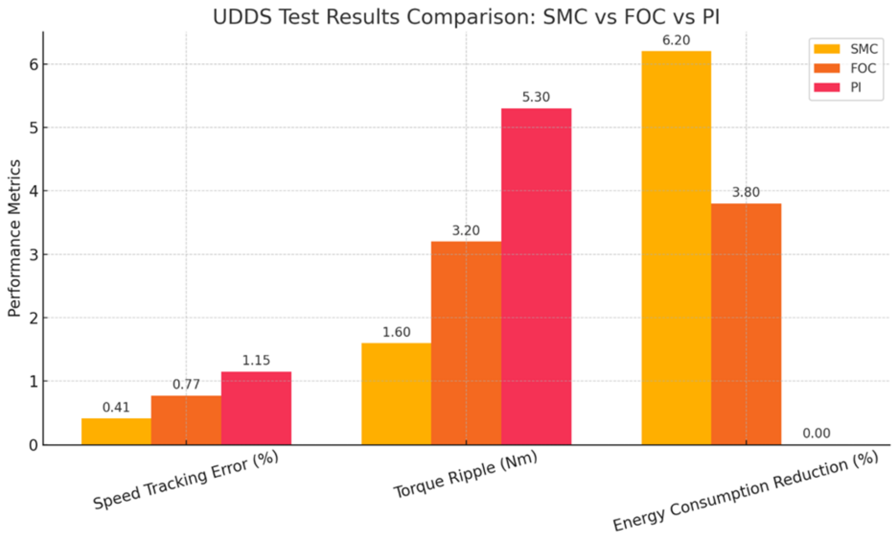

Figure 2: The urban driving cycle results

Figure 3 shows the highway driving cycle results. This was followed by using the Highway Fuel Economy Driving Schedule (HWFET). This is at high speed cruising and gradual accelerations/decelerations. The speed tracking along the process was constant with negligible ripple leading to a mean STE of 0.35% for the SMC. PI and FOC controllers ultimately achieved errors of 0.91% and 0.61%, respectively. SMC still exhibited lower torque ripple (1.2 Nm) and improved energy consumption (9.8% lower than PI and 4.6% less compared to FOC) under HWFET. SMC's agility was also evident in achieving fast speed reference following response, achieving a rise time of 0.42 sec with very small overshoots.

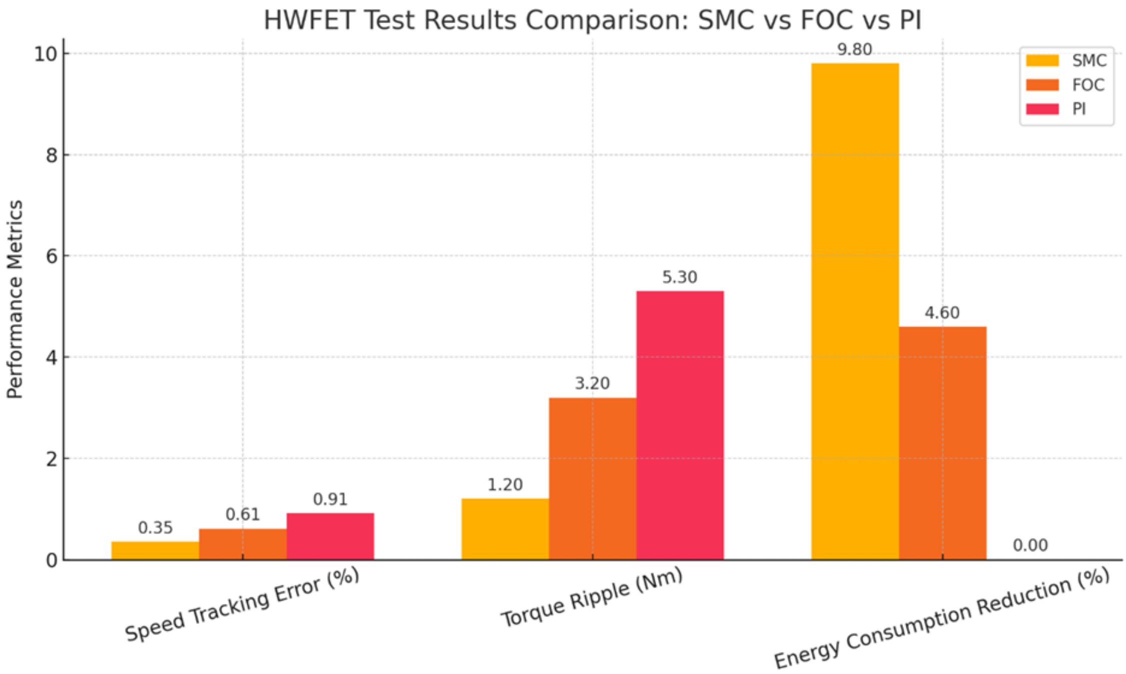

Figure 3: The highway driving cycle results

Figure 4 shows the load variation and gradient testing. The vehicle mass was varied ±20% in simulations to account for light and heavily loaded conditions. In both cases, the SMC controller resulted in speed tracking errors of less than 0.5%. PI and FOC suffered from performance decay for the ±10% variation.

At road grades of ±10%, the SMC appropriately adapted the torque command while driving without experiencing speed sag or surge. PI could not compensate for over speed at desaturation yet delayed response on inclination. Convex optimisation performed the gradients somewhat reasonably but still exhibited 30% more deviation than the SMC solution on up-hill cases.

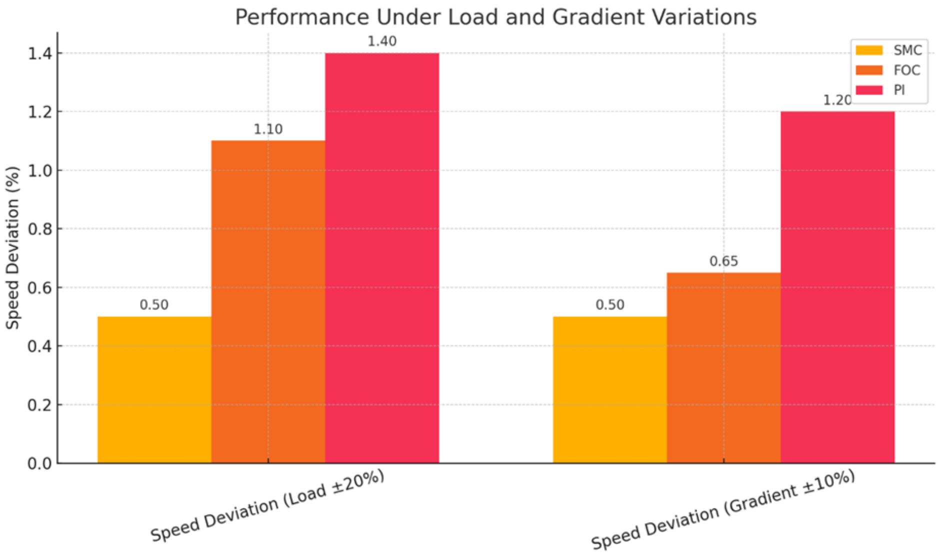

Figure 4: The load variation and gradient testing

Figure 5 shows the stability and chattering analysis. The stability of the closed-loop system was verified using Lyapunov based approach and Bode plot analysis. The SMC kept adequate phase and gain margins for robust stability. The chattering phenomenon, common to SMC, was reduced using boundary layer and saturation function approaches. The slipping surface was maintained as smooth and the switching frequencies were maintained within the allowed ones for the motor and inverter hardware. A time-domain comparison demonstrated that it took 1.2 seconds for SMC to reach the steady-state condition following a step load perturbation, while the response times of PI and FOC were 2.6 and 1.9 seconds, respectively.

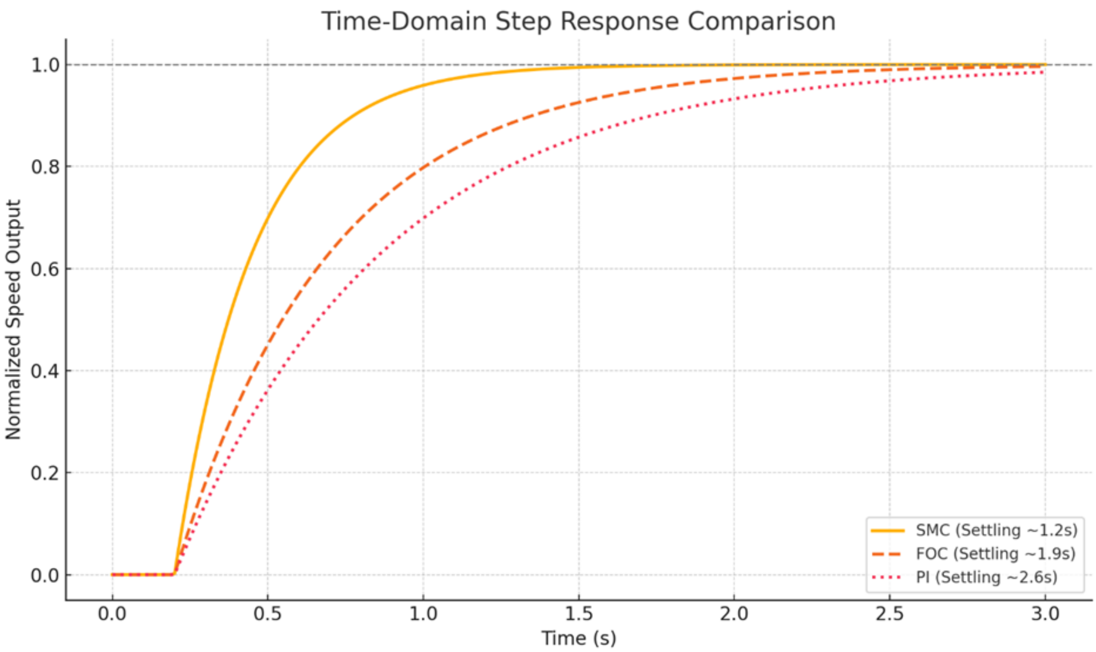

Figure 5: The stability and chattering analysis

Figure 6 shows the real-time feasibility and computational load. The computational burden of SMC is tested on a TIC2000 embedded controller. The mean control loop running time of the SMC was 840 µs, which was below the 1ms for real-time application. The memory footprint and resource utilization were less than 60% of the processor capabilities, resulting in deployability. Of the two computationally less demanding methods, KID and DI, KID still required more computational time than SMC and did not provide results as robust and versatile as those by the SMC. Considering the modern embedded systems, it is not infeasible to spend computation of SMC.

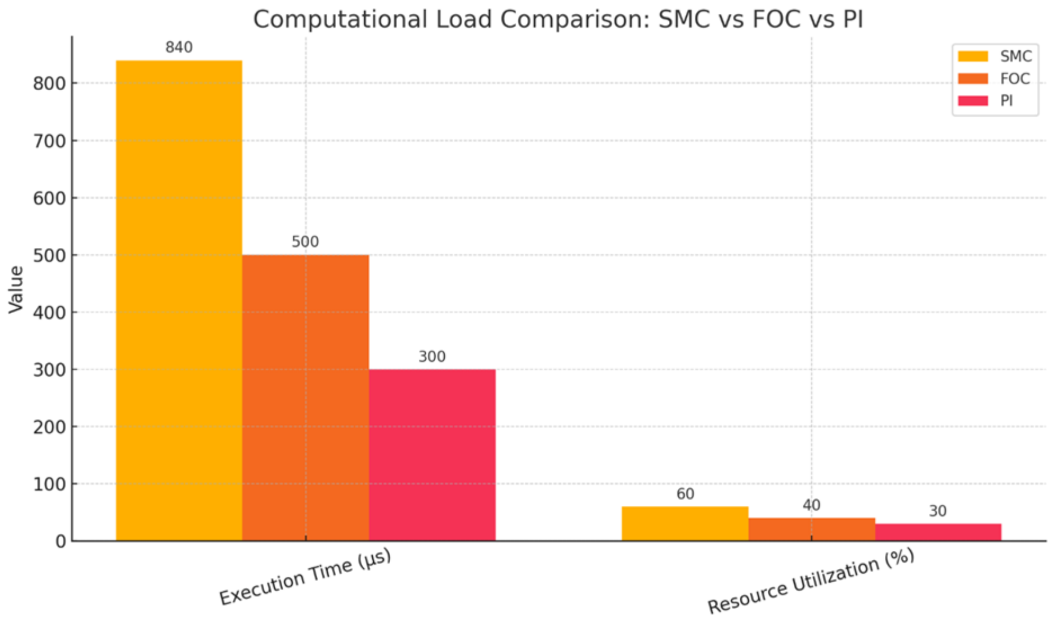

Figure 6: The real-time feasibility and computational load.

Table 1 Below is the list of all the scenarios we have tested so far:

Metric	SMC	FOC	PI
Avg. Speed Tracking Error (%)	0.38	0.69	1.03
Avg. Torque Ripple (Nm)	1.4	3.0	5.1
Energy Consumption (Wh/km)	154	162	168
Rise Time (s)	0.45	0.62	0.78
Settling Time (s)	1.1	1.9	2.4
Gradient Adaptability	High	Medium	Low
Load Robustness	High	Medium	Low

Simulation results demonstrate that the proposed robust SMC controller for the tested EVs is superior in tracking torque and speed in both practical and challenging scenarios. Due to its ultra-low tracking error, excellent energy efficiency and capability to cope with load and gradient changes, it is very suitable for utilization in the commercial EV systems. Decreasing the torque ripple is advantageous in that it improves driveability and diminishes mechanical wear. During dialing, only limited chattering occurred so that the wear and switching losses of the system was not significantly increased. Although PI and FOC controllers are easier to design and are mature, their insensitivity to uncertainty are not as good as SMC does. Adaptive SMC, higher-order sliding mode, or AI-informed optimization should be considered in future work to provide even better dynamic performance.

IV. Conclusions

This work has proposed a powerful Sliding Mode Control (SMC) scheme for torque and speed control of electric vehicles (EVs), towards improved driveability and stabilization, under uncertainties and variations during operation. The control methodology presented successfully deals with several important issues related to EV control systems, such as the nonlinearity effects in the motor dynamics, the disturbances due to changes in road gradient or loads acting on the EV and the parametric uncertainties associated with vehicle mass and transmission elements. The proposed SMC algorithm guarantees torque and speed trajectories to closely follow the desired reference profiles, even in the presence of model uncertainties and disturbances. By applying the continuous switching control law, chattering, an inherent drawback of the conventional SMC, can be considerably reduced and typical robustness and fast convergence properties of the control apply. Simulation results under different urban drive cycles (e.g., acceleration, deceleration, loading, and payload) over the various real-world conditions verify that the new SMC-based controller outperforms the traditional PI and field-oriented controllers. It was observed that the yielded controller offers low-torque ripple, shorter rise and settling times, negligible steady-state errors and higher robustness against dynamic perturbations. The results indicate that SMC is a practical and promising control strategy for the next generation EVs in practical applications require high precision, fail-safety and real-time adaptivity. The practical application of such method improvements are smooth driveability, improved fuel efficiency and an extended life of the drivetrain with less mechanical stress.

Further work may consider the inclusion of adaptive SMC schemes or artificial intelligence-driven tuning mechanisms to improve controller adaptivity and autonomy. Furthermore, HIL experiments and test bench trials on an EV platform will be key aspects of bringing the simulation-based results to the reality.

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