

Article

A Predictive Finite Speed-Set MRAS for Robust Sensorless Control of PMSM Drives in Electric Vehicles Under Driving Cycle

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Abstract

Model reference adaptive system (MRAS)-based techniques are widely used for sensorless speed estimation in permanent magnet synchronous motor (PMSM) drives. However, conventional MRAS approaches rely on PI/PID controllers in the adaptation mechanism, which require careful tuning and may suffer from performance degradation under varying operating conditions. This paper proposes a tuning-free finite speed-set model reference adaptive system (FSS-MRAS) for sensorless speed estimation in electric vehicle (EV) applications. The suggested design methodology substitutes the traditional adaptive controller design with a speed-set predictive selection approach, hence removing the need for controller parameter tuning and making the scheme more straightforward to implement. To validate the performance of the FSS-MRAS algorithm, a comprehensive EV model is simulated according to the FTP-75 driving cycle, which provides very dynamic and realistic test conditions. Simulation results prove that the suggested algorithm guarantees accurate speed estimation in all operational scenarios, including low-speed, high-speed, and high-dynamics modes. It is also demonstrated that the estimated value matches the actual value with negligible errors at the steady-state condition and stays bounded around the real value within ± 40 rpm during transient dynamics conditions. Moreover, compared with the conventional MRAS scheme, the proposed approach eliminates the need for PI controller tuning while maintaining accurate and stable speed estimation under the highly dynamic operating conditions of the FTP-75 driving cycle. Additionally, the proposed scheme proves stable performance without any oscillation or divergence issues through the whole driving cycle.



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Keywords: sensorless control; model reference adaptive system; finite speed-set MRAS; electric vehicles; driving cycles

1. Introduction

The growing worldwide focus on the reduction of greenhouse gas emissions and energy efficiency has led to an increase in the adoption of electric vehicles as an effective alternative to traditional internal combustion engine vehicles [1,2]. The growing interest in electric vehicles can be attributed to their capability to produce zero emissions, energy efficiency, and their ability to run on renewable energy sources. This has been made

possible through technological advancements in the areas of batteries, power electronics, and electric drives [3,4].

Contemporary electric vehicles are known for being systems consisting of different sub-systems that are interrelated with each other, namely energy storage systems, power electronics converters, electric machines, and vehicle dynamics. Such sub-systems function in a highly integrated manner as they all affect each other through electrical, mechanical, and thermal effects at the same time [5,6]. EVs' powertrains do not only depend on the efficiency of each element, but also on its performance while interacting with others, depending on various operational situations, which can be different types of driving cycles and environmental conditions [2]. Moreover, the development of the EV industry depends significantly on governmental regulations and the impact on the environment, in spite of ongoing challenges [7].

Among different types of electric machines used in electric vehicle (EV) powertrain designs, the permanent magnet synchronous motor (PMSM) appears as one of the most popular choices thanks to its high efficiency, high torque density, and small size [8,9]. Such features are responsible for the achievement of high dynamic performance and long travel distances that can be reached from a single charge, which are some of the key specifications of current EVs. Additionally, IPMSMs feature an increased constant power operation range and a high-speed regime, thus making them suitable for traction machines that are required to operate under variable speeds [9]. Moreover, PMSMs demonstrate excellent control properties when coupled with advanced drive systems that provide efficient torque adjustment and rapid dynamic response even under fluctuating loads. It should be noted that recent studies have demonstrated the potential for innovative approaches such as predictive and sensorless control methods that may improve the operation of PMSM drives [8,10].

The overall performance of drives that use PMSMs is significantly affected by the type of control scheme used. In particular, for electric vehicle applications, where there are very dynamic operating conditions, traditional control schemes such as FOC and DTC have been used extensively because of the fact that they offer decoupled control of both torque and flux and have fairly good steady-state performance [11,12]. Traditional control schemes, however, require information about rotor position and velocity which is usually gained from mechanical sensors like encoders and resolvers. While these mechanical sensors work well, they increase cost and complexity [12].

In order to overcome the above limitations, numerous studies have been conducted to estimate rotor speed and position via sensorless control that relies on electrical quantities alone. Among different sensorless control strategies, model-based sensorless methods, such as the model reference adaptive system (MRAS), extended Kalman filter (EKF), and sliding mode observer (SMO), have been widely used [11,12]. Among all these model-based sensorless approaches, the model reference adaptive system has been the most popular choice because of its simplicity, low computational cost, and accurate estimation capability across a broad range of operation [11,13].

Nonetheless, when applied in practice, traditional MRASs commonly adopt the use of PI adaptive laws, wherein the choice of the controller parameters greatly affects their accuracy. These are usually dependent on operating conditions and require much effort on the side of the designer for effective results at various speed ranges [14]. Therefore, other approaches have to be explored to maintain the benefits associated with MRAS without the effort required for parameter tuning especially in areas where there are variations in operational conditions.

The main contributions of this paper are summarized as follows:

- An innovative FSS-MRAS scheme is proposed for estimating the speed of PMSM drives without sensors based on a finite set of candidate speeds to identify the correct rotor speed.
- In comparison to traditional MRAS schemes employing PI-based adaptation techniques, the proposed scheme does not require PI tuning while retaining high accuracy of estimation.
- The novel FSS-MRAS scheme is applied to the PMSM drive system incorporated in an electric vehicle system by taking into account the real-world operation scenarios based on typical driving cycles.
- The practicality and reliability of the proposed scheme are demonstrated based on dynamic conditions with reliable speed estimation and high tracking accuracy.

The rest of this paper is structured as follows. The mathematical model of the PMSM drive system, its electric vehicle components and the conventional sensorless MRAS method are discussed in Section 2. The proposed predictive FSS-MRAS method for the speed estimation of the electric vehicle without speed sensors is presented in Section 3. The simulations and results are given in Section 4. Finally, the conclusions are drawn in Section 5.

2. Methodology

This section will introduce the general methodology used in this research, which includes modeling of the electric vehicle drive, formulation of the mathematical model of the PMSM, and introduction of the proposed finite speed-set model reference adaptive system (FSS-MRAS). The implementation of the proposed method into the control system of the PMSM drive will be discussed in Section 3.

2.1. System Description

The proposed system comprises a voltage source inverter (VSI)-fed PMSM drive used for electric vehicles (EVs), shown in Figure 1. The inverter transforms the DC input coming from the battery into three-phase AC voltages for the purpose of driving the PMSM. The resulting electromagnetic torque is transmitted to the vehicle wheels through the drivetrain, enabling vehicle motion.

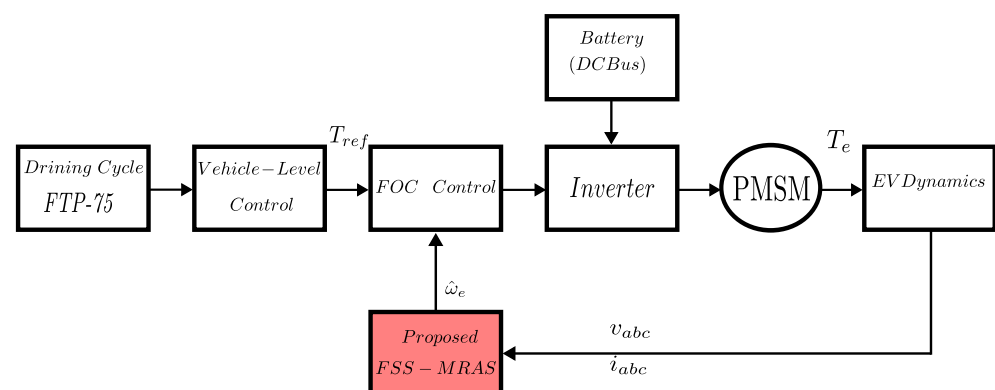


Figure 1. Overall control architecture of the proposed PMSM-based electric vehicle system.

The system operates under varying driving conditions defined by the applied driving cycle, leading to continuous variations in motor speed and load torque. A vehicle-level control layer generates the reference torque required for propulsion, which is tracked by the field-oriented control (FOC) scheme.

To eliminate the need for mechanical speed sensors, the proposed finite speed-set model reference adaptive system (FSS-MRAS) is integrated within the control loop. The estimator utilizes the measured stator voltages and currents in the abc reference frame to provide an accurate estimation of the rotor speed, ensuring reliable operation under dynamic conditions.

2.2. EV Drivetrain and Vehicle Model

The longitudinal dynamics of the electric vehicle are modeled based on well-established vehicle dynamics principles [15,16]. The electromagnetic torque generated by the PMSM is transmitted to the wheels through a reduction gearbox with a gear ratio i_g and efficiency η . The relationship between motor torque and wheel torque is given by

$$T_{\text{gearbox}} = \eta i_g T_{\text{motor}} \quad (1)$$

while the corresponding rotational speed is expressed as

$$\omega_{\text{gearbox}} = \frac{\omega_{\text{motor}}}{i_g} \quad (2)$$

The traction force applied to the vehicle is obtained from the wheel torque as

$$F_{\text{traction}} = \frac{T_{\text{gearbox}}}{r_w} \quad (3)$$

where r_w is the wheel radius.

The longitudinal vehicle dynamics are described by

$$m \frac{dv}{dt} = F_{\text{traction}} - (F_{rr} + F_d + F_{\text{slope}}) \quad (4)$$

where m is the vehicle mass and v is the vehicle speed. The rolling resistance force is given by

$$F_{rr} = f_r mg \cos(\theta) \quad (5)$$

and the aerodynamic drag force is expressed as

$$F_d = c v^2 \quad (6)$$

where f_r is the rolling resistance coefficient and c is the aerodynamic drag coefficient. The road slope force is defined as

$$F_{\text{slope}} = mg \sin(\theta) \quad (7)$$

Although the road slope angle θ is set to zero in the nominal case, it is included in the model to allow the evaluation of the proposed method under different road conditions.

2.3. PMSM Mathematical Model

The mathematical model of the permanent magnet synchronous motor (PMSM) is commonly expressed in the synchronous rotating reference frame (d–q frame), which enables independent control of torque and flux components [11,17].

The stator voltage equations in the d–q reference frame are given by

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (8)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_m \quad (9)$$

where v_d and v_q are the stator voltages, i_d and i_q are the stator currents, R_s is the stator resistance, L_d and L_q are the inductances, ω_e is the electrical angular speed, and λ_m is the permanent magnet flux linkage.

The electromagnetic torque is expressed as

$$T_e = \frac{3}{2}p(\lambda_m i_q + (L_d - L_q)i_d i_q) \quad (10)$$

where p is the number of pole pairs.

The mechanical dynamics of the motor are described by

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \quad (11)$$

where ω_m is the mechanical angular speed, J is the rotor inertia, B is the viscous friction coefficient, and T_L is the load torque.

The relationship between electrical and mechanical speeds is given by

$$\omega_e = p \omega_m \quad (12)$$

It should be noted that the mathematical model presented in this work corresponds to the general PMSM formulation. The simulation studies are conducted using a surface-mounted PMSM (SPMSM), which represents a particular case of the general model where $L_d = L_q$. Therefore, the proposed FSS-MRAS estimation strategy is derived from the general PMSM model and is not restricted to SPMSMs, making it readily applicable to IPMSM drives as well.

2.4. Vehicle-Level Control Strategy

The reference vehicle speed is generated based on a standard driving cycle, representing realistic operating conditions of electric vehicles [18]. This reference is processed through a vehicle-level control layer to determine the required traction torque.

Specifically, the torque demand is obtained using a nonlinear mapping between the accelerator pedal position and the motor speed through a predefined lookup table. This method allows realistic simulation of the driving conditions and also guarantees smooth torque production in all operating regimes.

2.5. Field-Oriented Control Strategy

The technique of field-oriented control (FOC) is used to control the PMSM drive because FOC provides independent control of the torque and flux components [11,17]. Through conversion of three-phase stator variables into synchronous reference frames (d–q reference frames), the PMSM may be controlled just like a separately excited DC motor.

In the implemented FOC scheme, the stator current is decomposed into two orthogonal components in the synchronous d–q reference frame. The d-axis current is associated with the flux component, whereas the q-axis current directly controls the electromagnetic torque. Since the PMSM considered in this study is a surface-mounted machine with nearly equal d- and q-axis inductances, the d-axis current reference is regulated to zero to achieve maximum torque-per-ampere operation, while the q-axis current is controlled to satisfy the required torque demand [17].

The control structure is made up of the internal current control loops using PI regulators, plus the coordinate transformations from the Clarke–Park transformation technique. The resulting voltages are fed into the inverter to control the PMSM [11].

The use of field-oriented control (FOC) ensures a robust and familiar control environment, allowing the proposed sensorless estimation technique to be effectively integrated within the overall system.

2.6. Conventional Sensorless Speed Estimation Using MRAS

The MRAS is a popular sensorless control strategy employed in the estimation of the rotor speed of PMSMs owing to its simplicity, lightweight computation requirements, and acceptable level of performance regardless of the operational circumstances [11,17]. In the MRAS approach, the two models that form the basis of comparison are the reference model and the adjustable model.

The reference model in PMSM drive control systems is typically not influenced by the rotor speed, whereas the adjustable model is directly dependent upon the rotor speed. The difference between the outputs of both models is employed for creating an estimation error that is further manipulated using an adaptation process to yield the rotor speed estimation [11,17].

Considering the PMSM mathematical model in the synchronous rotating reference frame, the stator current dynamics are given by

$$\frac{di_d}{dt} = -\frac{R_s}{L_d}i_d + \omega_r \frac{L_q}{L_d}i_q + \frac{v_d}{L_d} \quad (13)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q}i_q - \omega_r \frac{L_d}{L_q}i_d + \frac{v_q}{L_q} - \omega_r \frac{\lambda_m}{L_q} \quad (14)$$

where i_d and i_q are the stator currents, v_d and v_q are the stator voltages, R_s is the stator resistance, L_d and L_q are the d - and q -axis inductances, λ_m is the permanent magnet flux linkage, and ω_r is the electrical rotor speed.

To facilitate the MRAS formulation, modified current and voltage variables can be introduced, enabling the construction of the reference and adjustable models. The reference model utilizes measured quantities, whereas the adjustable model is driven by the estimated rotor speed [11,17].

The estimation error is formulated based on the mismatch between the currents of the reference and adjustable models as

$$e = \frac{L_q}{L_d}i_d\hat{i}_q - \frac{L_d}{L_q}\hat{i}_d i_q - \frac{\lambda_m}{L_q}(i_q - \hat{i}_q) + \hat{i}_q\hat{i}_d\left(\frac{L_d}{L_q} - \frac{L_q}{L_d}\right) \quad (15)$$

where $\hat{i}_d$ and $\hat{i}_q$ are the estimated currents obtained from the adjustable model.

This error signal is used as the input to the adaptation mechanism, which is commonly implemented using a proportional–integral (PI) controller. The estimated rotor speed is therefore updated as

$$\hat{\omega}_r = K_p e + K_i \int e \, dt \quad (16)$$

where $\hat{\omega}_r$ is the estimated rotor speed, and K_p and K_i are the proportional and integral gains, respectively.

This estimated rotor speed will be continuously adjusted until there is convergence in the estimation process, meaning that the difference between the reference model and the adjustable model becomes minimized. With respect to the classical application of MRAS schemes, the continuous adjustment process usually involves the use of a PI controller [11,17].

The overall structure of the conventional MRAS scheme, including the reference model, adjustable model, and error calculation stage, is illustrated in Figure 2. The adaptation mechanism of the conventional MRAS is illustrated in Figure 3, where the estimation error is processed using a PI controller to generate the estimated rotor speed.

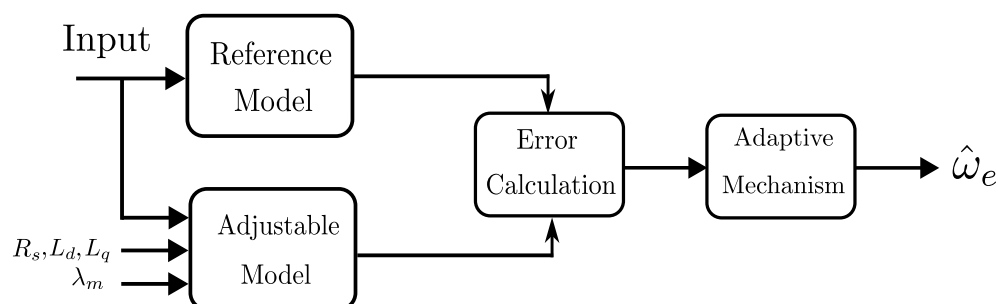


Figure 2. Block diagram of the conventional MRAS algorithm for speed estimation.

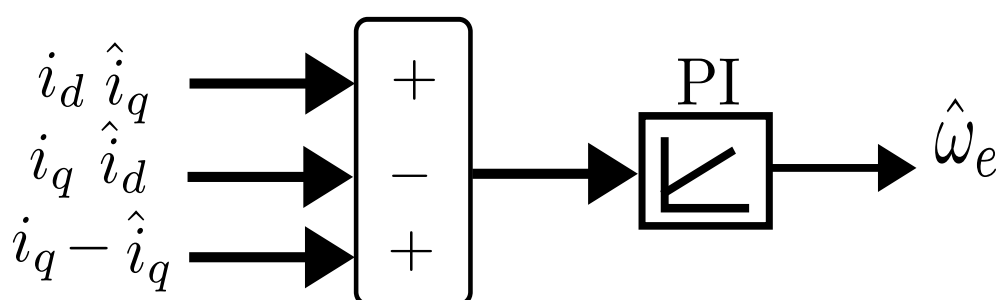


Figure 3. Adaptive mechanism of the conventional MRAS algorithm.

Despite being easy to implement, efficient, and accurate, the traditional MRAS suffers from a strong dependency on the precise adjustment of the PI controller gains. Indeed, the use of fixed PI gains is unlikely to result in satisfactory performance in a broad range of operation, especially when encountering varying dynamics or uncertainties in the model parameters. It thus becomes essential to propose an improved approach that does not rely on any PI tuning, which will be discussed in the next section.

To provide a comprehensive understanding of the overall control implementation, the complete conventional sensorless control structure is presented in Figure 4.

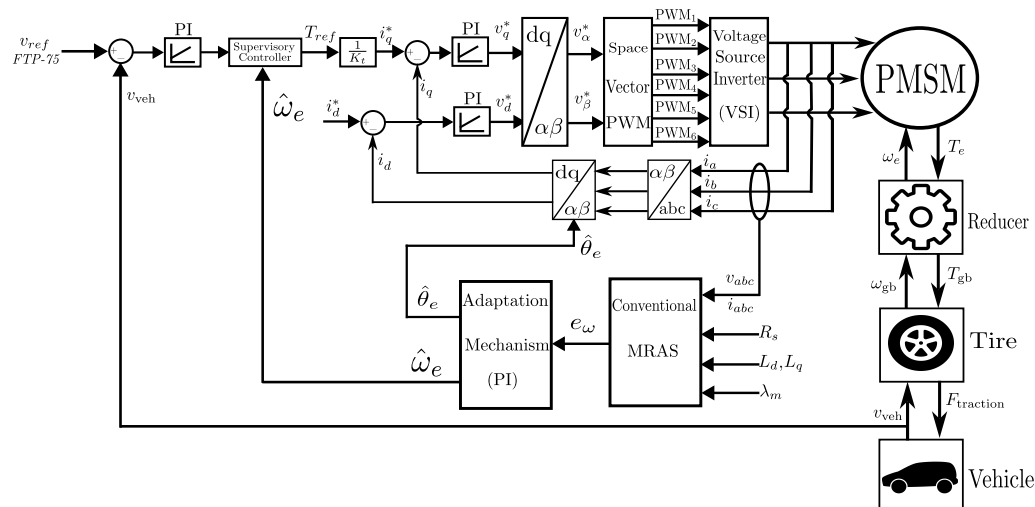


Figure 4. Overall control architecture of the electric vehicle (EV) drive system based on a conventional MRAS observer for sensorless PMSM operation.

3. Proposed FSS-MRAS for PMSM-Based Electric Vehicle

To eliminate the dependency on PI controller tuning in conventional MRAS observers, a finite speed-set model reference adaptive system (FSS-MRAS) is proposed and adapted for PMSM-based electric vehicle (EV) applications.

Unlike the conventional MRAS, where the rotor speed is obtained using a PI-based adaptation mechanism, the proposed approach estimates the rotor speed by evaluating a finite set of candidate speeds and selecting the optimal one based on a predefined cost function. This concept was originally introduced for wind energy systems [14] and is herein adapted to EV drive systems operating under field-oriented control (FOC).

3.1. Principle of Operation

The proposed FSS-MRAS relies on defining a finite set of electrical rotor speeds around the previously estimated value. For each candidate speed ω_{FSS} , a corresponding rotor position is predicted as

$$\theta_{FSS}(k+1) = \theta(k) + \omega_{FSS}T_s \quad (17)$$

where T_s is the sampling time.

3.2. Reference Model

The measured three-phase stator currents are transformed into the stationary reference frame using Clarke transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (18)$$

Then, using the predicted angle θ_{FSS} , the currents are transformed into the synchronous dq frame:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta_{FSS} & \sin \theta_{FSS} \\ -\sin \theta_{FSS} & \cos \theta_{FSS} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (19)$$

These currents represent the reference model.

3.3. Adjustable Model

Similarly, the measured stator voltages are transformed:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (20)$$

$$\begin{bmatrix} \hat{v}_d \\ \hat{v}_q \end{bmatrix} = \begin{bmatrix} \cos \theta_{FSS} & \sin \theta_{FSS} \\ -\sin \theta_{FSS} & \cos \theta_{FSS} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (21)$$

The predicted currents are then obtained using the discrete-time PMSM model:

$$\hat{i}_d(k+1) = \left(1 - \frac{R_s T_s}{L_d}\right) \hat{i}_d(k) + \frac{T_s}{L_d} (\hat{v}_d + \omega_{FSS} L_q \hat{i}_q) \quad (22)$$

$$\hat{i}_q(k+1) = \left(1 - \frac{R_s T_s}{L_q}\right) \hat{i}_q(k) + \frac{T_s}{L_q} (\hat{v}_q - \omega_{FSS} L_d \hat{i}_d - \omega_{FSS} \lambda_m) \quad (23)$$

These currents represent the adjustable model.

3.4. Cost Function Formulation

The cost function is defined based on the error signal used in the conventional MRAS adaptation mechanism:

$$g_{FSS} = \left| \frac{L_q}{L_d} i_d \hat{i}_q - \frac{L_d}{L_q} \hat{i}_d i_q - \frac{\lambda_m}{L_q} (i_q - \hat{i}_q) + \hat{i}_q \hat{i}_d \left(\frac{L_d}{L_q} - \frac{L_q}{L_d} \right) \right| \quad (24)$$

This formulation ensures consistency with the conventional MRAS error while removing the need for PI-based adaptation.

3.5. Speed Selection Mechanism

A finite set of candidate speeds ω_{FSS} is evaluated around the previous estimate. For each candidate speed, the cost function is computed. The optimal speed is selected as

$$\hat{\omega}_r = \arg \min(g_{FSS}) \quad (25)$$

3.6. Implementation Strategy

To improve computational efficiency, the search is performed adaptively:

- Two initial candidates are evaluated: $\omega(k) \pm \Delta\omega$.
- The search direction is determined based on cost comparison.
- A finite speed set is explored in the selected direction.
- Early stopping is applied when the cost function reaches a predefined threshold.

In the implemented FSS-MRAS algorithm, the search process is carried out in two stages to achieve a balance between estimation accuracy and computational efficiency. Initially, two candidate rotor speeds corresponding to $\hat{\omega}_r(k) \pm 1$ are evaluated to determine the search direction based on the resulting cost function values. Subsequently, the candidate speeds are explored only in the selected direction with a search resolution of 0.1, which significantly reduces the computational burden compared with searching the entire speed range while maintaining high estimation accuracy.

Furthermore, an early stopping criterion is incorporated into the search process. The search is terminated once the minimum cost function falls below a predefined threshold, indicating that a sufficiently accurate speed estimate has been obtained. In the implemented algorithm, the stopping threshold was set to $\varepsilon = 2000$, which was empirically determined through extensive preliminary simulation studies. This value was found to provide an effective compromise between estimation accuracy and computational efficiency by avoiding unnecessary cost function evaluations while preserving the estimation performance under the considered operating conditions.

The implementation steps of the proposed FSS-MRAS are summarized in Algorithm 1, while the corresponding flowchart is illustrated in Figure 5.

3.7. Discussion

The proposed FSS-MRAS eliminates the need for PI controller tuning and replaces it with an optimization-based estimation mechanism. Consequently, the proposed estimator maintains accurate and stable speed estimation under highly dynamic operating conditions without requiring retuning of controller parameters. This feature simplifies the implementation and improves the reliability of the estimation process for electric vehicle applications operating under varying driving conditions. Furthermore, the finite search strategy ensures real-time feasibility while maintaining high estimation accuracy.

Algorithm 1 Proposed FSS-MRAS Algorithm.

```

1: Initialize  $\hat{\omega}_r(k)$  and  $\theta(k)$ 
2: Define sampling time  $T_s$  and speed increment  $\Delta\omega$ 
3: for each sampling instant do
4:   Measure stator currents and voltages
5:   Transform to  $\alpha\beta$  frame
6:   Generate two candidate speeds:


$$\omega_1 = \hat{\omega}_r(k) + \Delta\omega, \quad \omega_2 = \hat{\omega}_r(k) - \Delta\omega$$


7:   for  $i = 1, 2$  do
8:     Predict rotor position:


$$\theta_i(k+1) = \theta(k) + \omega_i T_s$$


9:     Compute  $(i_d, i_q)$  and  $(\hat{i}_d, \hat{i}_q)$ 
10:    Compute cost function:


$$g_i = \left| \frac{L_q}{L_d} i_d \hat{i}_q - \frac{L_d}{L_q} \hat{i}_d i_q - \frac{\lambda_m}{L_q} (i_q - \hat{i}_q) + \hat{i}_q \hat{i}_d \left( \frac{L_d}{L_q} - \frac{L_q}{L_d} \right) \right|$$


11:   end for
12:   if  $g_1 < g_2$  then
13:     Select search direction:  $\omega > \hat{\omega}_r$ 
14:   else
15:     Select search direction:  $\omega < \hat{\omega}_r$ 
16:   end if
17:   Initialize  $g_{\min} = \infty$ 
18:   for each  $\omega_{FSS}$  in selected direction do
19:     Predict  $\theta(k+1)$ 
20:     Compute  $(i_d, i_q)$  and  $(\hat{i}_d, \hat{i}_q)$ 
21:     Compute:


$$g_{FSS} = \text{same cost function}$$


22:     if  $g_{FSS} < g_{\min}$  then
23:        $g_{\min} = g_{FSS}$ 
24:        $\hat{\omega}_r(k) = \omega_{FSS}$ 
25:     end if
26:     if  $g_{\min} < \varepsilon$  then
27:       break
28:     end if
29:   end for
30:   Update rotor position:


$$\theta(k+1) = \theta(k) + \hat{\omega}_r(k) T_s$$


31: end for

```

The overall structure of the proposed FSS-MRAS-based electric vehicle drive system is illustrated in Figure 6. The system integrates the supervisory control, current regulation loops, space vector PWM inverter, PMSM drive, and vehicle dynamics, along with the proposed FSS-MRAS estimator for accurate speed estimation.

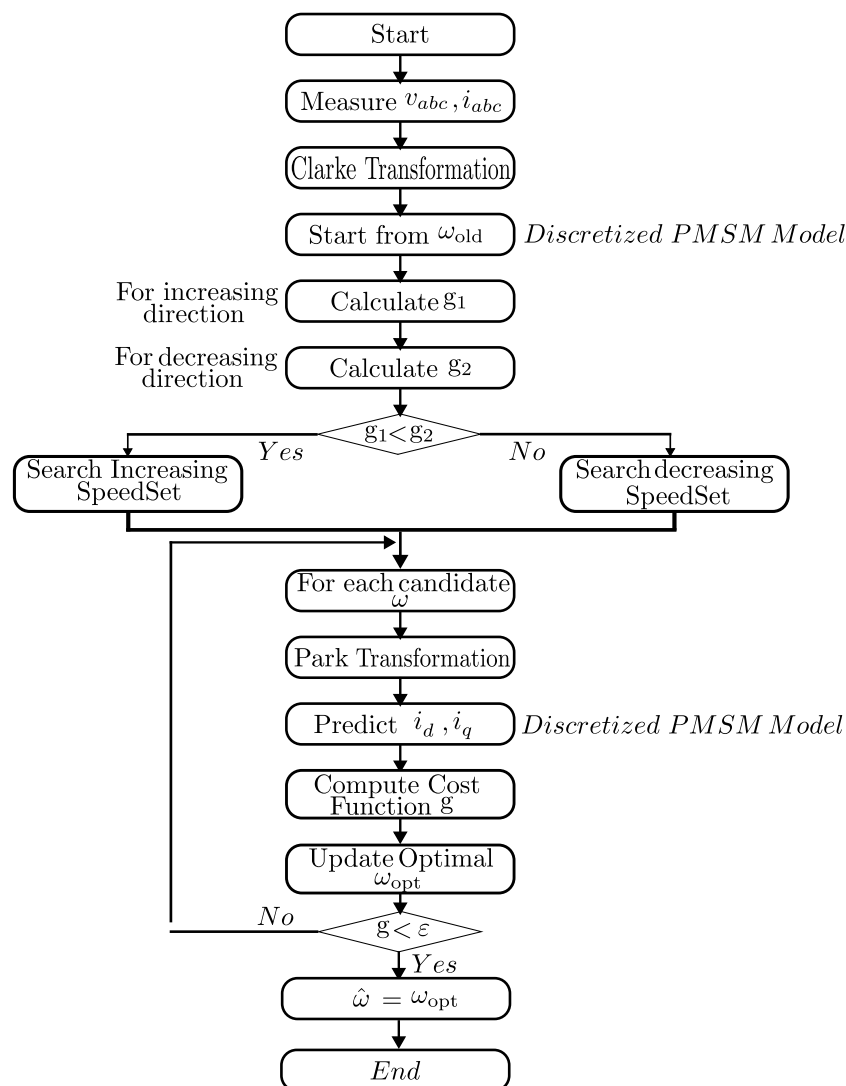


Figure 5. Flowchart of the proposed FSS-MRAS algorithm for PMSM-based electric vehicle system.

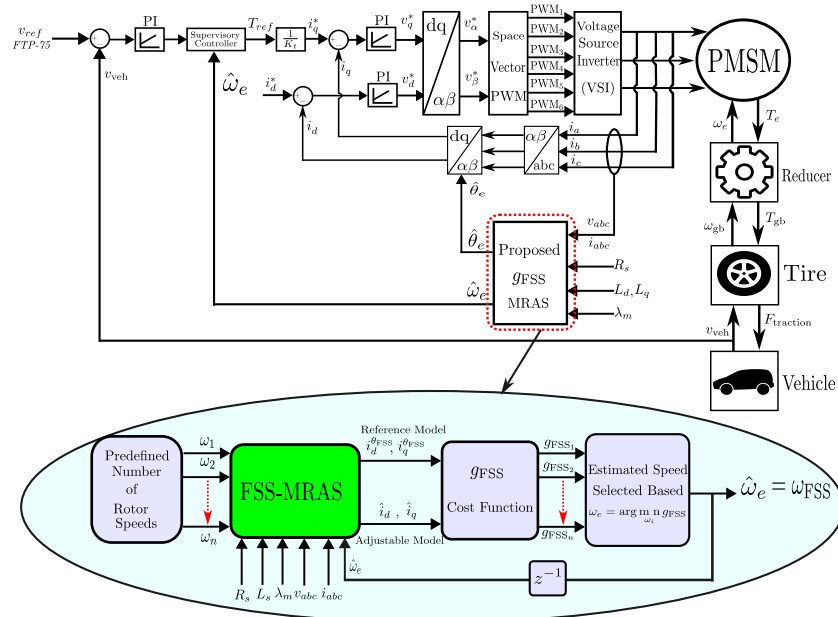


Figure 6. Overall structure of the sensorless proposed FSS-MRAS-based electric vehicle drive system, including the PMSM drive, control loops, and vehicle dynamics.

4. Simulation Results

The proposed sensorless control strategy is evaluated using MATLAB/Simulink R2023b environment. The system under study consists of a PMSM drive integrated within an electric vehicle (EV) model, including battery, drivetrain, and longitudinal vehicle dynamics.

The EV model considers the main resistive forces acting on the vehicle, including aerodynamic drag and rolling resistance. The vehicle dynamics are governed by the traction force generated by the PMSM through a gear transmission system.

The PMSM is controlled using field-oriented control (FOC), where the d -axis current is regulated to zero to ensure maximum torque per ampere operation, while the q -axis current is controlled to follow the torque demand.

The system is subjected to the Federal Test Procedure (FTP-75) driving cycle, which represents a standardized urban driving profile characterized by frequent acceleration, deceleration, and stop-and-go conditions. This driving cycle provides a realistic and highly dynamic test scenario for evaluating the performance of sensorless control strategies in EV applications.

The sensorless operation is achieved using two estimation techniques: the conventional MRAS and the proposed FSS-MRAS. Both methods are tested under identical operating conditions to ensure a fair comparison.

The sampling time for the control system is set to $T_s = 100 \mu\text{s}$. The main parameters of the EV and PMSM used in the simulation are summarized in Table 1.

The torque–speed characteristics of the PMSM used in this study are illustrated in Figure 7, showing the relationship between the developed electromagnetic torque and the rotor speed over the operating range.

Table 1. Parameters of the PMSM and EV system.

Parameter	Symbol	Value
Vehicle mass	m	2200 kg
Wheel radius (205/65R15)	r_w	0.37 m
Aerodynamic coefficient	c	0.28
Rolling resistance coefficient	f_{rr}	0.014
Gravitational acceleration	g	9.81 m/s ²
Transmission efficiency	η_T	0.9
Gear ratio	i_g	8
Maximum speed	—	15,000 rpm
Stator resistance	R_s	15 m Ω
d -axis inductance	L_d	0.202 mH
q -axis inductance	L_q	0.202 mH
PM flux linkage	λ_m	0.094 Wb
Battery capacity	—	55 kWh
Sampling time	T_s	100 μs

4.1. Driving Cycle Tracking Performance

To validate the effectiveness of the implemented electric vehicle (EV) drive system, the vehicle speed is evaluated under the FTP-75 driving cycle. Figure 8 illustrates the reference speed profile along with the actual EV speed.

It can be clearly observed that the actual vehicle speed closely follows the reference driving cycle over the entire simulation period. The tracking performance remains accurate under both low-speed and high-speed operating conditions, including frequent acceleration and deceleration phases.

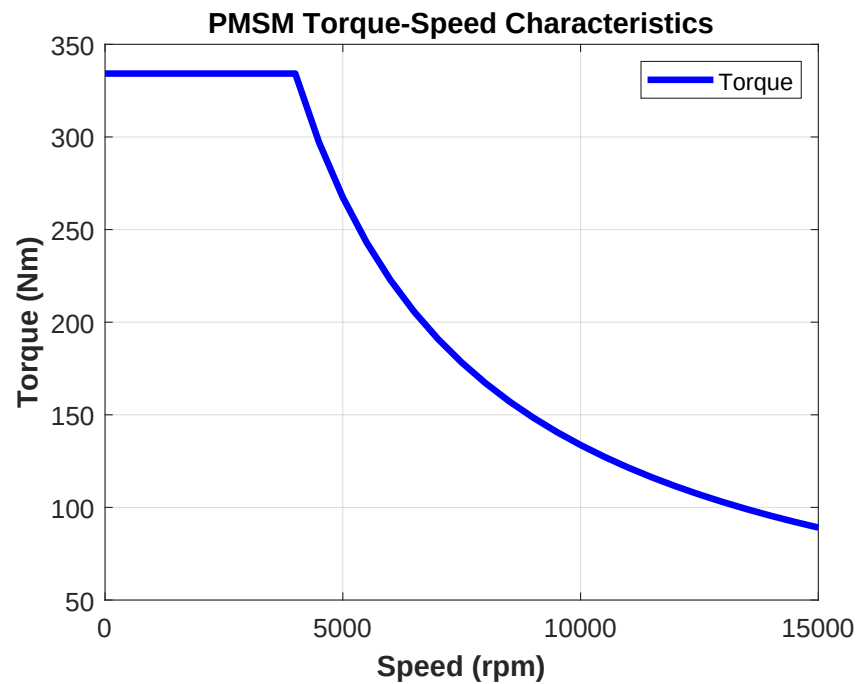


Figure 7. Torque–speed characteristics of the PMSM employed in the EV drive system, showing the variation in electromagnetic torque with rotor speed over the operating range.

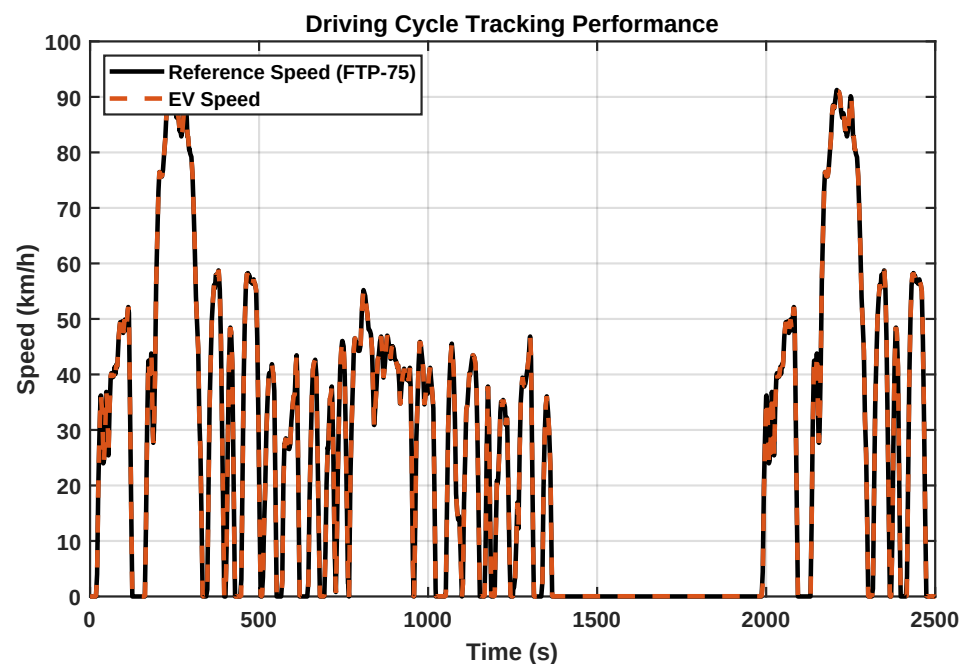


Figure 8. Reference and actual EV speed under the FTP-75 driving cycle using the proposed FSS-MRAS sensorless control.

Figure 9 shows the respective speed-tracking error. The error stays quite low at all times, with slight excursions taking place during fast changes in speed. This is an anticipated consequence of the dynamics of the system and the limitations of actuators.

The maximum tracking error remains within a very small range relative to the operating speed, indicating high tracking accuracy.

On the whole, it is clear that the developed control system has been able to track the driving cycle accurately, thus forming an ideal basis for analyzing the effectiveness of the suggested sensorless estimation approach.

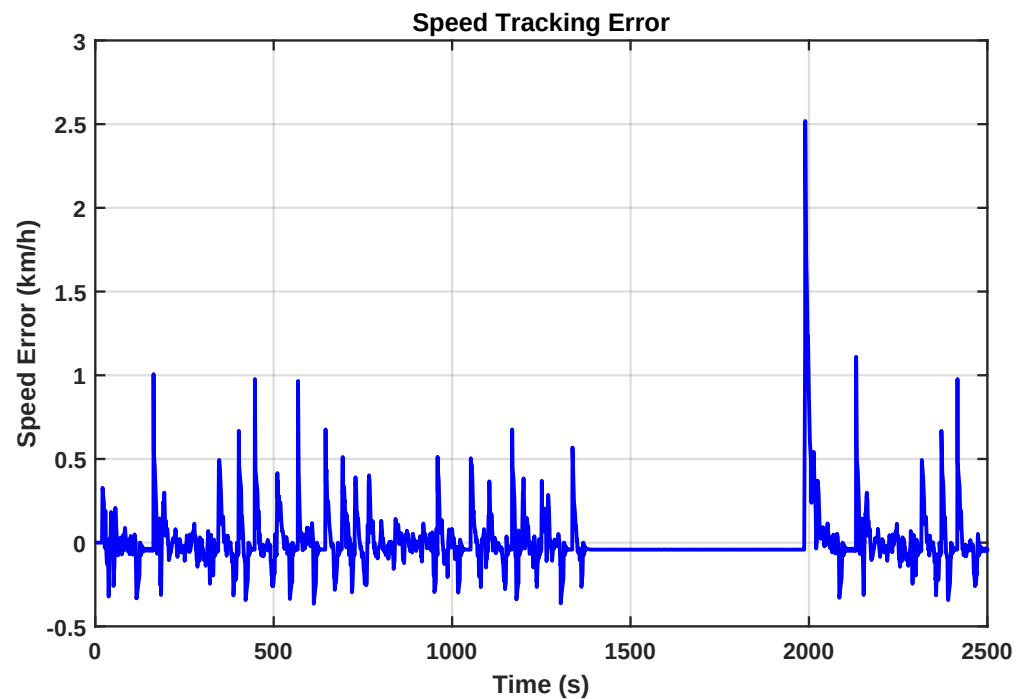


Figure 9. Speed tracking error of the EV under the FTP-75 driving cycle.

4.2. Comparison with Conventional MRAS

To ensure a fair comparison, both the conventional MRAS and the proposed FSS-MRAS are evaluated under identical operating conditions for the first 150 s of the FTP-75 driving cycle. The estimated rotor speed obtained from both methods is compared with the actual speed, as shown in Figure 10.

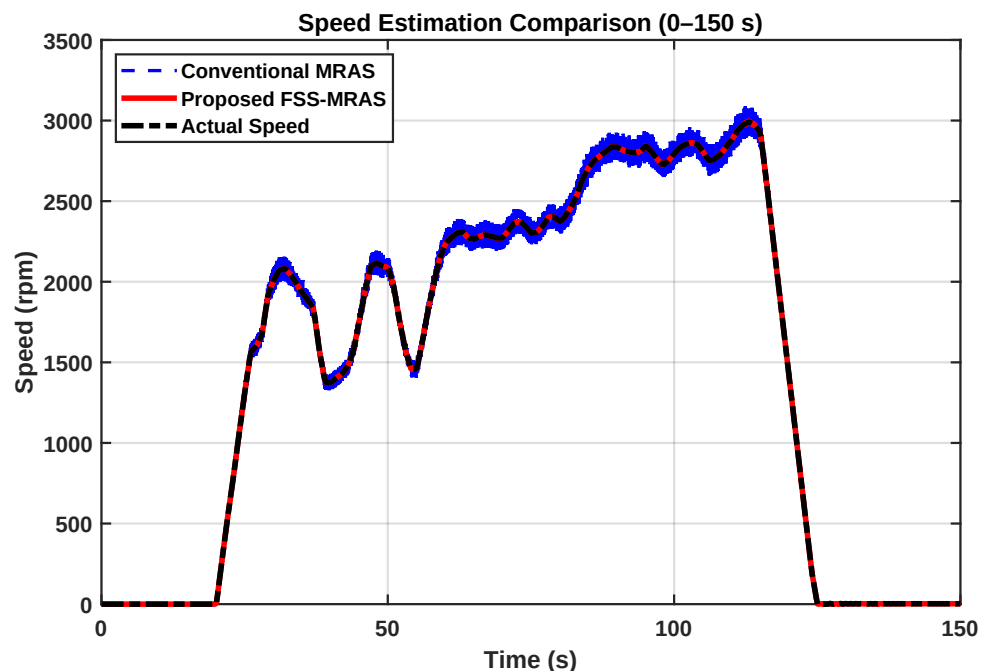


Figure 10. Comparison of motor actual speed, conventional MRAS, and proposed FSS-MRAS estimated speed for the first 150 s of the FTP-75 driving cycle.

It can be observed that both estimation methods are capable of tracking the actual speed under dynamic operating conditions. However, the conventional MRAS exhibits noticeable high-frequency oscillations around the actual speed, particularly during tran-

sient conditions. In contrast, the proposed FSS-MRAS provides a significantly smoother estimation that closely matches the actual speed.

The estimation error of the speed for both the schemes is shown in Figure 11. From this figure, it can be observed that the conventional MRAS exhibits significant oscillations in its estimation error of around ± 100 rpm. However, the suggested FSS-MRAS scheme provides an efficient solution, which significantly reduces the estimation error, keeping it near zero.

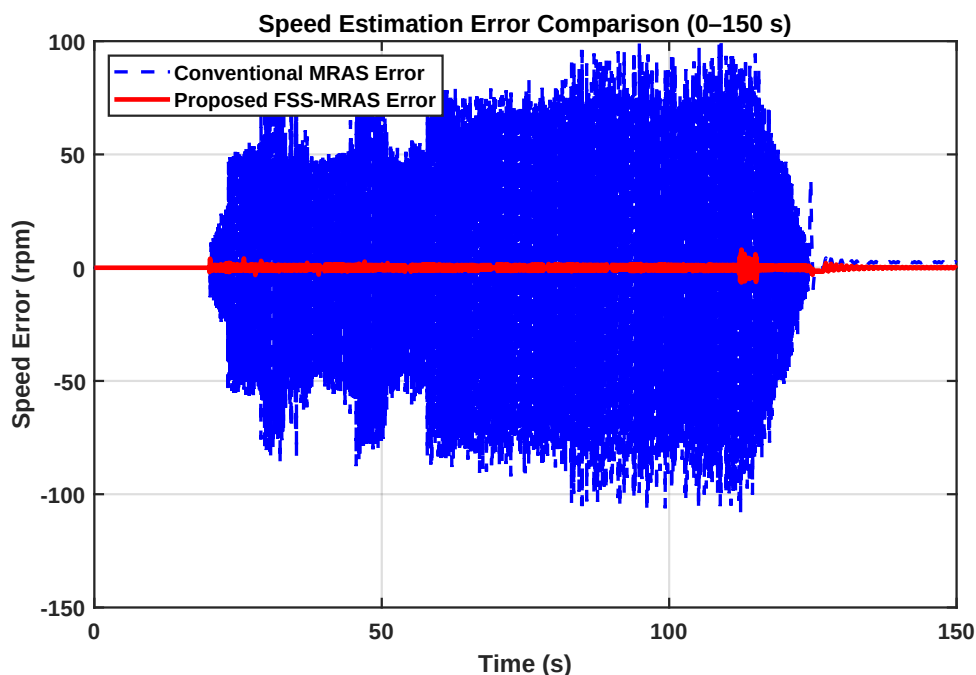


Figure 11. Motor speed estimation error comparison between conventional MRAS and proposed FSS-MRAS for the first 150 s.

In addition, proper tuning of the proportional integral controller parameters is needed for the traditional MRAS approach to obtain good results, adding another layer of complexity in implementation. The newly proposed FSS-MRAS, however, does not require any tuning and offers stable results.

These results clearly demonstrate that the proposed FSS-MRAS significantly improves estimation accuracy, reduces oscillations, and enhances robustness compared to the conventional MRAS.

4.3. Performance Under Full Driving Cycle

To validate the robustness of the proposed method, the FSS-MRAS is evaluated under the full FTP-75 driving cycle. The estimated rotor speed is compared with the actual speed over the entire simulation duration, as illustrated in Figure 12.

It is clear that the developed FSS-MRAS algorithm effectively estimates the exact rotor speed in all operational regions, such as low, medium, and high speeds. The algorithm operates effectively during very dynamic transients, with no divergences or instabilities observed in its performance.

Speed estimation error for this case is shown in Figure 13. Error mostly stays around zero, except some errors at fast accelerating/decelerating periods. Speed estimation error is constrained by almost ± 40 rpm, which shows high precision and reliability of the proposed algorithm.

In addition, the current results have been shown in Figures 14 and 15. As can be observed from the results, the d-axis current remains centered around zero with minor

deviations, which signifies that the system is properly decoupled and operating as desired under field-oriented control. On the other hand, the q-axis current tracks the reference current accurately.

On the whole, from the results obtained, it is possible to conclude that the presented FSS-MRAS can accurately estimate the velocity of electric vehicles without using cumbersome tuning procedures.

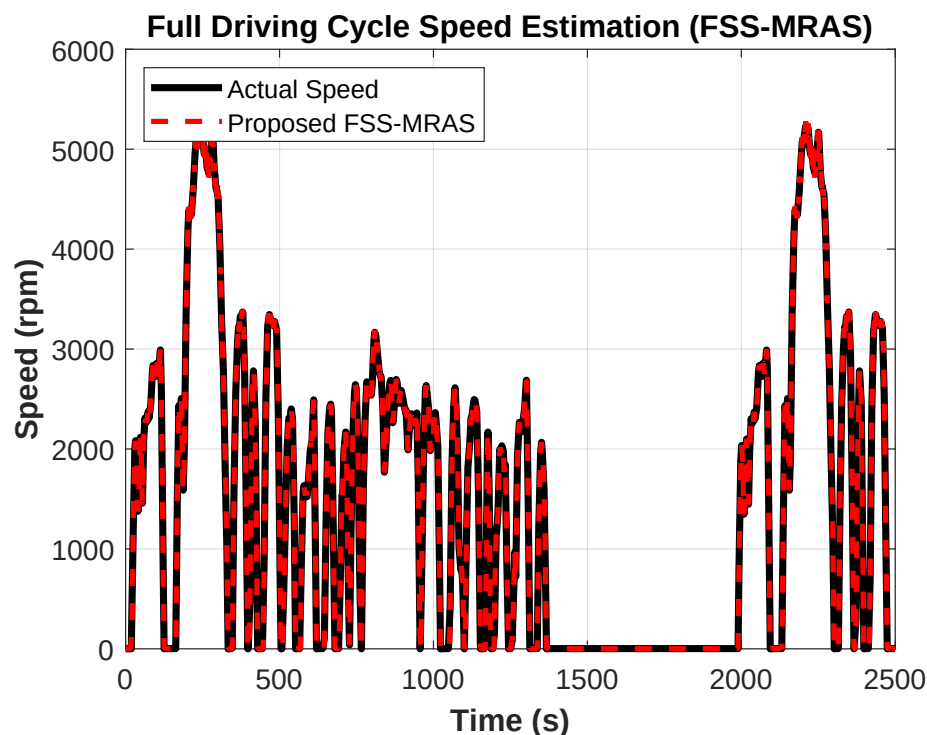


Figure 12. PMSM speed estimation using the proposed FSS-MRAS under the FTP-75 driving cycle.

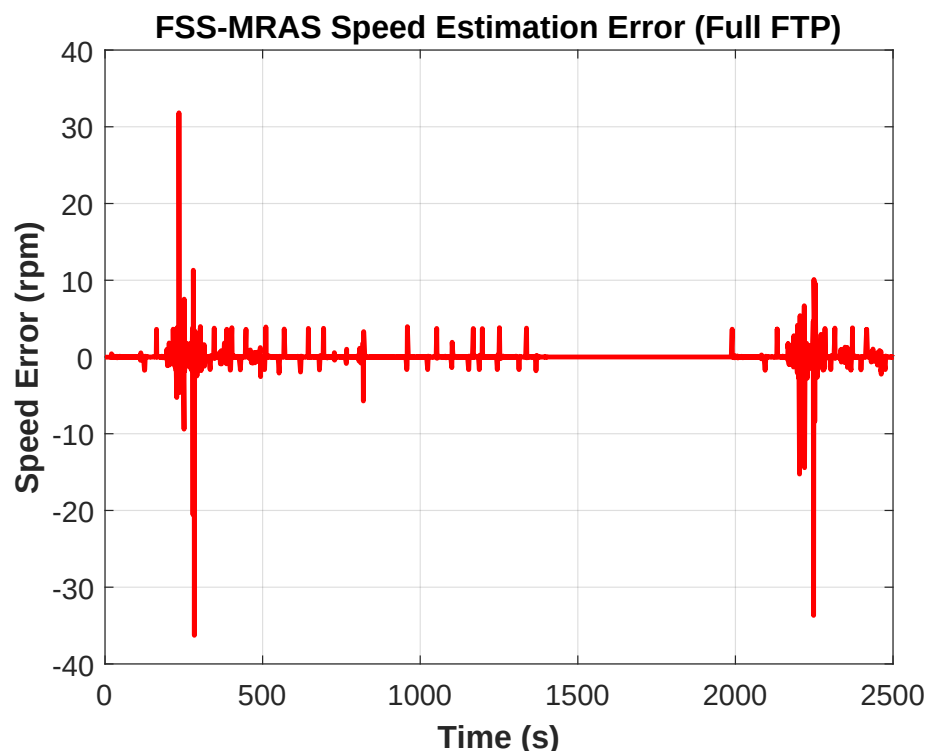


Figure 13. Speed estimation error of the proposed FSS-MRAS under the full FTP-75 driving cycle.

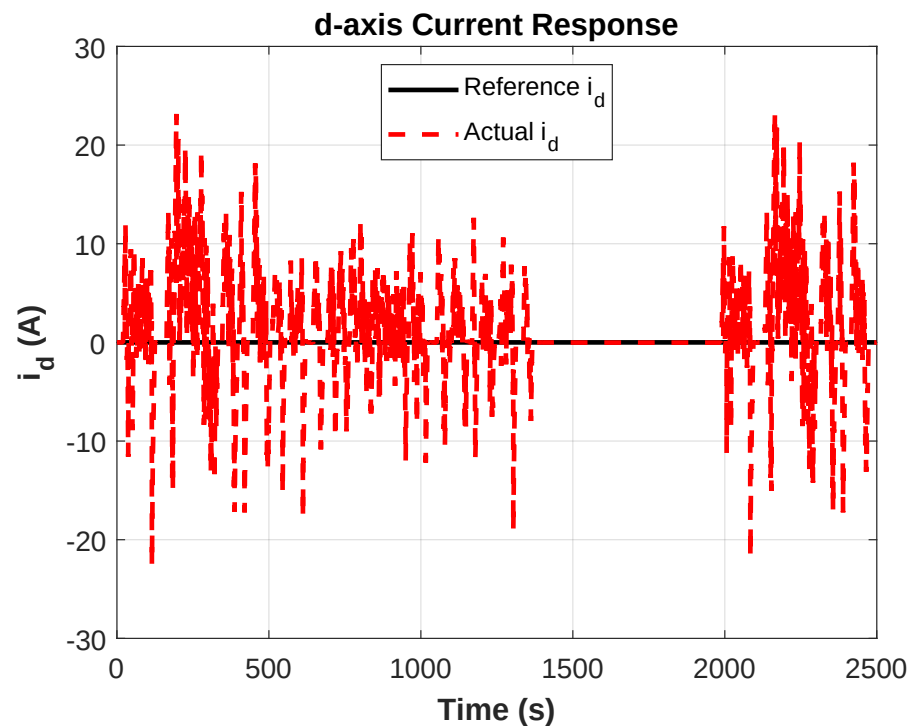


Figure 14. d-axis current response under the FTP-75 driving cycle, showing effective decoupling with the current maintained close to zero.

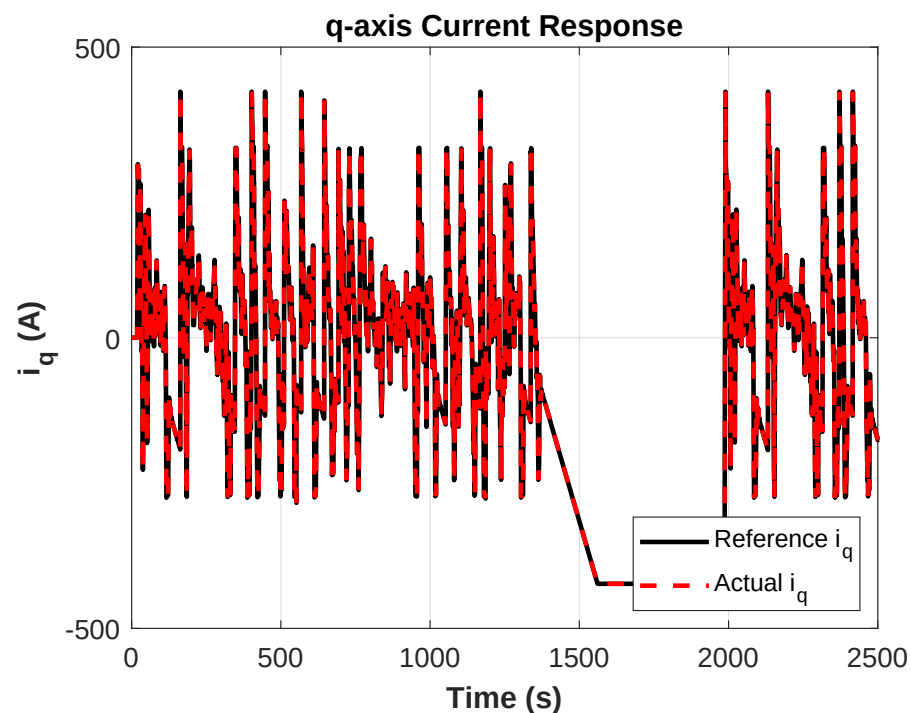


Figure 15. q-axis current response under the FTP-75 driving cycle, demonstrating accurate tracking of the reference torque-producing current.

4.4. Discussion and Comparative Analysis

From the results obtained, it is clear that both the traditional MRAS method and the FSS-MRAS technique are capable of estimating the speed with accuracy during dynamic operation. The primary distinction between the two methods lies in their robustness and implementation complexity.

The MRAS's performance depends heavily on the design of the PI/PID controller for adaptation. Such tuning of the controller is usually difficult and may take a lot of time, especially when the operation conditions change. It could lead to degradation in the estimator performance, which could sometimes result in oscillations and even instability under fast transients.

However, in contrast to this, the suggested FSS-MRAS eliminates the requirement for any controller tuning since it makes use of an algorithm that selects the speed set through prediction of future states. The simplicity of the design procedure is achieved by overcoming one of the major drawbacks of the standard MRAS.

Furthermore, the proposed approach achieves an estimation accuracy that is comparable to the conventional MRAS. This is reflected in the close tracking between the estimated and actual speeds, as well as the bounded estimation error observed throughout the driving cycle. These results highlight that the proposed method is able to combine simplicity with reliable performance.

Implementation-wise, the lower number of computations involved, along with the lack of a requirement for controller tuning, makes the FSS-MRAS approach preferable for real-time implementations in EVs.

Thus, it may be concluded that the suggested FSS-MRAS technique successfully compensates for the major drawback of the classical MRAS approaches—namely, tuning of the controllers—and ensures accurate estimations as shown in Table 2.

Table 2. Comparison between conventional MRAS and proposed FSS-MRAS.

Feature	Conventional MRAS	Proposed FSS-MRAS
Controller tuning	Required	Not required
Adaptation mechanism	PI/PID-based	Predictive finite speed set
Performance under transients	Moderate	High
Computational complexity	Moderate	Low
Implementation effort	High	Low
Estimation accuracy	High	High (with reduced tuning effort)
Stability margin	Dependent on tuning	Inherently robust

5. Conclusions

This paper presented a tuning-free finite speed-set model reference adaptive system (FSS-MRAS) for sensorless speed estimation of PMSM drives in electric vehicle applications. The proposed approach eliminates the need for conventional PI/PID-based adaptation mechanisms by introducing a predictive finite speed-set selection strategy.

The developed solution has been evaluated using the FTP-75 drive cycle test, reflecting practical and very dynamic operation of an actual EV. It can be seen from the results that the implemented finite speed-set-based MRAS ensures precise speed estimation, with the error not exceeding about ± 40 rpm at the transient stage and reaching nearly zero values when running at steady state.

As compared to the traditional MRA solution, the proposed algorithm offers better realization because there is no need for adjusting the controller and providing comparable, even superior, speed estimation quality. Another advantage is that the estimator is stable throughout the whole cycle and does not diverge nor shows any sign of oscillatory behavior.

Such properties demonstrate that the developed estimator could be successfully used in real-world electric vehicles because of high stability and other valuable qualities. Further studies will include practical evaluation in an experimental environment as well as implementation on embedded systems.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric Vehicle
PMSM	Permanent Magnet Synchronous Motor
IPMSM	Interior Permanent Magnet Synchronous Motor
MRAS	Model Reference Adaptive System
FSS-MRAS	Finite Speed-Set Model Reference Adaptive System
FOC	Field-Oriented Control
DTC	Direct Torque Control
EKF	Extended Kalman Filter
SMO	Sliding Mode Observer
VSI	Voltage Source Inverter
SVPWM	Space Vector Pulse Width Modulation
PI	Proportional–Integral
PID	Proportional–Integral–Derivative
FTP-75	Federal Test Procedure 75 Driving Cycle
DC	Direct Current
AC	Alternating Current

References

1. de Carvalho Pinheiro, H. PerfECT Design Tool: Electric Vehicle Modelling and Experimental Validation. *World Electr. Veh. J.* **2023**, *14*, 337. <https://doi.org/10.3390/wevj14120337>.
2. Adegbahun, F.; von Jouanne, A.; Phillips, B.; Agamloh, E.; Yokochi, A. High Performance Electric Vehicle Powertrain Modeling, Simulation and Validation. *Energies* **2021**, *14*, 1493. <https://doi.org/10.3390/en14051493>.
3. Rasool, H.; El Baghdadi, M.; Rauf, A.M.; Zhaksylyk, A.; D’hondt, T.; Sarrazin, M.; Hegazy, O. Accurate Electro-Thermal Computational Model Design and Validation for Inverters of Automotive Electric Drivetrain Applications. *Appl. Sci.* **2022**, *12*, 5593. <https://doi.org/10.3390/app12115593>.
4. Aslan, E.; Yasa, Y.; Meseci, Y.; Keskin Arabul, F.; Arabul, A.Y. Comprehensive Multidisciplinary Electric Vehicle Modeling: Investigating the Effect of Vehicle Design on Energy Consumption and Efficiency. *Sustainability* **2024**, *16*, 4928. <https://doi.org/10.3390/su16124928>.
5. Dini, P.; Saponara, S.; Chakraborty, S.; Hegazy, O. Modeling, Control and Monitoring of Automotive Electric Drives. *Electronics* **2025**, *14*, 3950. <https://doi.org/10.3390/electronics14193950>.
6. Urkizu, J.; Mazuela, M.; Alacano, A.; Aizpuru, I.; Chakraborty, S.; Hegazy, O.; Vetten, M.; Klink, R. Electric Vehicle Inverter Electro-Thermal Models Oriented to Simulation Speed and Accuracy Multi-Objective Targets. *Energies* **2019**, *12*, 3608. <https://doi.org/10.3390/en12193608>.
7. Afianto, D.; Han, Y.; Yan, P.; Yang, Y.; Elbarghthi, A.F.A.; Wen, C. Optimisation and Efficiency Improvement of Electric Vehicles Using Computational Fluid Dynamics Modelling. *Entropy* **2022**, *24*, 1584. <https://doi.org/10.3390/e24111584>.

8. Wang, Y.; Yao, M.; Cao, S. Integration of Innovative Paths for Permanent Magnet Motors in Electric Vehicles: Intelligent Control, Proactive Diagnosis, and Collaborative Design. *World Electr. Veh. J.* **2025**, *16*, 630. <https://doi.org/10.3390/wevj16110630>.
9. Amini, A.; Farrokh, F.; Mahmouditabar, F.; Baker, N.J.; Vahedi, A. Enhanced Interior PMSM Design for Electric Vehicles Using Ship-Shaped Notching and Advanced Optimization Algorithms. *Energies* **2025**, *18*, 4527. <https://doi.org/10.3390/en18174527>.
10. Ibrahim, M.; Järg, O.; Seppago, R.; Rassölkin, A. Performance Optimization of a High-Speed Permanent Magnet Synchronous Motor Drive System for Formula Electric Vehicle Application. *Sensors* **2025**, *25*, 3156. <https://doi.org/10.3390/s25103156>.
11. Adel, M.M.; Saleh, A.A.; Hassan, M.A.; Kennel, R.; Farhan, A. Efficient Sensorless Speed Predictive Control without Weighting Factors for PMSM Drive Based on MRAS Estimator. *J. Appl. Sci. Eng.* **2024**, *27*, 3697–3710. [https://doi.org/10.6180/jase.202412_27\(12\).0010](https://doi.org/10.6180/jase.202412_27(12).0010).
12. Xu, Y.; Yao, M.; Sun, X. Overview of Position-Sensorless Technology for Permanent Magnet Synchronous Motor Systems. *World Electr. Veh. J.* **2023**, *14*, 212. <https://doi.org/10.3390/wevj14080212>.
13. Nicola, M.; Nicola, C.I. Sensorless Predictive Control for PMSM Using MRAS Observer. In Proceedings of the 2019 International Conference on Electromechanical and Energy Systems (SIELMEN), Craiova, Romania, 9–11 October 2019; pp. 1–7. <https://doi.org/10.1109/SIELMEN.2019.8905815>.
14. Hassan, M.A.; Adel, M.M.; Farhan, A.; Saleh, A.A. Finite Speed-Set Model Reference Adaptive System Based on Sensorless Control of Permanent Magnet Synchronous Generators for Wind Turbines. *Machines* **2024**, *12*, 429. <https://doi.org/10.3390/machines12070429>.
15. Jinadasa, L.; Yadav, P.; Wray, A.; Ebrahimi, K. Experimental-Based Simulation of EV Drive Mechanism. *Machines* **2025**, *13*, 100. <https://doi.org/10.3390/machines13020100>.
16. Ramesh, P.; Umavathi, M.; Bharatiraja, C.; Ramanathan, G.; Athikkal, S. Development of a PMSM motor field-oriented control algorithm for electrical vehicles. *Mater. Today Proc.* **2022**, *65*, 176–187. <https://doi.org/10.1016/j.matpr.2022.06.080>.
17. Abd El Maguid Ahmed, W.; Adel, M.M.; Taha, M.; Saleh, A.A. PSO technique applied to sensorless field-oriented control PMSM drive with discretized RL-fractional integral. *Alex. Eng. J.* **2021**, *60*, 4029–4040. <https://doi.org/https://doi.org/10.1016/j.aej.2021.02.049>.
18. Fesli, U.; Ozdemir, M.B. Electric Vehicles: A Comprehensive Review of Technologies, Integration, Adoption, and Optimization. *IEEE Access* **2024**, *12*, 140908–140931. <https://doi.org/10.1109/ACCESS.2024.3469054>.

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