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Research Article

Enhanced Integral-Backstepping Control for Synchronous Reluctance Machines in Traction Applications

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Abstract – Electric vehicles (EVs) have gained immense popularity as a sustainable mode of transportation, and the choice of the electric machine greatly influences their performance and efficiency. This abstract discusses the application of Integral-Backstepping Control (IBC) to enhance the control of Electric Vehicles equipped with Synchronous Reluctance Machines (SynRM). SynRM presents itself as a promising alternative to traditional permanent magnet synchronous machines due to its simpler construction, cost-effectiveness, and robustness. The proposed Backstepping Control approach employs a systematic Lyapunov-based design to guarantee stability and performance improvements. It takes into account various EV operating conditions, including regenerative braking, acceleration, and deceleration. The controller aims to provide precise control of the SynRM to optimize energy usage and improve overall driving experience. Simulations result demonstrate the effectiveness of Backstepping Control for SynRM-based EVs. The controller achieves enhanced tracking performance, improved torque response, and increased energy efficiency compared to traditional control methods. Furthermore, it exhibits robustness to parameter variations and disturbances commonly encountered in real-world driving scenarios.

Keywords – Electric Vehicle; Synchronous Reluctance Machine; Backstepping Control; Nonlinear Control; Traction Chain.

I. INTRODUCTION

Electric vehicles are becoming increasingly prevalent as a sustainable and environmentally friendly mode of transportation[1]–[3]. One of the critical components in an electric vehicle's propulsion system is the electric motor. Among the various motor types available, the Synchronous Reluctance Machine (SynRM) has emerged as a promising candidate. SynRM offers several advantages, such as high efficiency, robustness, and the absence of permanent magnets, making it an attractive choice for EV manufacturers[4], [5].

Synchronous Reluctance Machine (SynRM) technology has gained significant attention in the electric vehicle (EV) industry due to its efficiency, reliability, and potential for improved performance[6]–[8]. Backstepping control is a sophisticated control technique that has been applied to enhance the operational characteristics of SynRM-based electric vehicles[9][10]. In this introduction, we will provide an overview of the key components, advantages, and challenges associated with the integration of Backstepping control in SynRM-based electric vehicles.

Control strategies play a pivotal role in the overall performance of electric vehicles. Backstepping control is an advanced control technique that focuses on tracking and stabilizing a system by designing controllers recursively. This approach is particularly suitable for SynRM-based electric vehicles due to the complexity of motor control and the desire for high-performance operation[11]. Backstepping control can effectively address challenges like torque ripple minimization, fast transient responses, and improved efficiency [12].

In this paper, we delve into the integration of Backstepping control in SynRM-based electric vehicles. Our primary objectives are to:

- Enhance the dynamic performance and efficiency of SynRM-based electric vehicle propulsion systems.
- Mitigate issues like torque ripple and instability commonly associated with SynRM technology.
- Provide a comprehensive overview of the Backstepping control strategy and its implementation in the context of electric vehicles.

The remainder of this paper is structured as follows:

- Section 2 will provide an in-depth review of SynRM technology, including its operating principles and advantages.
- Section 3 will introduce the Backstepping control technique, explaining its theoretical foundations and relevance to SynRM-based electric vehicles.
- Section 4 will detail the design and implementation of the Backstepping control system for SynRM electric vehicles, including control algorithms
- Section 5 will present simulations results and performance evaluations to validate the effectiveness of the proposed approach.
- Finally, Section 6 will conclude the paper with a summary of key findings, implications, and future research directions.

II. ELECTRIC VEHICLE MODELING

The traction chain of the electric vehicle shown in (Fig. 1) consists of an energy storage system, two bidirectional DC-DC converters, and synchronous reluctance motor drive.

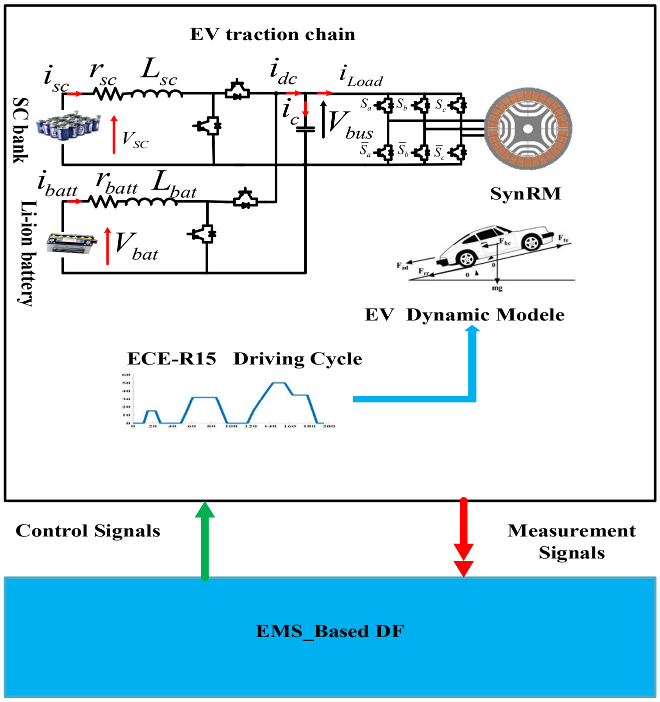

Fig. 1 Block diagram of the proposed EV

A. *Synchronous Reluctance Motor Model Speed Regulation*

The electromechanical model of the synchronous reluctance motor in the rotor reference (d-q) frame is given as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \Omega \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_d} i_{sd} + \frac{pL_q}{L_d} i_{sq}\Omega \\ \frac{-R_s}{L_q} i_{sq} - \frac{pL_d}{L_q} i_{sd}\Omega \\ \frac{3p(L_d - L_q) i_{sd} i_{sq}}{2J} - \frac{f}{J}\Omega - T_L \\ p\Omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix}$$

(1)

where v_{sq} and v_{sd} are the quadrature and direct axis terminal voltages, respectively. The i_{sq} and i_{sd} are the quadrature axis and direct axis terminal currents, respectively. The L_q and L_d are the quadrature and direct axis magnetizing inductances, respectively. Ω is the mechanical speed, and R_s is the stator resistance, and p is the pair poles. T_L , f and J are the torque load, viscous friction coefficient, and inertia moment of the rotor, respectively.

III. SYNRM DRIVE BACKSTEPPING CONTROL DESIGN

SynRM Drive Backstepping control Design

The Backstepping control of SynRM, depicted in (Fig. 2), consists of three control loops; one external speed control loop and two internal current control loops for i_{sd} and i_{sq} .

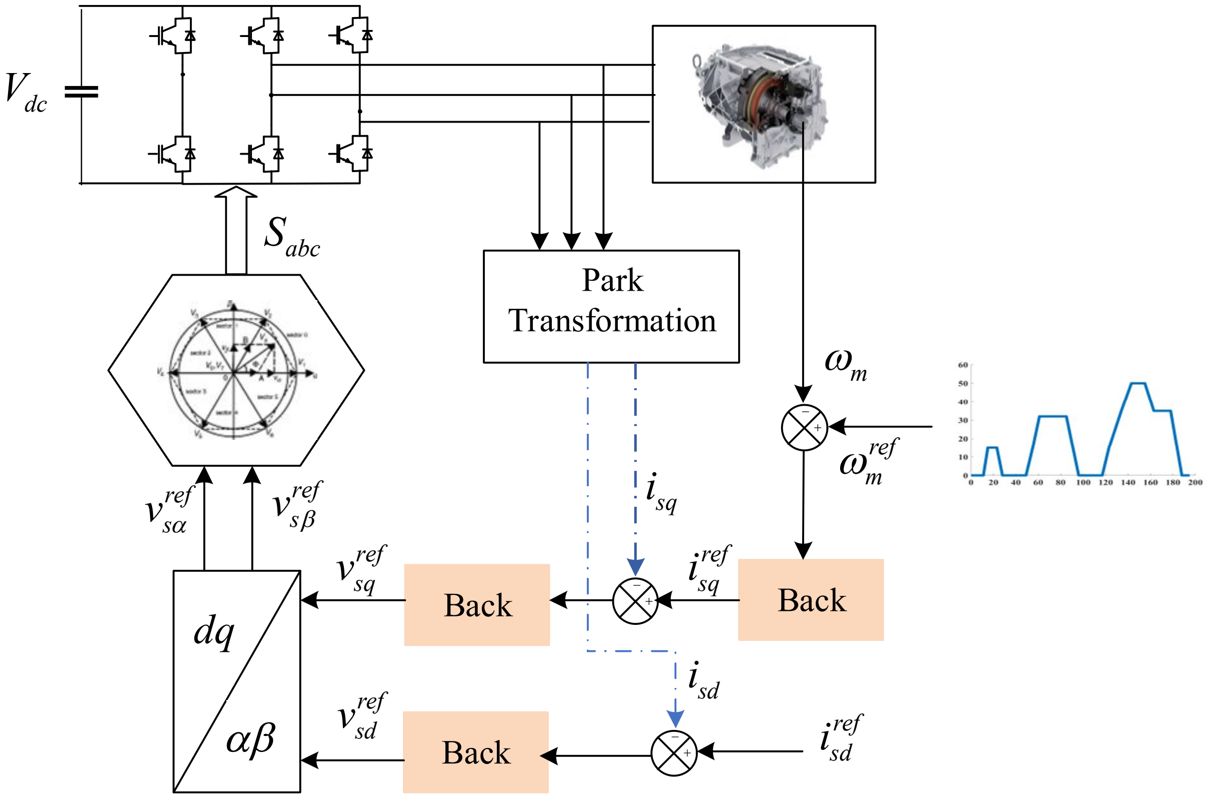

Fig. 2 Diagram of SynRM Backstepping control

A. SPEED REGULATION

The speed tracking error is:

$$e_1(\omega) = \omega_{ref} - \omega + k_\omega \int \left(\omega_{ref} - \omega\right) dt \qquad (2)$$

We consider the following Lyapunov candidate:

$$V(e_1) = \frac{1}{2} e_1^2 \qquad (3)$$

To ensure the stability of the system, it is necessary for $\dot{V}(e_1)$ to be negative.

$$\dot{V}(e_1) = e_1 \dot{e}_1 < 0 \qquad (4)$$

The reference of the quadrature current is given by:

$$i_{sqref} = \frac{2}{3p\left(L_d - L_q\right) i_{sdref}} \left[J(\dot{\omega}_{ref} + k_\omega e_\omega + k_1 e_1) + f\omega + T_L \right]$$

(5)

B. *quadrature current* i_{sq} *regulation*

The error in quadrature current tracking is:

$$e_2 = i_{sqref} - i_{sq} + k_q \int \left(i_{sqref} - i_{sq}\right) dt \qquad (6)$$

The augmented Lyapunov function is given by the expression :

$$V(e_1, e_2) = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 \qquad (7)$$

To ensure the stability of the system, it is necessary for $\dot{V}(e_1, e_2)$ to be negative.

$$\dot{V}(e_1, e_2) = e_1 \dot{e}_1 + e_2 \dot{e}_2 < 0 \qquad (8)$$

The control laws expressing the reference voltage vector components is given by (17)

$$v_{sq} = L_q \left(\dot{i}_{sqref} + k_q e_q + k_2 e_2 \right) + R_s \ \mathrm{i}_{sq} + p\omega_m L_d \ i_{sd}$$

(9)

C. *direct current* i_{sd} *regulation*

The error in direct current tracking is:

$$e_3 = i_{sdref} - i_{sd} + k_d \int \left(i_{sdref} - i_{sd}\right) dt$$

The augmented Lyapunov function is given by the expression :

$$V(e_1, e_2, e_3) = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 + \frac{1}{2} e_3^2 \qquad (10)$$

To ensure the stability of the system, it is necessary for $\dot{V}(e_1, e_2, e_3)$ to be negative.

$$\dot{V}(e_1, e_2, e_3) = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 < 0 \qquad (11)$$

The control laws expressing the reference voltage vector component is given by (17) :

$$v_{sd} = L_d \left(\dot{i}_{sdref} + k_d e_d + k_3 e_3 \right) + R_s \ \mathrm{i}_{sd} - p\omega_m L_q \ i_{sq}$$

(12)

IV. RESULTS THE SYSTEM DEPICTED IN

In o ensure the reliability of our results, we employed the MATLAB-Simulink environment, a widely accepted platform for modeling and simulating complex control systems. Additionally, the ECE-R15 driving cycle, which is a standardized driving profile, was chosen as the basis for our simulations. This choice allows for a realistic representation of real-world driving conditions.

The primary objective of these simulations was to evaluate how well the proposed control scheme performs under various driving conditions and scenarios. This encompassed assessing its ability to maintain vehicle performance, such as speed and acceleration.

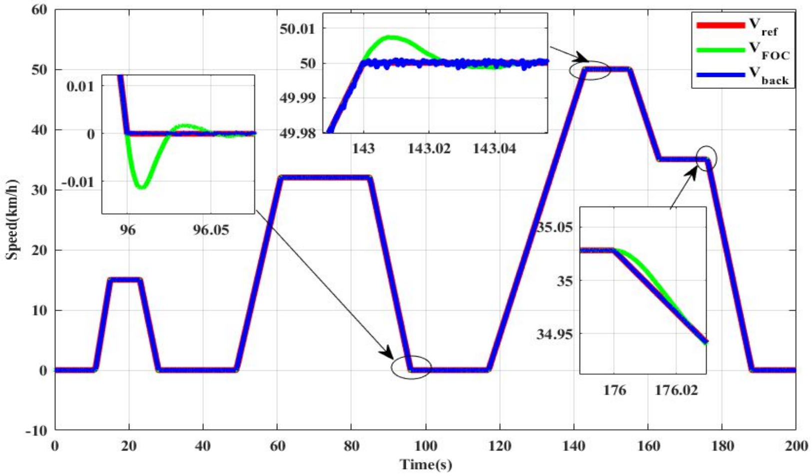

Fig. 3 linear speed of the vehicle

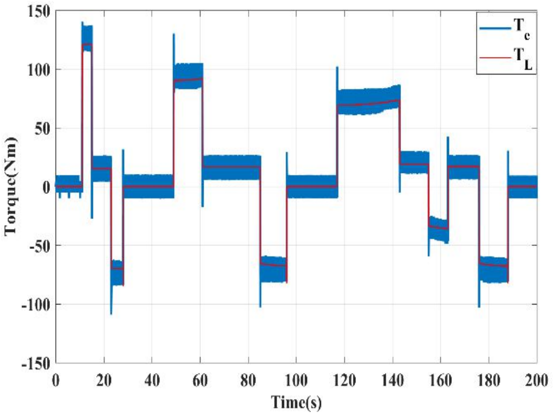

Fig. 4 Load torque (TL) and SynRM torque(Te)

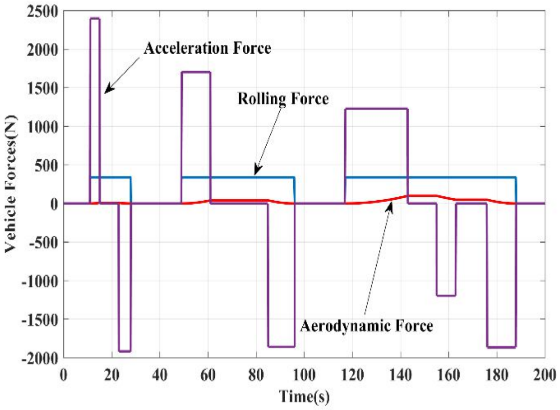

Fig. 5 EV Forces

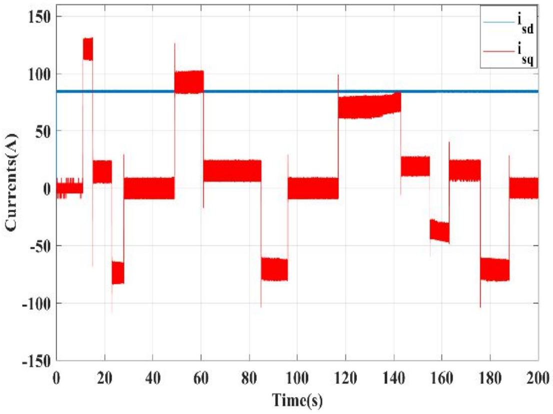

Fig. 5 direct and quadrature currents;

V. DISCUSSION

The speed response presented in (Fig. 3) shows that there is a good follow-up despite the change in the road profile, which confirms the efficiency of the Backstepping-Integral controller. From the torque curve illustrated in (Fig. 4), it can be seen that the motor develops maximum torque so that the vehicle speed reaches its reference path. The vehicle attains the steady state, and the motor produces less torque just enough to compensate for the total load torque. when crossing the positive slope, the motor develops a large torque to maintain its reference speed. when crossing the negative slope, the same task is done but with negative torque.

As illustrated in (Fig. 5), the quadrature current has the same shape as the electromagnetic torque, while the direct current   is set to a constant value.

By comparing the IBack to PI controller, it is can be seen that the IBack has fast response with good robustness against load torque variations.

VI. . CONCLUSION

The integration of Integral-Backstepping control in SynRM-based electric vehicles holds the promise of significantly improving their performance and efficiency. By addressing key challenges associated with SynRM technology, this research aims to contribute to the advancement of electric vehicle propulsion systems, ultimately promoting the adoption of eco-friendly transportation solutions. This work presents an Backstepping-Integral control of synchronous reluctance machine as part of an urban electric vehicle powered by battery/supercapacitor hybrid source. The obtained simulation results confirm the effectiveness of the proposed control system when compared to PI based control.

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