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Optimal Model Reference Lead Compensator Design for Electric Vehicle Speed Control Using Zebra Optimization Technique

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Abstract

Electric vehicle systems are growing in popularity as a promising solution to the problems associated with traditional transportation systems, such as environmental pollution. Nonetheless, the task of devising control algorithms that effectively control electric vehicle systems continues to persist as a complex realm of research. This is due to the ongoing pursuit of refining the dynamic attributes of the system, a task that is riddled with challenges. The inherent instability exhibited by the system and the presence of undesirable behaviors further compound the intricacy of this endeavor, demanding careful attention and comprehensive analysis of the system's unstable roots. In this paper, an advanced control algorithm is proposed for controlling the speed of the electric vehicle system based on the lead compensation. In addition, the control algorithm is designed to include the utilization of model reference control to improve the time response properties of the closed-loop system. Then, the Zebra Optimization Algorithm (ZOA) is used to optimally define the compensator parameters such that the reference model and system outputs be asymptotically identical with desirable steady-state error. Eventually, the simulation results show that the proposed optimal model reference lead compensator ensures stable and high-performance control of the electric vehicle system while maintaining simplicity and acceptable control action compared to other control approaches. This is substantiated by the noteworthy reductions it brings about: a staggering 90% decrease in rise time, a substantial 51% decrease in overshoot, and an impressive 99% reduction in cost value. In addition, the intervention of the proposed method completely eradicates steady-state errors, thus addressing a critical aspect of control system performance.

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Keywords: Electric vehicle system, Speed control, Lead compensator, Model reference control, Zebra optimization algorithm.

1. Introduction

Over the past few years, electric vehicles have garnered increasing attention as a viable alternative to traditional fuel-powered cars. This shift in attitude has been largely driven by growing concerns over the impact of transportation on the environment and a growing awareness of the importance of conserving energy. By using renewable resources, electric vehicles represent a sustainable and eco-friendly form of transportation that can help reduce the amount of pollution generated by traditional cars. As a result, electric vehicles have become an increasingly popular choice for individuals and organizations looking to reduce their carbon footprint and promote a more sustainable future [1, 5]. As electric vehicles become more prevalent, it is increasingly important to implement effective control systems to ensure that they operate safely and efficiently. Control engineering has emerged as a critical tool in this effort, providing the necessary tools and techniques to control and maintain electric vehicle performance. By using sophisticated algorithms and feedback mechanisms, control engineering can help ensure that electric vehicles operate under optimal conditions, maximizing energy efficiency and minimizing the risk of accidents or breakdowns. This has become an essential component of modern electric vehicle design, as the demands of this rapidly growing industry continue to evolve and expand. The successful integration of control engineering into electric vehicle design will be critical to realizing the full potential of this promising technology [6].

Lead compensation is a fundamental simple control technique that is commonly employed to improve the stability and transient response of dynamic systems. This method involves adding a lead gain, lead zero, and lead pole to the closed-loop system to help in reshaping the root-locus plot and ensure that it passes through the desired loci [7]. Nevertheless, the lead compensator may not always be sufficient to meet all of the required criteria. In some cases, it may be necessary to incorporate additional control techniques to achieve optimal performance. One such approach is the model reference control algorithm, which involves imposing the response of a reference model on the closed-loop system. By doing so, this technique can help to ensure that the system's behavior closely matches the desired response, improving its accuracy and responsiveness in the process [8, 9].

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There have been many approaches proposed to analyze and control the speed of the electric vehicle system, including the design of the of PID controller with speed constraints [1],fuzzy PD-I controller based on the adaptive black hole optimization [10], fuzzy PID controller based on the Grey Wolf Optimization (GEO) and Particle Swarm Optimization (PSO) techniques [11],fractional order PID controller based on Extra-X second-generation Current Conveyor (EX-CCII) [2],integration and PD algorithm approach for optimizing shifting control in electric clutchless automatic mechanical transmissions [12], multi-mode fuzzy control strategy with real-time recognition of driving patterns for enhancing the fuel efficiency in the hybrid electric vehicles [13], fuzzy fractional order PID controller based on Ant Colony Optimization (ACO) [14], torque adaptive drive anti-skid control by addressing the lateral wind interference and improving the driving performance [15],type-2 fuzzy neural network [16],robust optimal control based on the deep reinforcement learning [17], and robust Anti-Lock Braking System (ABS) control method with real-time road recognition for enhanced performance [18].Furthermore, preceding research has extensively explored the construction of lead compensators through the utilization of optimization algorithms. This includes investigations into lead compensator design achieved through methods such as the application of genetic algorithms (GA) and particle swarm optimization (PSO) [7], the employment of the Most Valuable Player Algorithm (MVPA)for lead compensator synthesis [19], as well as the formulation of an adaptive fuzzy lead-lag controller utilizing a customized grasshopper optimization algorithm (MGOA) [20].

The existing literature has motivated the design of a control algorithm that can effectively control the speed of electric vehicles using practical and straightforward controllers, such as lead compensators. These controllers must be able to ensure the system's stability and performance, while also adhering to relevant physical constraints. Furthermore, nature-inspired optimization techniques are utilized to refine the design process of the control algorithm that is highly efficient and effective in meeting the desired system specifications [21, 22], ultimately contributing to the wider adoption of electric vehicles and promoting sustainable transportation practices.

The main contribution of this paper is the design of optimal model reference lead compensator, which is aimed at controlling the speed of the electric vehicle system. Firstly, an accurate mathematical model for the system is formulated, taking into account the system's potential unwanted behavior. Then, a proper reference model containing the desired response specification is chosen. After that, the zebra optimization method is employed to optimally define the compensator parameters in a way that ensures the closed-loop system output follows the output of the reference model with better stability, performance and control voltage value.

The remaining sections of the paper consist of the electric vehicle mathematical modelling section, which presents an in-depth mathematical model of the electric vehicle and its components. The zebra optimization algorithm section describes the optimization method used to design the control algorithm, while the proposed model reference lead compensator design section presents the design methodology and control structure. Results and discussion section analyzes the simulations and experiments to evaluate the effectiveness of the proposed control algorithm, and finally, the conclusion section summarizes the key findings of the study and suggests areas for future research.

2. Electric Vehicle Mathematical Modelling

A schematic diagram of the electronic throttle control using a DC servo motor is shown in Figure 1 [23]. The vehicle's dynamicsare represented by the leader-follower configuration shown below, and the following equations can be used to derive the relationship between the follower vehicle's acceleration, propulsion force, and drag forces [11, 23]:

$$m\ddot{x} = f_e(\theta) - \alpha\dot{x}^2 - f_g \quad (1)$$

The vehicle's engine dynamics are modelled as a first order system.

$$\dot{f}_e(\theta) = \frac{1}{\tau_f}\left(-f_e(\theta) + f_i + \gamma\sqrt{\theta}\right) \quad (2)$$

wheref_e is engine force as the throttle position function, $f_g$represents the gravity-induced force which is 30% of vehicle's weight, as a function of the grade of the road, $\dot{x}$ is speed of the vehicle, t_f is constant time of the vehicle's typically ranges from [0.1, 1] seconds; in the current research, we have chosen t_f equals to 0.2 second and θ represents the position of the throttle.Table 1 displays the values of all other parameters[11].The state equation is obtained by using the transfer function that is determined from the given system dynamics[11, 23]:

$$\frac{V(s)}{\theta(s)} = \frac{8.29 \times 10^5}{s^2 + 5s} \quad (3)$$

The following are the state space equations for system equations[11, 23]:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -5 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0\ 8.29 \times 10^8 \end{bmatrix}, C = [1 \quad 0], \text{ and } D = [0] \quad (4)$$

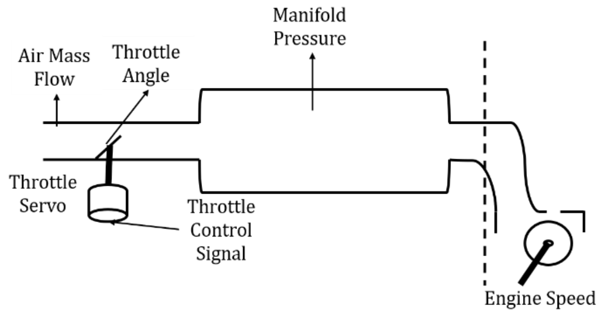

Figure 1. The electronic throttle control's schematic diagram [23]

Table 1. Quantitative values of the system parameters [11]

Constant	Notation	Value
Mass of the vehicle	m	1000 kg
Aerodynamic drag coefficient	α	4 $N/(m/s)^2$
Engine forcecoefficient	γ	12500 N
Engine Idle Force	f_i	6400 N
Time constant of engine	t_f	0.2 s

The characteristic equation of the system is$|\lambda I - A| = 0$, then the eigenvalues are $\lambda_1 = 0$ and $\lambda_2 = -5$. The system is completely state observable and controllable as the matrices M_c and N_o are of $rank = 2$:

$$M_c = 829000 \times \begin{bmatrix} 0 & 1 \\ 1 & -5 \end{bmatrix}, N_o = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (5)$$

where M_c and N_o stand for the controllability and observability matrices, respectively [11, 23].

This work proposes an enhanced control algorithm for lead compensation-based speed control of the electric vehicle system as demonstrated in Figure 2. Additionally, the control algorithm is built to use model reference control to enhance the closed-loop system's time response characteristics. The compensator parameters are then optimally defined using the Zebra Optimization Algorithm (ZOA) so that the reference model and system outputs are asymptotically identical with a suitable steady-state error.

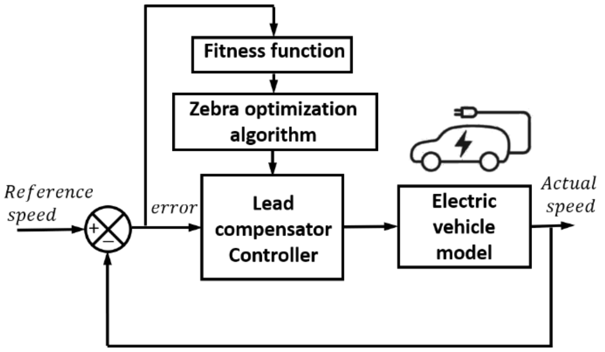

Figure 2. Schematic representation of the electric vehicle control system

3. Zebra Optimization Algorithm

Zebra Optimization Algorithm (ZOA), a metaheuristic algorithm inspired by nature, is described in this section along with a mathematical model of it. The behaviour of zebras in nature serves as ZOA's primary source of inspiration. ZOA simulates zebras' feeding behaviour as well as its defence mechanism against attacks from predators. After being described, the ZOA steps are mathematically modelled. By striking the right balance between exploration and exploitation, the ZOA may effectively handle optimization problems that arise in real-world situations [24].

3.1. Initialization

It is possible to mathematically model the number of zebras as a candidate or potential solution to the issue and the plain in which they live. This can be done by utilizing a matrix. The zebras are randomly placed in their initial positions within the search area. In Eq. (6), the ZOA population matrix is described [24].

$$X = \begin{bmatrix} X_1 \\ X_i \\ X_N \end{bmatrix}_{N\times m} = \begin{bmatrix} x_{1,1} & x_{1,j} & x_{1,m} \\ x_{i,1} & x_{i,j} & x_{i,m} \\ x_{N,1} & x_{N,j} & x_{N,m} \end{bmatrix}_{N\times m} \quad (6)$$

where N is the number of population members (zebras), m is the number of choice variables, X is the zebra population, $x_i$is the *ith* zebra, $x_{i,j}$ is the value for the *jth* problem variable proposed by the *ith* zebra, and so on. Using Eq. (7), the values discovered for the objective function are specified as a vector [24].

$$F = \begin{bmatrix} F_1 \\ F_i \\ F_N \end{bmatrix}_{N\times 1} = \begin{bmatrix} F(X_1) \\ F(X_i) \\ F(X_N) \end{bmatrix}_{N\times 1} \quad (7)$$

where $F_i$is the objective function value discovered for the *ith* zebra and F is the vector of objective function values. Members of the ZOA population are updated twice during each iteration [24].

3.2. Phase 1: Foraging Behaviour

Based on models of zebra behavior during forage seeking, population members are updated throughout the first phase. Eqs. (8) and (9) allow for the mathematical modeling of zebras changing their posture throughout the foraging phase [24].

$$x_{i,j}^{new,P1} = x_{i,j} + r \cdot \left(PZ_j - I \cdot x_{i,j}\right) \quad (8)$$

$$X_i = \begin{cases} X_i^{new,P1}, & F_i^{new,p1} < F_i; \\ X_{i,} & else, \end{cases} \quad (9)$$

where $X_i^{new,P1}$ is the new status of the *ith* zebra based on first phase, $x_{i,j}^{new,P1}$ is its *jth* dimension value, $F_i^{new,P1}$ is its objective function value, *PZ* is the pioneer zebra which is the best member, PZ_j is its *jth* dimension, *r* is a random number in interval [0,1], *I=round(1+rand)* , where rand is a random number in the interval [0,1]. Thus, $I\in\{1,2\}$ and if parameter I=2 , then there are much more changes in population movement [24].

3.3. Phase 2: Defense Strategies Against Predators

In the first tactic, when lions attack zebras, the zebras flee the area where they are located to avoid being caught up in the attack. As a result, this tactic can be mathematically represented using the mode S1 in Eq. (10). The other zebras in the herd move toward the attacking zebra in the second technique when other predators attack one of the zebras in an effort to terrify and confuse the predator by forming a protective structure. Zebras' behavior is mathematically represented by the mode S2 in Eq. (10). If the new position of a zebra has a better value for the objective function, that zebra's position is accepted when it is updated. Using Eq. (11), this update condition is represented [24].

$$x_{i,j}^{new,P2} = \begin{cases} S_1: x_{i,j} + R.(2r-1)\cdot\left(1-\frac{t}{T}\right)\cdot x_{i,j}, & P_s \le 0.5; \\ S_2: x_{i,j} + r\cdot\left(AZ_j - I.x_{i,j}\right), & else, \end{cases} \quad (10)$$

$$X_i = \begin{cases} X_i^{new,P2} & F_i^{new,P2} < F_{i;} \\ X_i, & else, \end{cases} \quad (11)$$

where $X_i^{new,P2}$ is the new status of the *ith* zebra based on second phase, $x_{i,j}^{new,P2}$ is its *jth* dimension value, $F_i^{new,P2}$ is its objective function value, *t* is the iteration contour, T is the maximum number of iterations, *R* is the constant number equal to 0.01, P_s is the probability of choosing one of two strategies that are randomly generated in the interval [0, 1], *AZ* is the status of attacked zebra, and AZ_j is its *jth* dimension value. The ZOA steps are presented as flowcharts in Figure 3 [24].

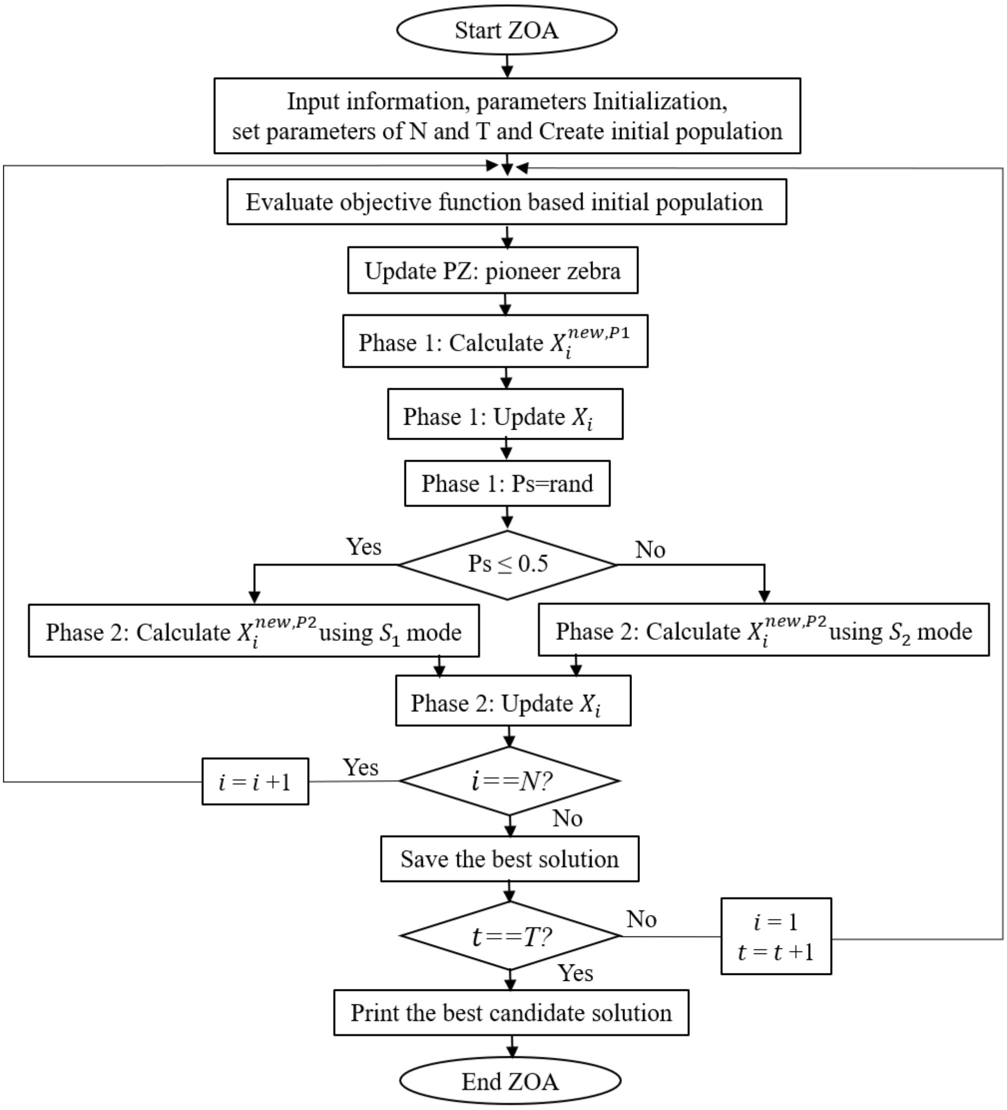

Figure 3. Flowchart of ZOA [24]

4. Proposed Model Reference Lead Compensator Design

In this section, the proposed model reference lead compensator is designed to control the speed of the electric vehicle system model described in Eq. (3). Firstly, Figure 4 displays the open-loop response of the system before control, highlighting the inherent instability behavior of the system as time elapses. Therefore, an efficient control algorithm is required to achieve desirable stability and performance properties. Typically, the lead compensator is the preferred choice for this issue due to its simplicity, reliability, and practical applicability. The following formula is usually used to develop the control algorithm [7, 25]:

$$K(s) = \frac{U(s)}{E(s)} = K_c \frac{s+z}{s+p}; \quad p > z \tag{12}$$

where z and p are the desired locations of the lead zero and pole, respectively, and K_c is the lead gain. However, the lead compensator may not achieve satisfactory transient response characteristics by itself. Therefore, it is integrated with the model reference control approach, resulting in the development of an advanced model reference lead compensation. In this case, a suitable reference model is introduced that incorporates the necessary time response specifications for the closed-loop control system. The reference model chosen for this study is the standard second-order system as described below [8, 9]:

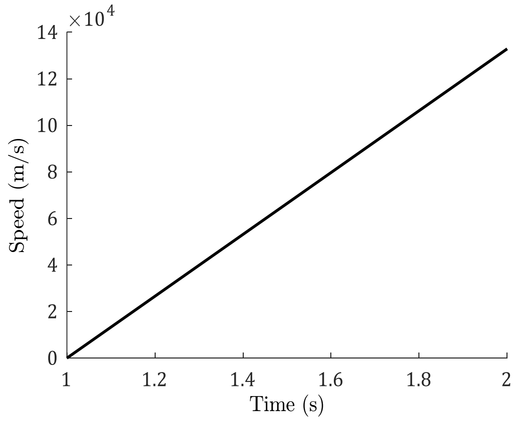

Figure 4. Open-loop response of the system

$$G_d(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{13}$$

where ω_n and ζ are the natural frequency in rad/s and damping factor, respectively. These parameters are under disposal and used to launch and fit the response specifications. Moreover, the main challenge in control design is in obtaining the desired locations for the lead zero and pole, as well as the lead gain value to achieve the necessary stability and performance specifications adequately. Two common theoretical methods are presented in literature for designing lead compensators in the time-domain [25]. However, the first method, referred to as method 1, lacks reliability as it relies on manual calculations. Consequently, unwanted response specifications may appear due to the actual impact of the lead zero on the overall closed-loop control system. The second method, or method 2, addresses the previous issue by choosing the location of the lead zero to be the same as one of the system poles, thus canceling out their effects of each other. However, it should be noted that this cancellation may not be actually realized in the closed-loop control system. As a result, essential properties regarding the closed-loop system stability and performance may be lost. Furthermore, the previous methods do not guarantee desirable steady-state error as they are prone to trade-offs between transient and steady-state characteristics. Therefore, this study proposes an optimal model reference lead compensator utilizing the zebra optimization technique as a powerful new approach to optimally determine the lead compensator parameters with the following Integral Square Error (ISE) cost function:

$$J(K_c, z, p) = \int_{t=0}^{\infty} e(t)^2 \, dt \tag{14}$$

such that the tracking error:

$$e(t) = y_d(t) - y(t) \tag{15}$$

between the reference model output $y_d(t)$ and system output $y(t)$ approached zero as time tends to infinity:

$$\lim_{t\to\infty} |y_d(t) - y(t)| = 0 \tag{16}$$

Finally, the control scheme proposed is denoted by the block diagram displayed in Figure 5.

5. Results and Discussion

In this section, the simulation results of the proposed optimal model reference lead compensator for controlling the speed of the electric vehicle system are presented using MATLAB software. Firstly, the values ofω_n and $\zeta$are selected to be $100\ rad/s$ and 0.9, respectively. With these values, the proposed control approach is intended to achieve a fast and precise response, characterized by short durations for the system to reach steady-state, minimal oscillations around the reference input, and small deviations between the system output and reference input. Thezebra optimization is then conducted with the optimization settings shown in Table 2 to optimally compute the compensator parameters, while minimizing the value of the cost function given in Eq. (14) and maintaining a satisfactory low control voltage applied by the controller (compensator). Figure 6 demonstrates how the cost value converge to zero, achieving minimum cost value of 1.3647×10^{-3}in short iterations and remains at that minimum cost for many other iterations, indicating that there are no other better cost and solutions, and the global optimization is achieved. Therefore, the designed compensator is optimal well-known rather than suboptimal. The optimal values of the optimized variables are listed in Table 3. After that, the compensator model given in Eq. (12) is implemented with the previously obtained parameters for a setpoint of $r(t) = 20\ m/s$.

Table 2. Optimization settings of the zebra technique

Optimization Setting	Value
Search dimension (No. of optimized variables)	3
Lower bounds	$[-100 \quad -100 \quad -100]$
Upper bounds	$[100 \quad 100 \quad 100]$
Search agents (Population size)	50
Search iterations	100

Table 3. Results of the zebra optimization

Parameter	Optimal Value
Compensator gain (K_c)	24.6566
Compensator zero (z)	16.6218
Compensator pole (p)	20.4210
ISE Cost	0.0013647

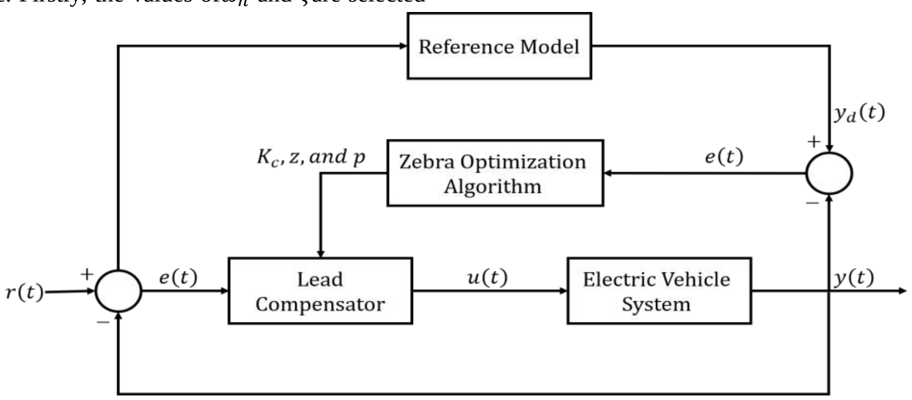

Figure 5. Entire block diagram of the proposed control scheme

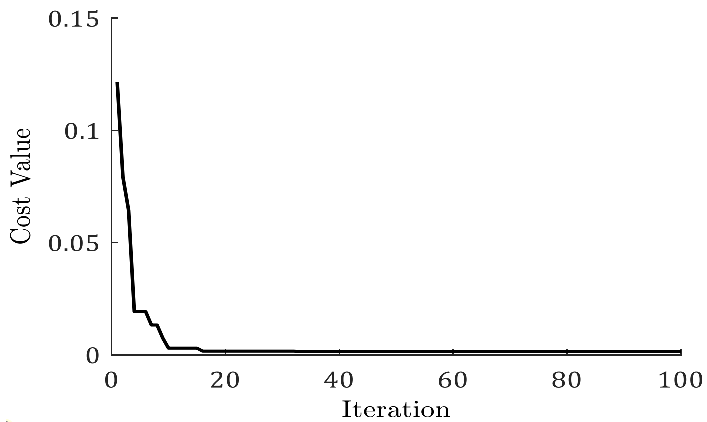

Figure 6. Convergence of the cost function

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Figure 7 depicts the performance of the controlled electric vehicle system. The speed trajectory, which closely follows the reference model output and the desired setpoint speed, showcases excellent stability and performance characteristics. The system's response exhibits a rapid rise time of 0.349 seconds, a settling time of 0.44 seconds, a minimal overshoot of 1.84%, and attains zero steady-state error. These statistics emphasize the system's capability to achieve precise tracking and meet stringent performance criteria. Additionally, Figure 8 depicts the tracking error between the reference model and system outputs, which was reduced to zero with the time increment, indicating that the necessary condition for tracking presented in Eq. (16) has been satisfied. Moreover, Figure 9 displays the performance of the control voltage input. This figure shows that the applied voltage magnitude from the compensator as a control action was acceptable and practically applicable with a value of 20 volts, highlighting one of the advantageous aspects of the proposed control method and emphasizing the method's practicality and utility in real-world scenarios. Furthermore, the ramp response of the system under control is depicted in Figure 10. This figure demonstrates the steady-state characteristics of the closed-loop system. It is evident that the proposed control method has achieved a zero steady-state error in response to the ramp input, and it is powerful in making the controlled system track a uniformly increasing input.

Comparing to the previous works [1-3], where different control methods were suggested for controlling the electric vehicle system with mathematical models that are stable and exhibit satisfactory performance even without any control, the proposed approach has adopted an accurate mathematical model for the electric vehicle system. This model takes into account the potentially bad behavior of the system, and a powerful compensation has been proven to achieve effectiveness against the system instability. In addition, the control effort provided from the proposed compensator to the vehicle motors is efficiently adequate and applicable as shown in Figure 9, in contrast to the methods presented in [1-3, 11, 14, 23], where a high control voltage may be applied, causing many problems such as overheating, reduced lifespan, safety hazards, compatibility issues, and regulatory compliance challenges. While high voltage can offer performance and efficiency benefits, it requires careful control to avoid these issues. Finally, in Table 4, the performance properties of the proposed control method have been compared to those presented in [11], where a Fuzzy-PID controller was designed for the same system model and applied using the Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO) techniques. It is clear that the proposed model reference lead compensator is significantly more efficient in compensating the electric vehicle system with better stability and performance specifications. Notably, the compensator yields remarkable improvements, reducing the rise time by an impressive 90%, curtailing overshoot by 51%, and entirely eliminating steady-state error. Additionally, there is a substantial 99% reduction in cost value when compared to the minimum values reported in [11]. Nonetheless, the proposed method leads to a minor 2% reduction in settling time. This enhancement could be of significant interest to companies seeking rapid acceleration in their electric vehicle control systems. Conversely, this percentage improvement remains fairly consistent with the minimum values achieved in the previous study [11].

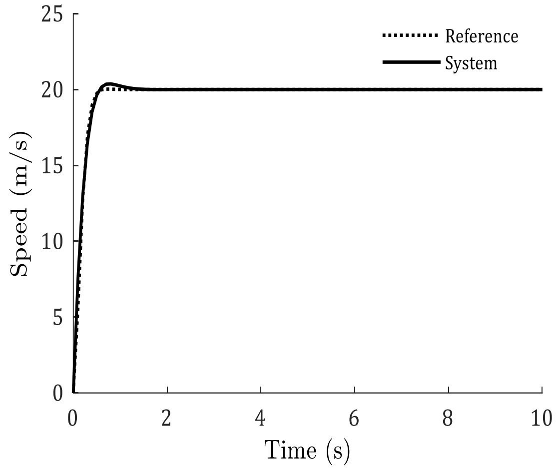

Figure 7. Speed trajectory of the controlled electric vehicle system

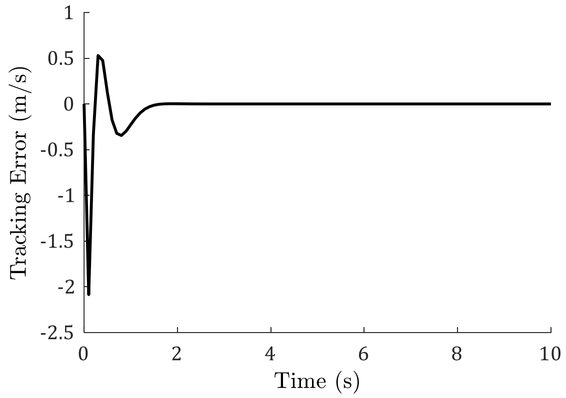

Figure 8. Trajectory of the tracking error behavior

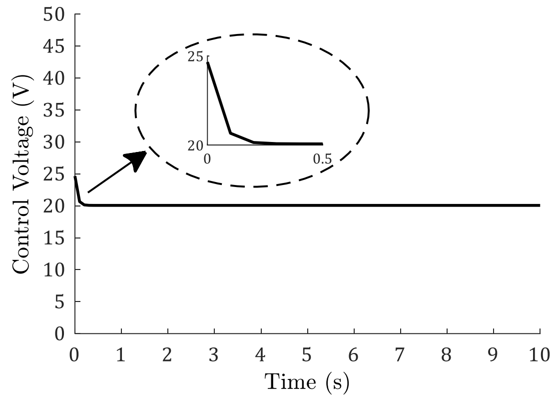

Figure 9. Performance of the control voltage

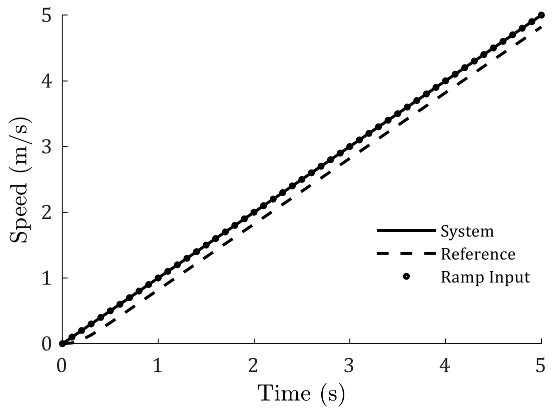

Figure 10. Ramp response of the control system in trackingthe reference model and ramp input

Table 4. Comparison of the proposed control approach versus the previous control method [11]

Performance Specification	PID [11]	PSO-Based PID [11]	GWO-Based PID [11]	PSO-Based Fuzzy PID [11]	GWO-Based Fuzzy PID [11]	Optimal Model Reference Lead Compensator	Enhancement Rate (%)
Rise time (s)	3.5	4.3	4.2	3.85	3.4	0.349	Reduced by 90%
Settling time (s)	0.8	0.78	0.6	0.57	0.45	0.44	Reduced by 2% (Fairly similar)
Overshoot (m/s)	61%	53%	58%	61%	59%	1.84%	Reduced by 51%
Steady-state error (m/s)	0.15%	0.3%	0.15%	0.10%	0.05%	Not exist	Eliminated
ISE Cost	Undefined	Undefined	Undefined	Undefined	2.6	0.0013647	Reduced by 99%

6. Conclusion

In this work, an advanced control algorithm was proposed to control the speed of the electric vehicle system based on the lead compensation frame work. The proposed algorithm utilized the model reference control theory to enhance the time response of the closed-loop system by compelling the system output to track an effective reference model asymptotically. Besides, the compensator parameters have optimized using the zebra optimization technique to ensure the achievement of both transient and steady state characteristics. Finally, the simulation results demonstrate that the proposed optimal model reference lead compensator was effective in compensating the electric vehicle system with adequate stability, performance, simplicity, and acceptable control action. This is corroborated by the significant diminutions it yields: a remarkable 90% reduction in rise time, a substantial 51% decrease in overshoot, and an impressive 99% decrement in cost value. Furthermore, the integration of the introduced technique entirely eliminates steady-state errors, thereby effectively addressing a pivotal facet of control system efficacy.For future research, the proposed control method can be more enhanced by designing it based on the H-infinity control approach to take into account the issue of system robustness.

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