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Sliding innovation filter to estimate Power Converters of Electric Vehicles

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ABSTRACT

The sliding innovation filter (SIF) is a recently developed estimation technique that has gained widespread use. It is a predictor-corrector filter that utilizes a hyperplane and applies a force to allow estimates to fluctuate about it. SIF belongs to the same family as the smooth variable structure filter and sliding mode observer, and it is stable and robust in the face of uncertainties. This paper discusses the use of SIF for estimating the states of Power Converters, which play a crucial role in Electric Vehicles (EVs) by converting high-voltage DC from the battery to low-voltage AC used by the motor. One of the main challenges in Power Converters is accurately estimating their states, such as input voltage, output voltage, and inductor current, which are critical for optimal control and efficient operation. The SIF has demonstrated promising results in addressing this challenge.

Keywords: SIF, SVSF, electric vehicles, EVs, performance

1. INTRODUCTION

Filters play a crucial role in a wide range of estimation applications [1-9] by extracting meaningful information from signals and minimizing the impact of uncertainties, disruptions, and noise. The main objective of filters is to enhance the overall dynamics performance of the system [10-20] by improving the system controller. However, there are various challenges to achieving optimal performance due to the presence of several obstacles, such as limited measured signals, non-measured or hidden states, and disturbances and noise.

In the field of estimation, the sliding innovation filter (SIF) [21-29] is a commonly used filter derived from the sliding mode theory. The SIF is known for its resilience to shocks and uncertainty and employs a system model to provide an initial estimate, which is then stimulated by input from the system. The estimate is further improved using a corrective gain derived from the Lyapunov stability theorem. As a result, the SIF is categorized as a robust filter along with sliding mode observers [47-71] and smooth variable structure filters [30-46].

Despite its robustness, the performance of the SIF may not always be optimal, particularly in the presence of disruptions and noise. Additionally, when there are fewer observed signals than states, the filter becomes heavily dependent on the system and measurement matrices, which can hinder the extraction of essential information. This is especially true when non-measured states are not directly correlated with the observed states or measures, resulting in decreased accuracy and effectiveness. To address these limitations, various alternative approaches have been proposed, including integrating the SIF with other filters, such as the Regular [72-87].

Plug-in hybrid electric vehicles (PHEVs) have become increasingly popular due to their hybrid technology and ability to charge from the utility grid, leading to improved fuel efficiency and reduced pollution compared to internal combustion engine (ICE) cars. Wind and solar power are also prominent choices for producing electricity due to their environmental friendliness and economic competitiveness. PHEVs and renewable energy systems use a DC/DC power converter, inverter, and Power Factor Corrected (PFC) [88-93]. The DC/DC power converter converts the high voltage of the PHEV battery to a low voltage for the vehicle's auxiliary systems, which is then boosted to replenish the battery. In renewable energy systems, the DC/DC converter adjusts the power source's voltage to match the inverter's voltage.

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On the other hand, the inverter is responsible for converting DC power generated by the battery or renewable energy sources into AC power that can be used to drive the electric motor or to inject energy into the grid in renewable energy systems. PFC is crucial for ensuring that the grid current is in phase with the voltage, which helps reduce power loss and increase AC power production. Moreover, a comprehensive comparison of sigma-point Kalman filters and smooth variable structure filters, with applications in robotics and aerospace systems [94-112]. Recent studies have investigated a variety of adaptive Kalman filters in addition to other estimation methods in order to improve the accuracy of state estimation for a wide variety of applications. Some of these applications include battery management, motion control, vehicle running states, symmetry recognition, unmanned aerial vehicle flight trajectory tracking, smart grids, nanosatellite attitude estimation, and generator parameter estimation [113-140].
The primary objective of this research is to demonstrate and evaluate the effectiveness of the SIF as a dependable and valuable technique for assessing the states of intricate systems, such as power converters utilized in PHEVs. The article highlights the SIF's resilience in the presence of uncertainties and disruptions, as well as its ability to provide precise real-time estimates of system states.

2. METHODOLOGY

2.1 EV Battery system

Figure 1 illustrates the power circuit arrangement that is currently being used. The Power Factor Corrected (PFC) boost converter is associated with the switch SB, and switches S1 and S2 have the ability to exercise control over the bi-directional converter.

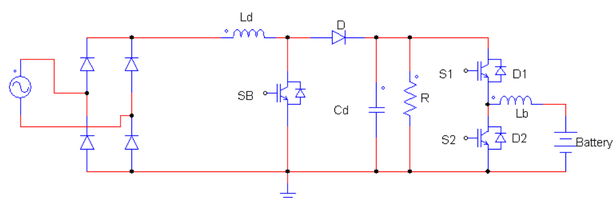


Fig. 1 Power Circuit Configuration [93]

The EV battery system has the following equations:

$$\dot{x}_1 = -(1-u)\frac{1}{L_d}x_1 + \frac{V_s}{L_d} \quad (1)$$

$$\dot{x}_2 = (1-u)\frac{1}{L_d}x_1 - \frac{1}{R_d C_d}\, x_2 \quad (2)$$

$$\dot{x}_3 = -(1-u_2)\frac{1}{L_b}x_4 + \frac{V_{bat}}{L_b} \quad (3)$$

$$\dot{x}_4 = (1-u_2)\frac{1}{C_b}x_3 - \frac{1}{R_b C_b}\, x_4 \quad (4)$$

$$\dot{x}_5 = \frac{1}{C_b}x_3 - \frac{1}{R_b C_b}\, x_5 \quad (5)$$

Where $x_i, i = 1 \ldots 5$ are current and voltage for PFC, and Bi-Directional Convertor (BDC) in boost mode, and the voltage of the latter one in Buck mode, respectively. R, C, V_s and V_{bat} are the Resistance, Capacitance, Source voltage, and battery voltage.

2.2 Sliding Innovation Filter (SIF)

The SIF is comprised of the following two steps:

1- <u>Prediction Stage</u>,

The a priori estimate/measurement, ($\hat{\mathbf{x}}_{k+1|k}$/$\hat{\mathbf{z}}_{k+1|k}$) are obtained as:

$$\hat{\mathbf{x}}_{k|k-1} = \mathbf{A}_{k-1}\hat{\mathbf{x}}_{k-1|k-1} + \mathbf{B}_{k-1}\mathbf{u}_{k-1},\ \hat{\mathbf{z}}_{k|k-1} = \mathbf{H}_k\hat{\mathbf{x}}_{k|k-1} \quad (6)$$

2- Update/Correction Stage:

The a posteriori estimate/measurements ($\hat{\mathbf{x}}_{k|k}/\hat{\mathbf{z}}_{k|k}$), are generated as:

$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \left[\mathbf{H}_k^{+}\left(\mathbf{z}_k - \hat{\mathbf{z}}_{k|k-1}\right)\right]^{\circ} sat\left(\left|\mathbf{z}_k - \hat{\mathbf{z}}_{k|k-1}\right|, \boldsymbol{\Psi}_k\right), \hat{\mathbf{z}}_{k|k} = \mathbf{H}_k \hat{\mathbf{x}}_{k|k} \tag{7}$$

Where the pseudoinverse vector of $\mathbf{H}_k$ is represented by $\mathbf{H}_k^{+}$ +, while $\boldsymbol{\Psi}_k$ refers to the boundary layer. $A^{\circ}B$ is the Schur product. The saturated function is denoted as ' sat '.

3. RESULTS AND DISCUSSION

To compare the performance of the SIF filter with the Kalman Filter (KF), we introduce uncertainties into the model assumption. This is done by deliberately providing an inaccurate model. The results are then analyzed through Monte Carlo Simulations (MCS), which repeat the simulation 1000 times. Figure 2 and Figure 3 depict the MCS root mean squared error (RMSE) and maximum absolute error (MAE) for SIF and KF, respectively. The results demonstrate that SIF has RMSE values less than 5% of the corresponding values of KF, while the MAE has values that are less than 10% of their corresponding values of KF.

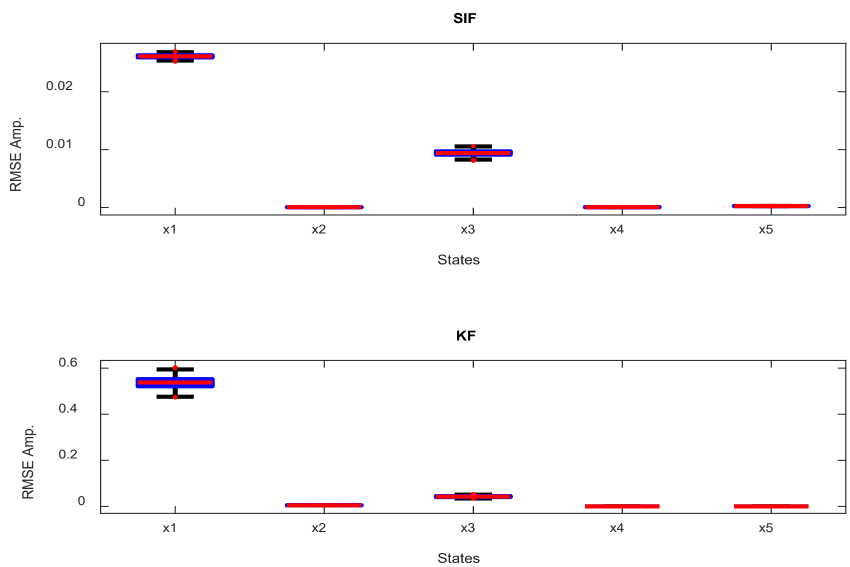


Figure 2. The MCS's RMSE

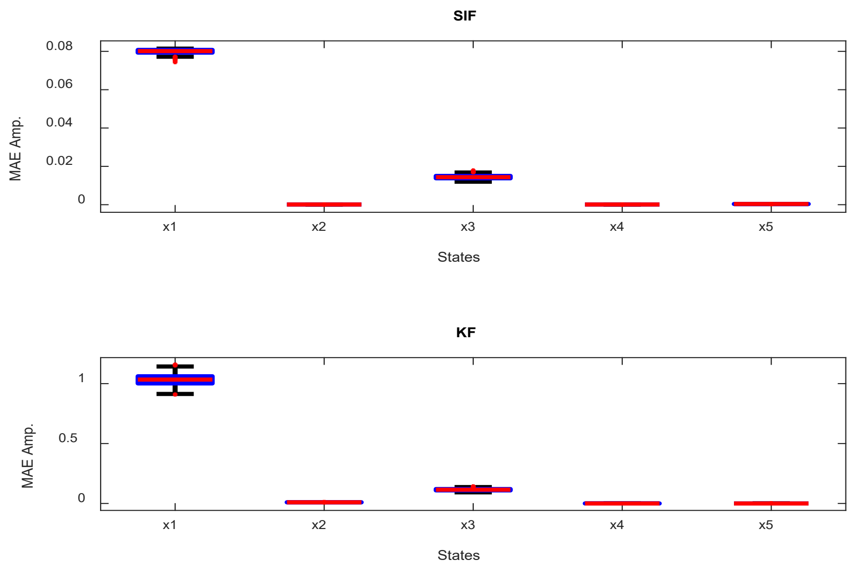
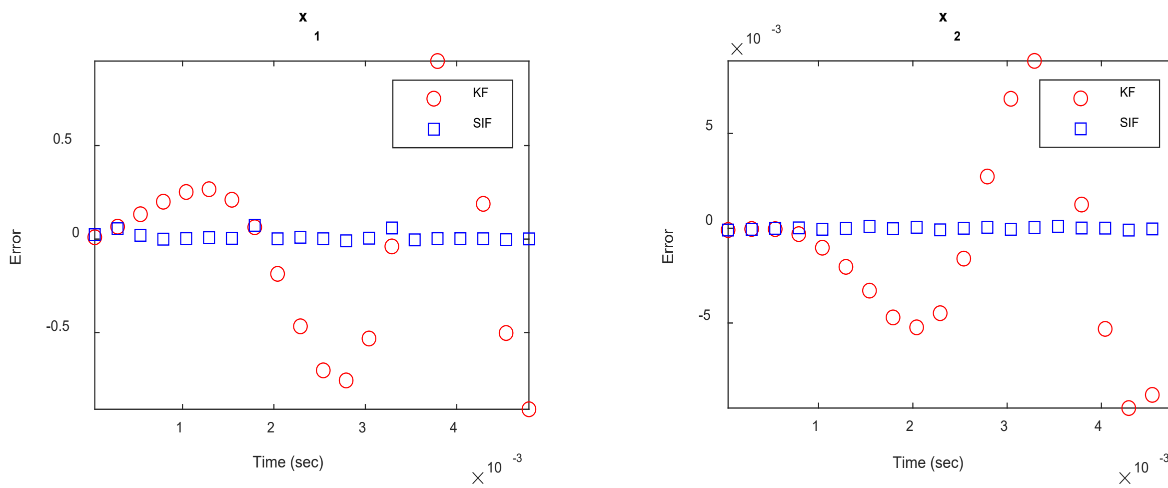
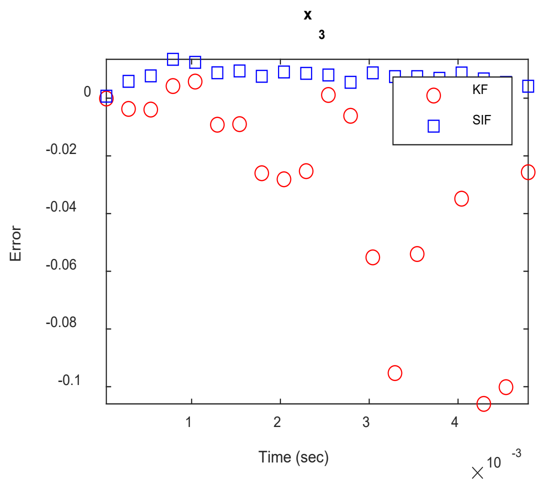


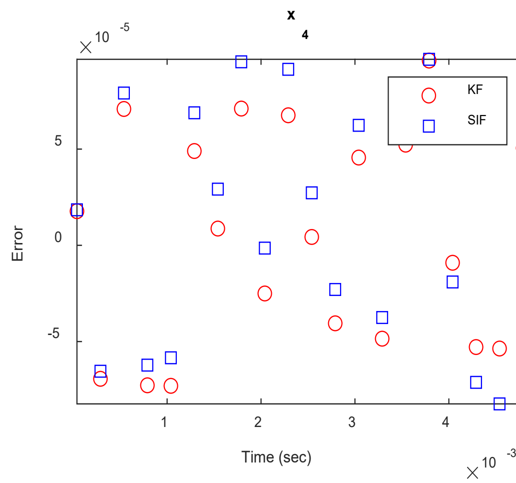
Figure 3. The MCS's MAE



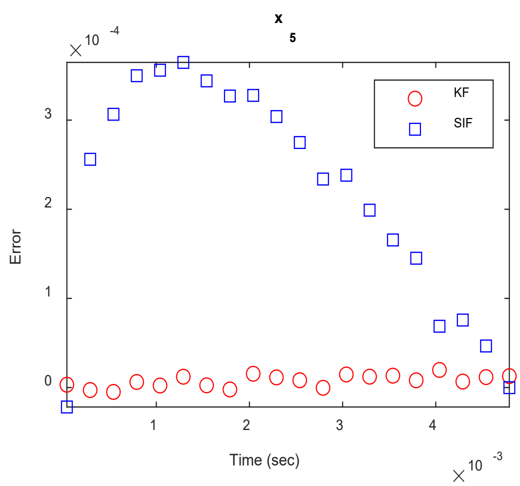
(a) (b)



(c)



(d)



(e)

Figure 4. The error of the best solution of (a) first, (b) second, (c) third, (d) fourth and (e) fifth states.

Figure 4 shows the error in the states for SIF and KF. For the first three states, the figure shows clear superiority performance for the SIF. For fourth state, both SIF and KF have similar performance. However, KF takes the lead for the fifth state, although the errors in SIF are insignificant.

4. CONCLUSION

Based on the results of the MCS and individual evaluations, the SIF outperforms the KF in 80% of the states, as evidenced by the smaller RMSE magnitude in the SIF. Figure 4 further supports the superiority of the SIF in most states. However, to determine the practicality and effectiveness of the proposed strategy in real-time applications, experimental verification is needed. Such verification could highlight any limitations or difficulties when implementing the method in real-world scenarios, and assess its performance in various operating conditions and system dynamics.

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