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Fault-Tolerant Control Strategy for Robot-Joint PMSM Drives Under Encoder Faults

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Statements and Declarations

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Abstract Encoder faults in permanent magnet synchronous motor (PMSM) drives for robot joints can cause coordinate-transformation errors and closed-loop disturbances. This paper proposes an encoder fault diagnosis and fault-tolerant control method based on fused high-frequency injection (HFI) and sliding-mode observer (SMO) estimates. Healthy-encoder closed-loop data independently calibrate the fusion weight and HFI injection voltage, allowing angle-estimation accuracy and additional high-frequency current to be tuned separately. During operation, the alignment offset between the encoder angle and fused angle estimate is updated online and frozen when either residual triggers entry into the suspect state. After fault confirmation, the encoder angle and speed feedback are isolated simultaneously. The frozen alignment offset provides temporary angle compensation during takeover and fades out within 50 ms. In closed-loop simulations, faults occurring during operation are confirmed within 16–31 ms. Across five fault cases, the post-takeover root-mean-square (RMS) control-angle error ranges from 0.363° to 1.526°. Experiments on a TI C2000 platform cover estimation from 0 to 3000 r/min and zero-speed encoder self-check with HFI startup. They also examine feedback takeover under an 800 r/min abrupt-bias fault and a 3000 r/min pulse-loss-equivalent fault. After fault confirmation, the fused estimates maintain closed-loop operation.

Keywords: permanent magnet synchronous motor; encoder fault; fault-tolerant control; high-frequency injection; sliding-mode observer; sensorless control

1 Introduction

Permanent magnet synchronous motors (PMSMs) in robot joints commonly rely on encoders to provide rotor position and speed feedback. Encoder failure can introduce coordinate-transformation errors and speed-loop disturbances, reducing servo accuracy and increasing operating risk [1]. Existing fault-detection and fault-tolerance methods can generally be grouped into hardware redundancy, analytical redundancy, and robust control [2,3]. This paper focuses on analytical-redundancy fault tolerance in robot-joint PMSM drives with cascaded speed and current control loops.

When an incremental encoder loses pulses, produces abnormal counts, becomes stuck, or suffers signal interruption, the feedback received by the controller may appear as an angle jump, a speed deviation, or a loss of output. Previous studies have investigated these faults using data-driven classification, signal-feature analysis, and current-signal detection [4–8]. This study focuses on encoder-feedback anomalies directly observable by the closed-loop controller, with emphasis on abrupt-bias, stuck-output, and pulse-loss-equivalent faults.

To maintain closed-loop operation after a position-sensor fault, previous studies have reconstructed rotor position and speed using sensorless observers or motor models [9–12]. Other studies have used signal residuals or composite observers for fault detection and feedback reconstruction [13,14]. Recent position-sensor fault studies have likewise combined fault detection with control reconfiguration to preserve PMSM operation after sensor failure [33,34]. Analytical redundancy can provide both a fault criterion and an alternative feedback signal. In practical applications, however, the estimation scheme must remain effective over the full speed range, diagnostic false alarms must be limited during normal transients, and the feedback-takeover transient must be controlled.

High-frequency injection (HFI) exploits motor saliency to estimate rotor position and provides good observability at zero and low speed. However, continuous injection introduces additional high-frequency current and associated losses [15–18]. HFI startup also requires resolution of the magnetic-polarity ambiguity in the initial position estimate [19–22]. A sliding-mode observer (SMO) relies on back electromotive force and is therefore more suitable for medium- and high-speed operation, while its accuracy can be affected by chattering, filtering delay, and parameter mismatch [23–27]. Accordingly, previous studies have combined low-speed HFI with medium- and high-speed model-based observers through speed-dependent weights or switching logic [28–32,35].

In the HFI/SMO analytical-redundancy architecture adopted in this paper, three issues directly affect fault diagnosis and feedback takeover. First, the fusion weight determines the contribution of each estimation channel, whereas the injection voltage directly affects HFI accuracy and additional high-frequency current. Using the same scheduling law for both quantities makes them difficult to tune independently. Second, the encoder angle and fused estimate contain an installation offset and a phase difference caused by estimation delay. If the alignment offset continues to be updated during fault confirmation, part of the abnormality may be absorbed, weakening the residual. Third, direct switching from the encoder angle to the fused angle can cause a discontinuity in the control coordinates. These issues are addressed by decoupled scheduling of the fusion weight and injection voltage, freezing the alignment offset when a suspect state is entered, and applying a 50 ms temporary angle compensation that fades out after takeover.

The main contributions are as follows:

(1) The fusion weight and HFI injection voltage are independently designed from calibration data characterizing the speed-dependent HFI/SMO estimation-error trends and the additional high-frequency current, and are subsequently scheduled using the estimated speed.

(2) Angle and speed residuals are constructed from an online alignment offset between the encoder and fused estimates during healthy operation. The last healthy alignment offset is frozen when either residual triggers entry into the suspect state, and a dual-path persistence criterion is used for fault confirmation.

(3) After fault confirmation, the encoder angle and speed feedback are isolated simultaneously, and the fused angle and speed are used to reconstruct the closed-loop feedback. The frozen alignment offset is used only for initial takeover compensation and fades to zero within 50 ms. The diagnosis, isolation, and takeover process is verified by closed-loop simulation and experiments on a TI C2000 platform.

2 PMSM Drive System and Encoder Fault Model

This study considers an encoder-equipped PMSM drive with cascaded speed and current control loops to investigate how encoder faults in robot-joint PMSM drives affect coordinate transformations, speed feedback, and closed-loop operation.

2.1 Structure of the PMSM Vector-Control System

Robot-joint actuators commonly integrate a permanent magnet synchronous motor, a gear reducer, and a position sensor within a compact housing. The encoder is mounted at the end of the rotor shaft and provides rotor position and speed feedback for coordinate transformations and the speed control loop. Encoder bias, stuck output, or pulse loss may cause commutation errors, current transients, and torque fluctuations. The system therefore includes an encoder-independent angle- and speed-estimation path for fault takeover.

The control-system structure is shown in Fig. 1. The system uses an outer speed loop and inner d- and q-axis current loops, with $i_d^*=0$. The encoder provides the primary feedback during normal closed-loop operation, while the HFI estimation channel and SMO run in parallel in the background.

During normal operation, the encoder outputs the rotor mechanical angle $\theta_{enc,m}$ and mechanical speed n_{enc} . After pole-pair conversion and installation-offset compensation, the control electrical angle is obtained as

$$\theta_{(enc,e)} = \text{wrap}_{2\pi}(p\theta_{(enc,m)} + \theta_0) \quad (1)$$

where p is the number of pole pairs and θ_0 is the encoder installation offset. The function $\text{wrap}_{2\pi}(\cdot)$ maps an absolute electrical angle to $[0, 2\pi)$. The encoder electrical angle is used for the Park and inverse-Park transformations, whereas the mechanical speed is used in the speed control loop.

When the encoder is healthy, its angle and speed are used as the primary closed-loop feedback, while the fused estimates provide analytical redundancy and residual monitoring. After fault confirmation, the encoder angle and speed feedback are isolated simultaneously, and the closed-loop feedback is reconstructed using the fused angle and speed estimates.

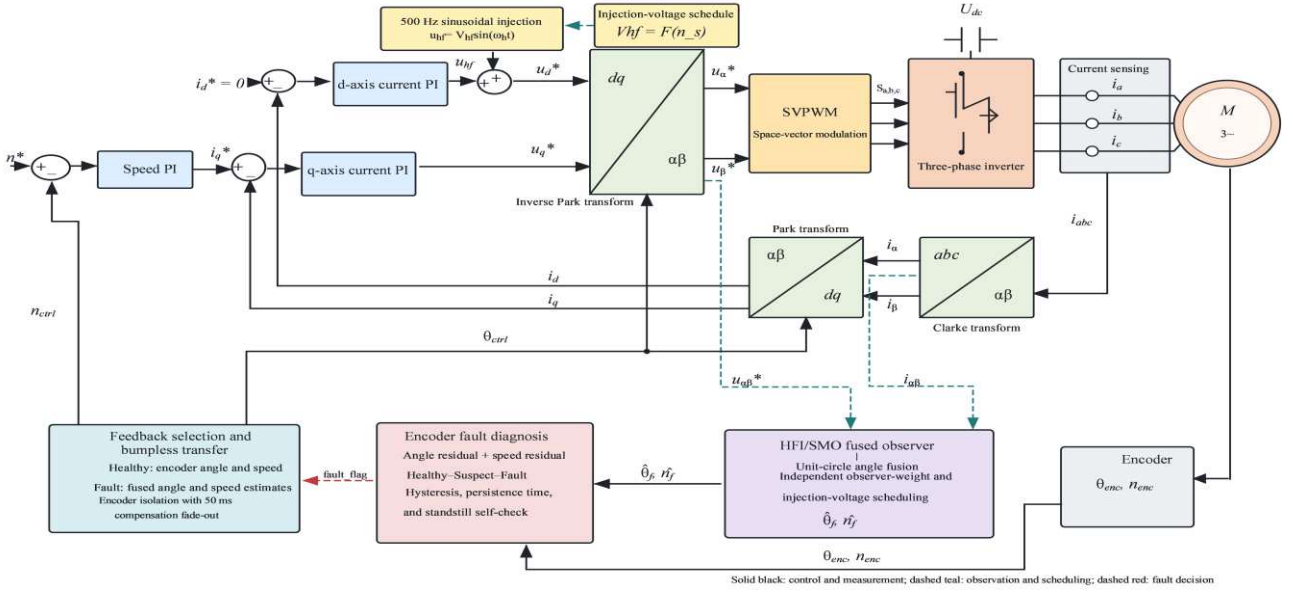


Fig. 1 PMSM drive and encoder fault-tolerant control architecture

2.2 Mathematical Model of the PMSM

Assuming symmetrical three-phase windings and neglecting iron losses and parameter variations caused by temperature, the PMSM voltage equations in the synchronously rotating d-q reference frame are

$$u_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (2)$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f \quad (3)$$

where u_d and u_q are the d- and q-axis voltages, respectively; i_d and i_q are the corresponding currents; R_s is the stator resistance; L_d and L_q are the d- and q-axis inductances; ψ_f is the permanent-magnet flux linkage; and ω_e is the electrical angular speed. The electromagnetic torque is given by

$$T_e = \frac{3p}{2} [\psi_f i_q + (L_d - L_q) i_d i_q] \quad (4)$$

With $i_d^* = 0$ and $i_d \approx 0$, the reluctance-torque term can be neglected, and the electromagnetic torque is approximated as:

$$T_e \approx \frac{3p}{2} \psi_f i_q \quad (5)$$

Since $L_d \neq L_q$, the motor exhibits rotor saliency, which provides the basis for HFI-based position estimation at low speeds. In practice, however, the strength of the saliency-related signal is also affected by differential inductance, inverter nonlinearities, and current-sampling noise. The mechanical dynamics are described by

$$J \frac{d\omega_m}{dt} = T_e - T_L - B \omega_m \quad (6)$$

where J is the moment of inertia, B is the viscous damping coefficient, and T_L is the external mechanical torque acting on the shaft. In the simulations, $T_L = 0$ is assumed. The relationship between the mechanical and electrical quantities is

$$\theta_e = p \theta_m, \omega_e = p \omega_m, \frac{d\theta_m}{dt} = \omega_m \quad (7)$$

2.3 Encoder Fault Models

Under healthy conditions, the encoder mechanical angle is converted into the control electrical angle through pole-pair conversion and calibrated installation-offset compensation:

$$\theta_{(enc,e)} = \text{wrap}_{2\pi}(p\theta_{(enc,m)} + \theta_0) \quad (8)$$

where θ_0 is the calibrated encoder installation zero-offset angle. The mechanical speed is obtained by differentiating the encoder angle and applying a low-pass filter. To describe different encoder faults in a unified form, the faulty encoder electrical angle is expressed as

$$\theta_{(enc,e)}^f(t) = \text{wrap}_{2\pi}[\theta_{enc,e}(t) + f_\theta(t)] \quad (9)$$

where $f_\theta(t)$ denotes the equivalent electrical-angle fault introduced into the encoder feedback. Only three signal-level equivalent faults are considered in this study: abrupt-bias, stuck-output, and pulse-loss-equivalent faults. All angle variables in the following analysis are expressed as electrical angles.

For an abrupt-bias fault, the encoder angle changes abruptly at the fault instant and retains the resulting offset thereafter. Slow zero-position drift is not considered in this study. The fault is modeled as

$$f_{\theta}(t) = \begin{cases} 0, & t < t_f \\ \Delta\theta_b, & t \geq t_f \end{cases} \quad (10)$$

When $t=0$, Eq. (10) represents an initial angle offset that is already present before startup. For a stuck-output fault, the encoder angle remains fixed at its last value before the fault:

$$\theta_{(enc,e)}^f(t) = \begin{cases} \theta_{(enc,e)}(t), & t < t_f \\ \theta_{(enc,e)}(t_f), & t \geq t_f \end{cases} \quad (11)$$

After the output becomes stuck, the differentiated and filtered speed estimate gradually approaches zero. Pulse loss may appear at the encoder-feedback level as an angle jump accompanied by a speed deviation. Rather than explicitly reproducing missing A/B/Z pulses and the associated counting process, this study represents the equivalent feedback behavior using a combination of angle and speed deviations:

$$\theta_{(enc,e)}^f = \text{wrap}_{2\pi}[\theta_{(enc,e)} + \Delta\theta_p H(t - t_f)], n_{(enc)}^f = n_{(enc)} + \Delta n_p H(t - t_f) \quad (12)$$

where $\Delta\theta_p$ and Δn_p are the equivalent angle jump and speed deviation, respectively, and $H(\cdot)$ is the Heaviside step function. The main feedback characteristics of the three encoder faults are summarized in Table 1.

Table 1 Typical encoder faults and their equivalent signal characteristics

Fault type	Electrical-angle behavior	Speed-feedback behavior	Main diagnostic feature
Abrupt-bias fault	Fixed offset in the output angle	Usually continues to follow the actual speed	Step change in the angle residual
Stuck-output fault	Holds the last angle before the fault	Gradually approaches zero after filtering	Increasing angle and speed residuals
Pulse-loss-equivalent fault	Instantaneous angle jump or gradual deviation	Transient spike or persistent deviation	Simultaneous changes in angle and speed residuals

2.4 Effects of Encoder Faults on Closed-Loop Control

Encoder faults affect the closed-loop system through both the angle- and speed-feedback paths. An angle error misaligns the control reference frame with the actual synchronous reference frame, whereas a speed error directly affects the output of the speed controller. The electrical-angle error between the faulty encoder angle and the actual rotor electrical angle is defined as

$$\Delta\theta_e = \text{wrap}_{\pi}(\theta_{(enc,e)}^f - \theta_e) \quad (13)$$

where $\text{wrap}_{\pi}(\cdot)$ confines an angular difference to the interval $[-\pi, \pi)$. According to the Park transformation adopted in Fig. 1, the currents in the erroneous synchronous reference frame and the actual synchronous reference frame satisfy

$$\begin{bmatrix} i_d^c & i_q^c \end{bmatrix}^T = \begin{bmatrix} \cos \Delta\theta_e & \sin \Delta\theta_e \\ -\sin \Delta\theta_e & \cos \Delta\theta_e \end{bmatrix} \begin{bmatrix} i_d & i_q \end{bmatrix}^T \quad (14)$$

When i_d^c in the erroneous synchronous reference frame is regulated to zero, $i_d \approx -i_q^c \sin(\Delta\theta_e)$ and $i_q \approx i_q^c \cos(\Delta\theta_e)$. The encoder angle error therefore introduces cross-coupling between the d- and q-axis currents and reduces the effective torque-producing current, which in turn causes current and speed fluctuations.

A speed-feedback fault acts directly on the speed PI controller. Considering the saturation of the q-axis current reference,

$$e_n = n^* - n_{(enc)}^f, i_q^* = \text{sat}[K_{(pn)}e_n + K_{(in)}\int e_n dt] \quad (15)$$

where K_{pn} and K_{in} are the proportional and integral gains of the speed controller, respectively, and $\text{sat}(\cdot)$ denotes the q-axis current-reference limiter.

When the encoder output becomes stuck, the measured speed gradually approaches zero. The resulting persistent speed error may drive i_q^* to its saturation limit. An abrupt-bias fault mainly causes reference-frame misalignment, whereas a stuck-output fault also leads to an accumulating angle error and corrupted speed feedback. In the equivalent fault model used in this study, a pulse-loss-equivalent fault appears as a combination of an angle jump and a speed deviation. The encoder angle and speed feedback must therefore be isolated simultaneously once a fault is confirmed.

An initial encoder-angle anomaly cannot be identified reliably from encoder output alone. An independent HFI-based position reference is therefore used. In the experimental implementation, the encoder admission check follows magnetic-polarity identification. In simulation, the HFI estimate is assumed to be on the correct magnetic-polarity branch. If an anomaly is detected, the encoder is excluded from the coordinate transformations and speed-control loop. The HFI angle and speed estimates are then used for sensorless startup. During subsequent operation, the fused HFI/SMO estimates construct the angle and speed residuals. Once a fault is confirmed, the encoder feedback is isolated and sensorless fault-tolerant takeover begins.

3 Encoder Fault Diagnosis and Fault-Tolerant Control Method

The proposed method consists of sinusoidal HFI, a Sigmoid-based SMO, decoupled scheduling, and encoder fault diagnosis with feedback reconstruction. During healthy operation, the encoder provides the primary feedback, while the HFI and SMO estimation channels run in parallel. Once an encoder fault is confirmed, the encoder angle and speed feedback are isolated simultaneously. For faults occurring during operation, the last healthy alignment offset is retained and used as temporary angle compensation, which is faded out over a prescribed compensation interval. For faults present before startup, HFI is used for encoder self-check and sensorless startup.

3.1 Rotor-Position Estimation Using Sinusoidal High-Frequency Voltage Injection

At zero and low speeds, the PMSM back electromotive force (back EMF) is weak, limiting position estimation based on back EMF. Rotor saliency causes the high-frequency current response to vary with rotor position and provides an encoder-independent estimation channel [15–18]. In this study, a sinusoidal high-frequency voltage is injected along the d-axis of the estimated synchronous reference frame:

$$u_d^* = u_{d0}^* + u_{(dh)}, u_{(dh)} = V_{(hf)} \sin(\omega_h t), \omega_h = 2\pi \times 500 \text{ rad/s} \quad (16)$$

The injection frequency is 500 Hz, while the voltage amplitude V_{hf} is scheduled according to speed. After the three-phase stator currents are transformed into the stationary reference frame by the Clarke transformation, their high-frequency components are extracted and projected onto the q-axis of the HFI estimated reference frame:

$$i_{(qh)} = -i_{(\alpha h)} \sin \hat{\theta}_{HFI} + i_{(\beta h)} \cos \hat{\theta}_{HFI} \quad (17)$$

The high-frequency current response passes through a 500 Hz band-pass filter and is synchronously demodulated with a reference at the injection frequency. The 1000 Hz second-harmonic component is suppressed. Denoting the signal-processing operation by $D\{\cdot\}$, the resulting position-error signal is approximated as

$$\varepsilon_{HFI} = D\{i_{qh}\} \approx K_{HFI} \sin[2(\theta_e - \hat{\theta}_{HFI})] \quad (18)$$

The position-error signal is processed by the HFI regulator to generate an electrical angular-speed correction, which is integrated to obtain the estimated electrical angle. After filtering and conversion using the number of pole pairs, the corresponding mechanical speed estimate is obtained as

$$\hat{\omega}_{HFI} = C_{HFI}(s)\varepsilon_{HFI}, \frac{d\hat{\theta}_{HFI}}{dt} = \hat{\omega}_{HFI}, \hat{\theta}_{HFI} = \frac{30}{\pi p} G_{\omega}(s)\hat{\omega}_{HFI} \quad (19)$$

In the simulations, $K_p, HFI=1000$ and $K_i, HFI=10000$, and both the control and estimation periods are 100 μs . Fig. 2 shows the signal-processing structure. This encoder-independent channel provides angle and speed estimates for low-speed fault diagnosis and feedback takeover. Sinusoidal HFI first identifies the rotor-axis position from the saliency response. Because the rotor axis cannot distinguish the two magnetic-pole directions separated by 180° electrical, the initial estimate has a magnetic-polarity ambiguity. In the experimental controller, magnetic-polarity identification uses the difference between the high-frequency current responses for the two possible pole directions. The simulations assume that this correction has already been completed. If the estimate lies on the incorrect polarity branch, an electrical-angle correction of π gives the initial rotor electrical angle with the correct magnetic polarity [19–22].

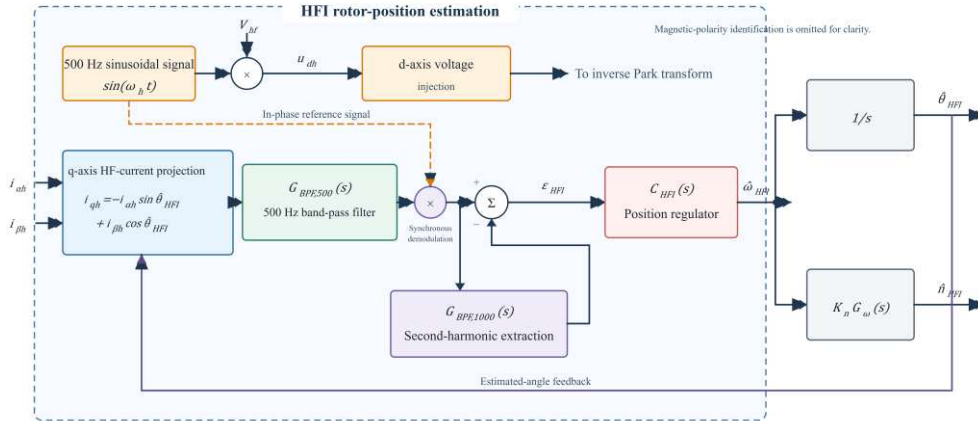


Fig. 2 Sinusoidal HFI position estimation

3.2 Sliding-Mode Observer with a Sigmoid Switching Function

HFI is effective at zero and low speed, but continuous injection increases high-frequency current and losses. As rotor speed rises, the back EMF becomes sufficient for an SMO to estimate rotor position and speed from the stator voltage and current [23,24]. A single equivalent inductance is used to formulate the current model in the stationary α - β reference frame:

$$\frac{di_{\alpha}}{dt} = -\frac{R_s}{L_s} i_{\alpha} + \frac{u_{\alpha} - e_{\alpha}}{L_s}, \frac{di_{\beta}}{dt} = -\frac{R_s}{L_s} i_{\beta} + \frac{u_{\beta} - e_{\beta}}{L_s} \quad (20)$$

where $L_s = L_q = 160 \mu\text{H}$ is the equivalent stator inductance used in the SMO current model; the inputs are the stator voltages and currents in the stationary reference frame, and the extended back EMF components carry the rotor-position information. Based on Eq. (20), the current sliding-mode observer is constructed as

$$\frac{d\hat{i}_{\alpha}}{dt} = -\frac{R_s}{L_s} \hat{i}_{\alpha} + \frac{u_{\alpha} - z_{\alpha}}{L_s}, \frac{d\hat{i}_{\beta}}{dt} = -\frac{R_s}{L_s} \hat{i}_{\beta} + \frac{u_{\beta} - z_{\beta}}{L_s} \quad (21)$$

The current estimation errors along the α - and β -axes are defined by $\tilde{i}_j = \hat{i}_j - i_j, j \in \{\alpha, \beta\}$. A conventional sign function tends to introduce high-frequency chattering near the sliding surface. A continuous Sigmoid function is therefore used to construct the switching term [25]:

$$z_j = K_{(sw)} \left[\frac{2}{1 + \exp(-k\tilde{i}_j)} - 1 \right], j \in \{\alpha, \beta\} \quad (22)$$

The estimates are obtained using the discrete low-pass filter $G_{SMO}(z)$:

$$\hat{e}_{\alpha} = G_{SMO}(z)z_{\alpha}, \hat{e}_{\beta} = G_{SMO}(z)z_{\beta} \quad (23)$$

To reduce the effect of the speed-dependent back EMF amplitude on PLL position tracking, the estimated back EMF components along both axes are normalized before entering the phase-locked loop (PLL) [27]. According to the sign convention used in the implementation, the PLL position-error signal is defined as

$$\varepsilon_{(SMO)} = -\hat{e}_\alpha \cos \hat{\theta}_{PLL} - \hat{e}_\beta \sin \hat{\theta}_{PLL} \quad (24)$$

where the estimated back EMF components along both axes have been normalized. The position-error signal is processed by the PLL regulator to obtain the estimated electrical angular speed, which is then integrated to give the rotor electrical angle. To compensate for the phase lag introduced by the back EMF low-pass filter, speed-dependent phase compensation is applied [26]:

$$\hat{\omega}_{SMO} = C_{PLL}(s)\varepsilon_{SMO}, \quad \hat{\theta}_{SMO} = \text{wrap}_{2\pi}[\int \hat{\omega}_{SMO} dt + \text{atan2}(\hat{\omega}_{SMO}, \omega_{LPF})] \quad (25)$$

In the simulations, $K_{sw}=12$ and $k=1$. The cutoff frequency of the back EMF low-pass filter is 1000 rad/s, and the PLL parameters are $\omega_n=225$ rad/s and $\zeta=0.707$. The speed-filter cutoff frequency is 100 rad/s. The SMO operates independently of the encoder. At low speeds, its performance is limited by the back EMF signal-to-noise ratio. As speed increases, it becomes the dominant estimation channel. Fig. 3 shows the overall structure.

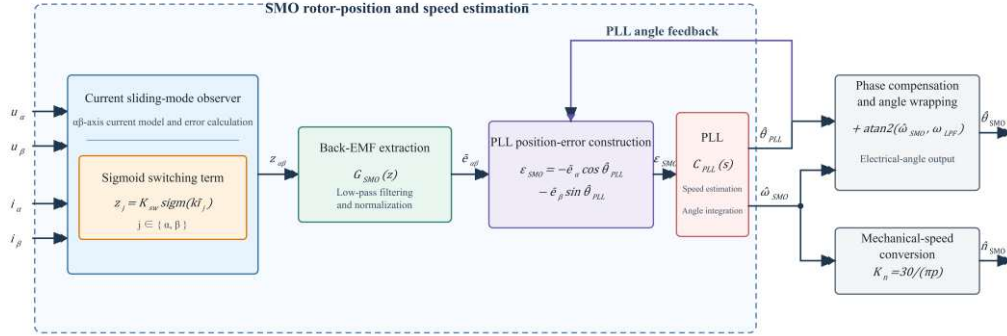


Fig. 3 Sigmoid SMO structure

3.3 Full-Speed-Range HFI/SMO Fusion and Injection Voltage Scheduling

Full-speed-range sensorless position estimation commonly combines low-speed HFI with a model-based observer at medium and high speeds [28–32]. The HFI/SMO fusion region and injection voltage are calibrated under healthy-encoder closed-loop operation without fault injection. The actual rotor angle and speed are used only for error evaluation and do not participate in scheduling. The electrical-angle error is calculated as the shortest angular difference on the unit circle. The RMS error and the 95th-percentile error (P95) are evaluated over 1.2–2.0 s:

$$e_j = \text{atan2}[\sin(\hat{\theta}_j - \theta_e), \cos(\hat{\theta}_j - \theta_e)], j \in \{HFI, SMO, f\} \quad (26)$$

With a fixed 3 V injection, the RMS HFI angle error increases from 0.331° at 100 r/min to 4.111° at 3000 r/min, whereas the RMS SMO angle error decreases from 5.243° to 1.018°. HFI is therefore used as the dominant channel below 300 r/min. The SMO contribution is gradually increased above 300 r/min, and the transition is completed at 1000 r/min, where high-frequency injection is disabled. All HFI angle estimates used for fusion have undergone magnetic-polarity correction.

The injection voltage is swept from 0.5 to 3.0 V at 100, 300, 500, 700, and 900 r/min. The additional high-frequency current is evaluated using

$$I_{(hf,rms)} = \sqrt{I_{(d,hf,rms)}^2 + I_{(q,hf,rms)}^2} \quad (27)$$

As shown in Fig. 4, increasing the injection voltage beyond a certain level provides little further improvement in HFI accuracy, whereas the high-frequency current continues to increase. At 700 r/min, increasing the injection voltage from 1.5 to 3.0 V reduces the RMS angle error only from 1.073° to 1.056°, while increasing the RMS high-frequency current from 0.111 A to 0.197 A. The injection voltage is therefore maintained at 3 V at low speeds, reduced through the fusion region, and disabled at 1000 r/min and above.

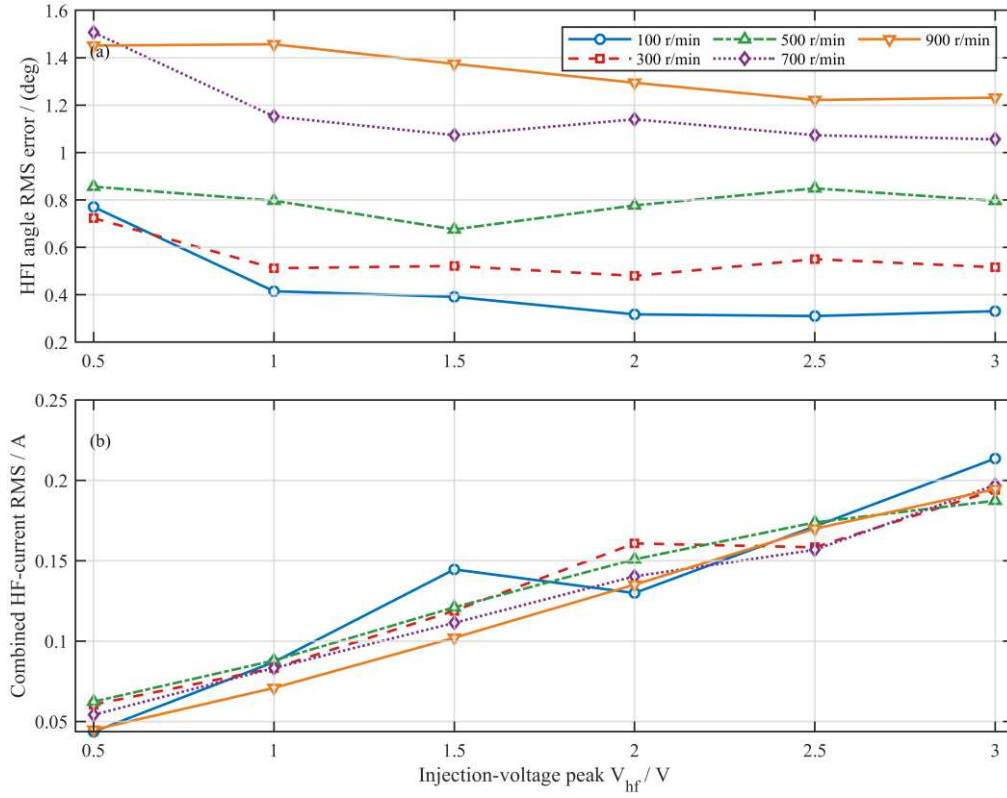


Fig. 4 HFI angle error and additional high-frequency current: (a) RMS angle error and (b) RMS high-frequency current

To prevent encoder faults from affecting the scheduling variables, the scheduling speed is constructed from the HFI and SMO mechanical-speed estimates rather than the encoder speed. To avoid an algebraic loop, the corrected and smoothed SMO weight from the previous control cycle, $w^- = w(k-1)$, is used to calculate the scheduling speed in the current cycle:

$$n_s = |(1 - w^-)\hat{n}_{HFI} + w^-\hat{n}_{SMO}| \quad (28)$$

where $\hat{n}_{HFI}$ and $\hat{n}_{SMO}$ are the HFI and SMO mechanical-speed estimates, respectively. The scheduling variable n_s is the magnitude of the weighted HFI/SMO speed estimate and is used only for region selection and parameter lookup. No absolute-value operation is applied to the fused speed in Eq. (31), so its sign is retained in the feedback path.

For two adjacent scheduling breakpoints $[n_{k,n} \ k+1]$, the normalized variable is defined as $\xi = (n_s - n_k) / (n_{k+1} - n_k)$, where n_s is the scheduling speed and $0 \leq \xi \leq 1$. The cubic function $S(\xi) = 3\xi^2 - 2\xi^3$ is used to interpolate the SMO weight and injection voltage independently:

$$w_{cmd} = w_k + [w_{k+1} - w_k]S(\xi), V_{hf,cmd} = V_k + [V_{k+1} - V_k]S(\xi) \quad (29)$$

The injection-voltage breakpoints are selected according to the trade-off between HFI angle error and additional high-frequency current. The fusion-weight breakpoints are determined from the HFI and SMO error trends and further adjusted using closed-loop simulation. The resulting values are listed in Table 2. A directly tied weight-voltage scheme is included for comparison:

$$w_{bind} = 1 - \frac{V_{hf,cmd}}{V_{hf,max}}, V_{hf,max} = 3V$$

Compared with the directly tied scheme, the decoupled schedule reduces the mean RMS angle error over 400–900 r/min from 1.204° to 1.128°, corresponding to a reduction of approximately 6.3%, without increasing the injection level.

Table 2 Breakpoint schedule for the fusion weight and high-frequency injection voltage

Scheduling speed n_s (r/min)	Estimation region	Scheduled SMO weight	Peak HFI voltage (V)
0–300	HFI dominant	0	3.00
400	HFI/SMO fusion	0.15	2.10
500	HFI/SMO fusion	0.25	1.65
600	HFI/SMO fusion	0.40	1.20
700	HFI/SMO fusion	0.55	0.90
800	HFI/SMO fusion	0.70	0.60
900	HFI/SMO fusion	0.90	0.30
≥ 1000	SMO only	1.00	0

To prevent unreliable SMO estimates from contributing to the fusion, the SMO weight is corrected using the back EMF magnitude confidence and the angular consistency between the HFI and SMO estimates:

$$E_{\text{cmf}} = \sqrt{\hat{e}_{\alpha,f}^2 + \hat{e}_{\beta,f}^2}, E_{\text{ref}} = \max\left(|\hat{n}_{\text{SMO}}| \frac{\pi}{30} p\psi_f, 0.2V\right)$$

$$C_{\text{SMO}} = \text{sat}\left(\frac{E_{\text{cmf}}}{E_{\text{ref}}}\right), \Delta\theta_{\text{HS}} = \text{atan2}\left(\sin(\hat{\theta}_{\text{SMO}} - \hat{\theta}_{\text{HFI}}), \cos(\hat{\theta}_{\text{SMO}} - \hat{\theta}_{\text{HFI}})\right)$$

The normalization denominator has a lower bound of 0.2 V, and $\text{sat}(\cdot)$ confines the confidence ratio to $[0,1]$. The 5th-percentile values of the steady-state SMO confidence are 0.611–0.729. The acceptance threshold is set to 0.60, and the forced-fallback threshold is 0.35. Let $\delta\theta = |\Delta\theta_{\text{HS}}|$. The angular-consistency criterion then adjusts the actual SMO weight:

$$w_{\text{lim}}(k) = \begin{cases} 0 & , n_s < 300 \\ \Phi(k) & , 300 \leq n_s < 1000 \\ 1 & , n_s \geq 1000 \end{cases}$$

$$\Phi(k) = \begin{cases} 0 & , C_{\text{SMO}} < 0.35 \\ w_{\text{lim}}(k-1) & , 0.35 \leq C_{\text{SMO}} < 0.60 \\ 1 & , C_{\text{SMO}} \geq 0.60, \delta\theta > 30^\circ \\ w_{\text{cmd}} & , C_{\text{SMO}} \geq 0.60, \delta\theta \leq 30^\circ \end{cases}$$

When the SMO confidence is at least 0.60 and the angular discrepancy exceeds 30° , full SMO weighting prevents an inconsistent HFI estimate from entering the fusion. High-frequency injection is disabled at scheduling speeds of 1000 r/min and above. At lower scheduling speeds, the target injection voltage is 3 V in the HFI-dominant or forced-fallback state and otherwise follows the independent schedule. First-order dynamics smooth both the fusion weight and injection voltage.

$$\tau_w \frac{dw}{dt} + w = w_{\text{lim}}, \tau_w = 30\text{ms}; \tau_v \frac{dV_{\text{hf}}}{dt} + V_{\text{hf}} = V_{\text{lim}}, \tau_v = 10\text{ms}$$

Considering the 2π -periodicity of the electrical angle, the fused electrical angle is obtained using unit-circle vector fusion:

$$x_f = (1-w) \cos \hat{\theta}_{\text{HFI}} + w \cos \hat{\theta}_{\text{SMO}}, y_f = (1-w) \sin \hat{\theta}_{\text{HFI}} + w \sin \hat{\theta}_{\text{SMO}} \quad (30)$$

$$\hat{\theta}_f = \text{wrap}_{2\pi}[\text{atan2}(y_f, x_f)], \hat{n}_f = (1-w)\hat{n}_{\text{HFI}} + w\hat{n}_{\text{SMO}} \quad (31)$$

The scheduling variable in Eq. (28) is used only for region selection, whereas the fused mechanical speed in Eq. (31) retains its sign in the feedback path. The fused-angle RMS error ranges from 0.308° to 1.483° over 100–1000 r/min. In the SMO-only region from 1200 to 3000 r/min, the RMS error ranges from 0.478° to 1.000° . No pronounced increase in angle error is observed at the transitions between the HFI-dominant, fusion, and SMO-only regions. The full-speed-range estimation performance and the corresponding scheduling profiles are summarized in Fig. 5.

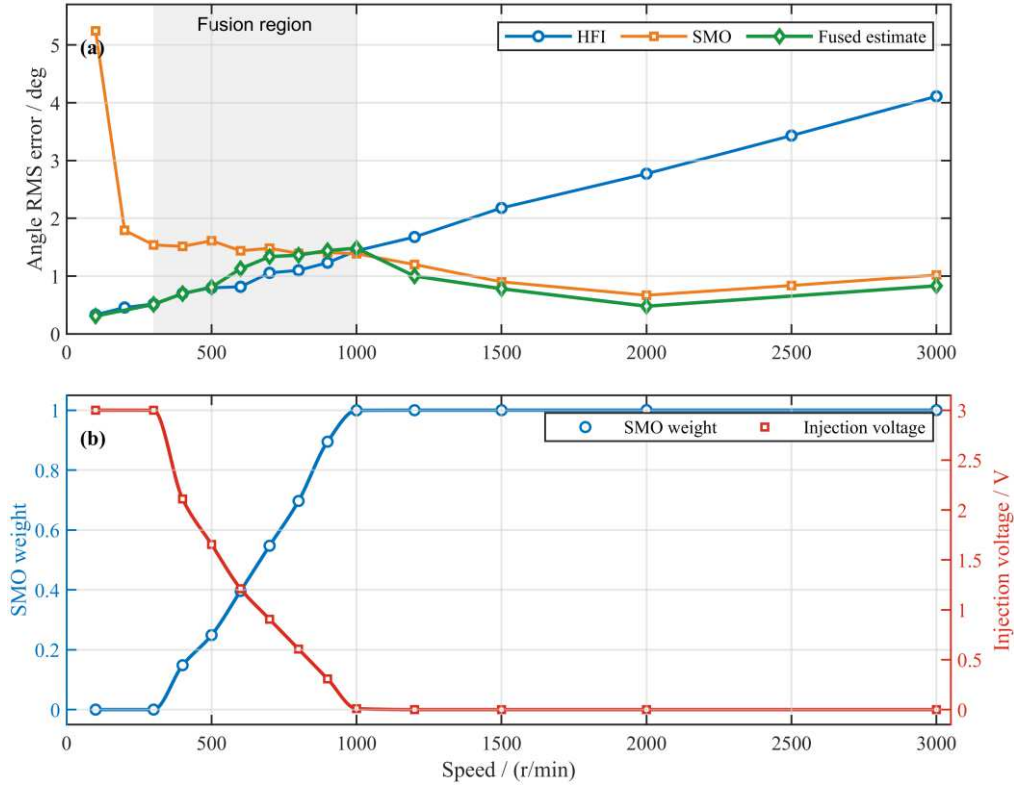


Fig. 5 HFI/SMO fusion performance and scheduling: (a) angle-estimation errors and (b) fusion-weight and injection-voltage scheduling

3.4 Encoder Fault Diagnosis, Isolation, and Feedback Takeover Strategy

The encoder angle and the fused angle estimate may differ by a steady offset associated with the encoder installation zero offset and estimation delay. Direct comparison may therefore generate additional residuals even under healthy operation.

An alignment offset $\Delta\theta_a$ is updated online while the encoder is healthy, and the signed angle and speed errors and their absolute residuals are defined as

$$\begin{aligned} e_\theta &= \text{wrap}_\pi(\theta_{\text{enc}} - \hat{\theta}_f - \Delta\theta_a), \quad e_n = n_{\text{enc}} - \hat{n}_f \\ r_\theta &= |e_\theta|, \quad r_n = |e_n| \end{aligned} \quad (32)$$

where θ_{enc} and n_{enc} denote the encoder electrical angle and mechanical speed, and $\hat{\theta}_f$ and $\hat{n}_f$ denote the corresponding fused estimates. The function $\text{wrap}_\pi(\cdot)$ confines the angular residual to $[-\pi, \pi)$. During healthy operation, $\Delta\theta_a$ is updated with a time constant of $\tau_\Delta=0.20$ s:

$$\Delta\theta_a[k] = \text{wrap}_\pi(\Delta\theta_a[k-1] + a_\Delta e_\theta[k]), \quad a_\Delta = \frac{T_s}{\tau_\Delta + T_s} \quad (33)$$

where T_s is the control sampling period. The alignment offset accounts for the steady deviation caused by the installation offset and estimation delay. Since slow encoder zero drift may be partly tracked by this online alignment process, only abrupt-bias, stuck-output, and pulse-loss-equivalent faults are considered here.

The residual-based diagnosis and post-fault feedback reconstruction draw on the approaches reported in [7,13,14]. The thresholds and persistence times are calibrated from residuals under fault-free dynamic operation and from the responses to injected faults. The diagnostic logic has three states: healthy, suspect, and fault. The angle-residual entry and exit thresholds are 15° and 9° , respectively. The corresponding speed-residual thresholds are $(80+0.15|\hat{n}_f|)$ r/min and $(50+0.10|\hat{n}_f|)$ r/min.

The angle and speed diagnostic paths operate in parallel. When a residual exceeds its entry threshold, the corresponding counter accumulates. The count is held while the residual remains within the hysteresis band and is reset when the residual falls below the exit threshold. If either residual exceeds its entry threshold, the system enters the suspect state, $\Delta\theta_a$ is no longer updated, and the last healthy value is frozen as $\Delta\theta_0$. This prevents fault-induced angle deviations from being absorbed by the online alignment process.

In the suspect state, the angle residual is calculated using the frozen $\Delta\theta_0$. The system returns to the healthy state only when both residuals fall below their respective exit thresholds. An encoder fault is confirmed when the angle- or speed-path persistence criterion reaches 30 or 15 ms, respectively:

$$F_{\text{enc}} = F_\theta \vee F_{n,\text{ind}} \quad (34)$$

where the left-hand-side flag is the final encoder-fault flag, and the two right-hand-side flags are the angle- and speed-path fault decisions, respectively.

After fault confirmation, the fault flag is latched and the encoder angle and speed feedback are isolated simultaneously. For faults occurring during operation, direct switching from the encoder angle to the fused estimate may cause a discontinuity in the control reference frame. The frozen $\Delta\theta_0$ is therefore used only as temporary angle compensation during takeover. Let t_c denote the confirmation time and T_f the compensation fade-out time. A cubic function with zero slope at both endpoints is used:

$$\lambda(t) = 1 - 3s^2 + 2s^3, \quad s = \text{sat}\left(\frac{t-t_c}{T_f}\right) \quad (35)$$

where $\text{sat}(\cdot)$ limits its argument to the interval $[0, 1]$.

The post-fault control feedback is then given by

$$\theta_{\text{ctrl}} = \text{wrap}_{2\pi}[\hat{\theta}_f + \lambda(t)\Delta\theta_0], \quad n_{\text{ctrl}} = \hat{n}_f \quad (36)$$

At $t=t_c$, $\lambda=1$, so the frozen alignment offset is fully retained to preserve control-angle continuity. When $t-t_c \geq T_f$, $\lambda=0$, and the control angle is provided entirely by the fused estimate. Thus, $\Delta\theta_0$ is used only during the takeover transient and does not serve as a long-term angle correction.

The startup procedure is handled separately. HFI magnetic-polarity identification and angle correction are completed before the encoder self-check. Since no reliable last healthy alignment offset is available before startup, $\Delta\theta_0=0$ and no temporary compensation is applied. In simulation, the polarity-corrected HFI angle is used directly, whereas magnetic-polarity identification is implemented only in the experimental controller. The startup self-check is evaluated over a fixed 120 ms observation window. At the end of this window, a healthy encoder is admitted to the control loop; otherwise, the startup-isolation state is latched and HFI angle and speed estimates are used for sensorless startup. In the experimental controller, the angle-path persistence criterion is 30 ms; once satisfied, encoder isolation is latched, and motor startup is subsequently enabled by an independent hardware startup sequence. The complete procedure is shown in Fig. 6.

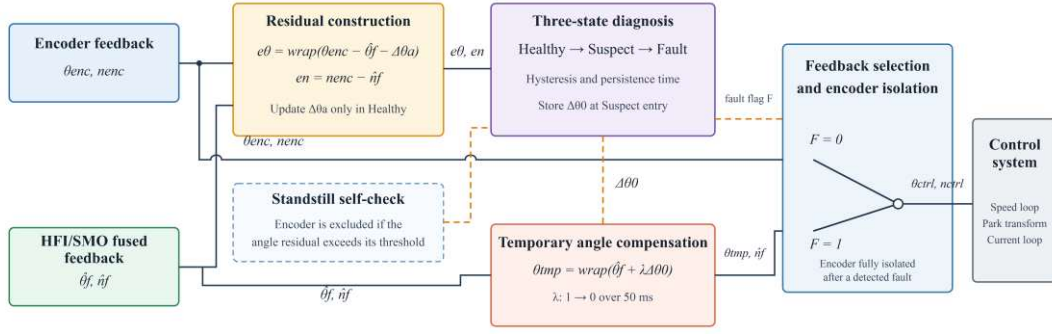


Fig. 6 Encoder fault diagnosis and feedback takeover

4 Simulation Validation

4.1 Simulation Model and Parameter Settings

A PMSM model with cascaded speed and current control loops is implemented in MATLAB/Simulink. For faults occurring during operation, fault confirmation occurs when the angle- or speed-path persistence criterion reaches 30 or 15 ms, respectively. For pre-startup faults, the simulation evaluates encoder admission over a 120 ms observation window; the resulting admission or isolation decision is applied at the end of this window. The simulations directly use the polarity-corrected HFI angle, while magnetic-polarity identification is implemented only in the experimental controller.

Encoder faults are injected between the actual rotor signals and the encoder-feedback channels. The diagnostic logic follows Section 3.4: the last healthy alignment offset is frozen upon entry into the suspect state, and the encoder angle and speed feedback are isolated simultaneously after fault confirmation. Except for the parameter sweep in Section 4.2, the compensation fade-out time is set to $T=50$ ms.

A fixed-step discrete solver is used, with a $1 \mu\text{s}$ step for the power stage and control and estimation periods of $100 \mu\text{s}$. The dc-link voltage is 24 V. The main PMSM parameters are listed in Table 3.

Under fault-free acceleration and deceleration, the maximum angle residual between the encoder and fused estimate is 4.15° . Allowing for normal dynamic variations, the angle-residual entry and exit thresholds are set to 15° and 9° , respectively. The speed-residual entry and exit thresholds are defined as

$$E_{n,on} = 80 + 0.15 |\hat{n}_f|, \quad E_{n,off} = 50 + 0.10 |\hat{n}_f| \quad (r/min)$$

These thresholds depend on the motor parameters, estimation accuracy, and speed-signal processing method. They should be recalibrated if the motor parameters or signal-processing settings are changed.

Table 3 Main PMSM Parameters

Parameter	Symbol	Value
Stator resistance	R_s	0.3Ω
d-axis inductance	L_d	$140 \mu\text{H}$
q-axis inductance	L_q	$160 \mu\text{H}$
Permanent-magnet flux linkage	ψ_f	0.0083333 Wb
Number of pole pairs	p	4
Moment of inertia	J	$1 \times 10^{-7} \text{ kg} \cdot \text{m}^2$
Viscous damping coefficient	B	$1 \times 10^{-4} \text{ N} \cdot \text{m} \cdot \text{s/rad}$

4.2 Selection of the Temporary-Compensation Fade-Out Time and Takeover-Transient Comparison

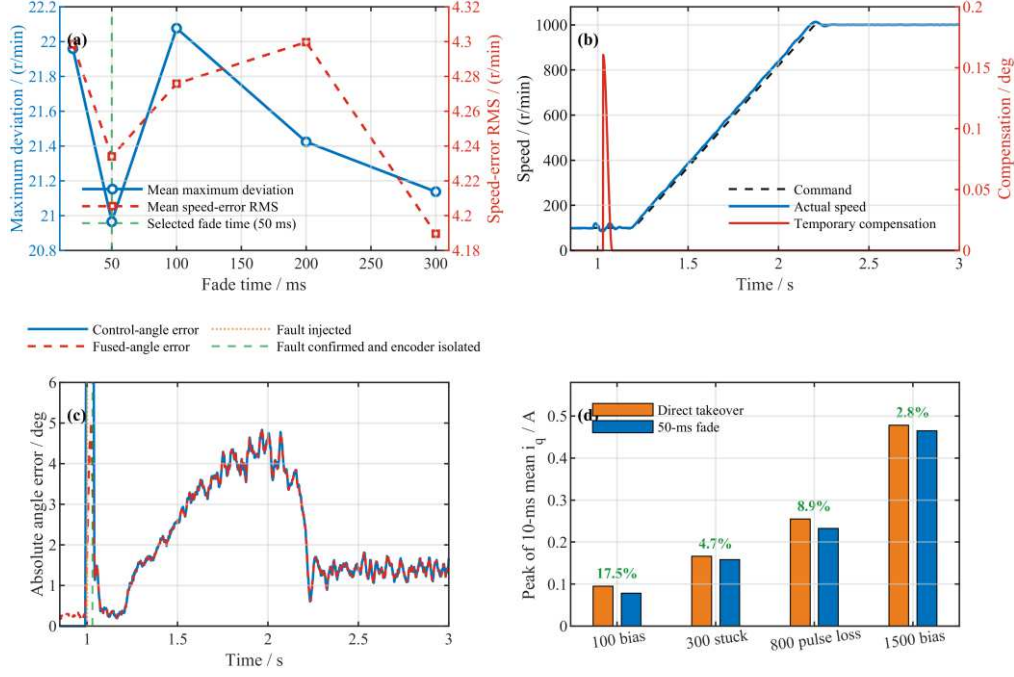


Fig. 7 Fade-out-time selection and takeover transient: (a) fade-out-time sweep, (b) speed response and temporary compensation, (c) control-angle error, and (d) q-axis current-envelope peak

To determine the temporary angle-compensation fade-out time, $T_f=20, 50, 100, 200,$ and 300 ms are compared under fault conditions at different speeds. Fig. 7(a) shows that $T_f=50$ ms gives the lowest mean maximum speed deviation, 20.965 r/min, among the tested values. This value is therefore used in the subsequent simulations.

Figs. 7(b) and 7(c) show the acceleration response through the HFI/SMO transition region after the temporary compensation has faded out, together with the control-angle error. The system moves from the HFI-dominant region through the HFI/SMO fusion region and reaches SMO-only operation at 1000 r/min. No estimation divergence or pronounced speed discontinuity is observed during the transition.

Fig. 7(d) compares the $T_f=50$ ms scheme with direct takeover without temporary compensation ($T_f=0$). The comparison includes abrupt-bias faults at 100 and 1500 r/min, a 300 r/min stuck-output fault, and an 800 r/min pulse-loss-equivalent fault. A 10 ms moving average is applied to the q-axis current to extract its low-frequency envelope peak. Across these four running-fault cases, the peak is reduced by 2.75% – 17.54% , with a mean reduction of 8.46% . The RMS q-axis current during the takeover transient is reduced by 6.44% on average. The moving average is used only for visualization and statistical analysis and does not participate in closed-loop control.

4.3 Validation of HFI/SMO Fusion Estimation Performance

The estimation accuracy of the HFI/SMO fused estimates is evaluated under nominal motor parameters and healthy-encoder conditions. During the simulations, the encoder remains the closed-loop feedback source, while the fused estimates run in parallel and are not used for the Park transformation or speed-control loop. This avoids using the evaluated estimates as feedback in the same closed loop. The actual rotor angle and mechanical speed provided by the simulation model are used only as references for error statistics.

Thirteen steady-state operating points are selected over 100 – 3000 r/min, with a common evaluation interval of 1.2 – 2.0 s. The electrical-angle error is calculated as the shortest angular difference on the unit circle, and P95 denotes the 95th percentile of the absolute error. The fused speed estimate and actual mechanical speed are processed using the same 50 ms moving average before calculating the RMS and P95 speed errors. This processing is used only for statistical evaluation and is not used in the estimation or control loops. Zero-speed operation is excluded from the steady-state sweep and is evaluated separately in Section 4.4 for initial-position estimation, encoder self-check, and sensorless startup.

Fig. 8 shows RMS angle errors of 0.336° to 0.539° in the HFI-dominant region and 0.713° to 1.476° in the HFI/SMO fusion region. In the SMO-only region at 1000 r/min and above, the RMS angle error ranges from 0.510° to 1.511° . Across all 13 operating points, the angle-error RMS and P95 do not exceed 1.511° and 2.396° , respectively. The corresponding speed-error RMS and P95 do not exceed 1.585 r/min and 2.881 r/min, respectively. No pronounced error increase occurs between adjacent operating points. Figs. 7(b) and 7(c) also show continuity through the fusion region.

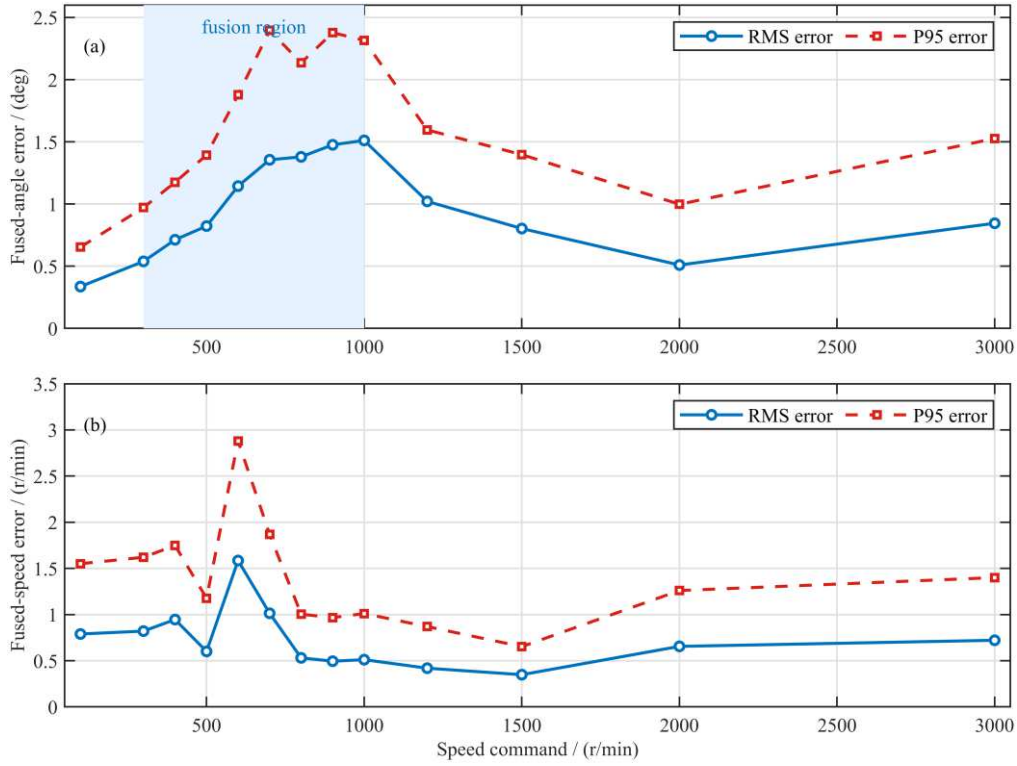


Fig. 8 HFI/SMO estimation errors under nominal conditions: (a) electrical-angle error and (b) mechanical-speed error

4.4 Simulation of Encoder Fault Diagnosis, Feedback Isolation, and Takeover

Six simulation cases are considered: a pre-startup angle bias; abrupt-bias faults at 100 and 1500 r/min; a 300 r/min stuck-output fault; an 800 r/min pulse-loss-equivalent fault; and fault-free acceleration/deceleration. Together, they evaluate fault detection, confirmation, isolation, and sensorless feedback takeover. For faults during operation, encoder angle and speed feedback are isolated simultaneously after confirmation, and a 50 ms temporary angle compensation is applied to provide a continuous transition of the control angle. For the pre-startup case, no reliable healthy alignment offset is available. The 120 ms simulation observation window determines encoder admission or startup isolation; if the encoder is rejected, HFI angle and speed estimates are used for sensorless startup. Figs. 9 to 13 show the startup self-check, representative low-speed, fusion-region, and SMO-region takeovers, and the fault-free transient. Table 4 summarizes all simulated cases.

At 100 r/min, a $+30^\circ$ angle bias is confirmed when the angle-path persistence criterion reaches 30 ms. The speed enters and remains within the $\pm 2\%$ error band approximately 125 ms after confirmation. At 300 r/min, a stuck-output fault is confirmed by the speed-residual path within 16 ms, and the same recovery criterion is satisfied approximately 115 ms after confirmation, as shown in Fig. 10. The 300 r/min case is selected as the representative low-speed transient because it remains in the HFI-dominant region while exhibiting both angle and speed feedback degradation. For the pre-startup 40° bias, the encoder is rejected at the end of the 120 ms simulation observation window, after which HFI-based startup is enabled, as shown in Fig. 9.

At 800 r/min, a -20° angle jump and a -120 r/min speed deviation are introduced to represent the equivalent feedback behavior of pulse loss. The fault is confirmed and the encoder is isolated after 31 ms. The maximum speed deviation during the complete takeover is 69.83 r/min, and the speed satisfies the recovery criterion approximately 87 ms after confirmation. Fig. 11 shows the angle and speed responses during this fusion-region takeover.

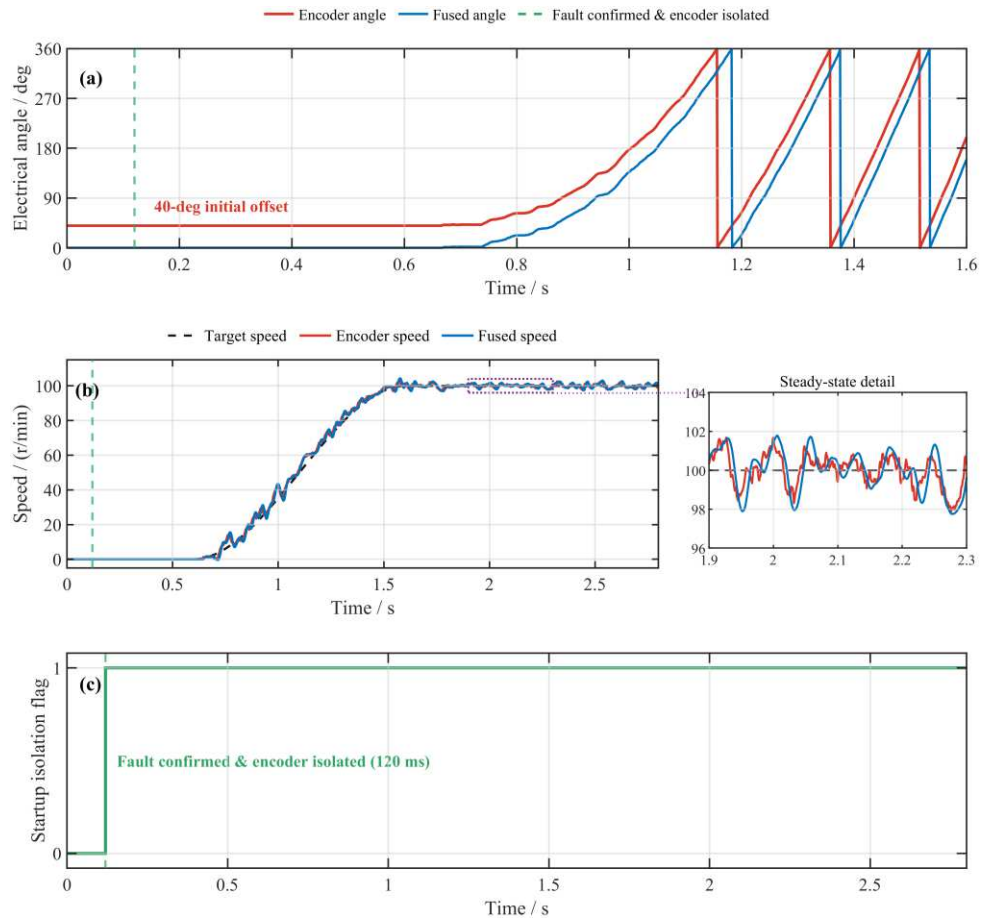


Fig. 9 Zero-speed self-check and HFI startup: (a) electrical angles, (b) speed response, and (c) startup-isolation flag

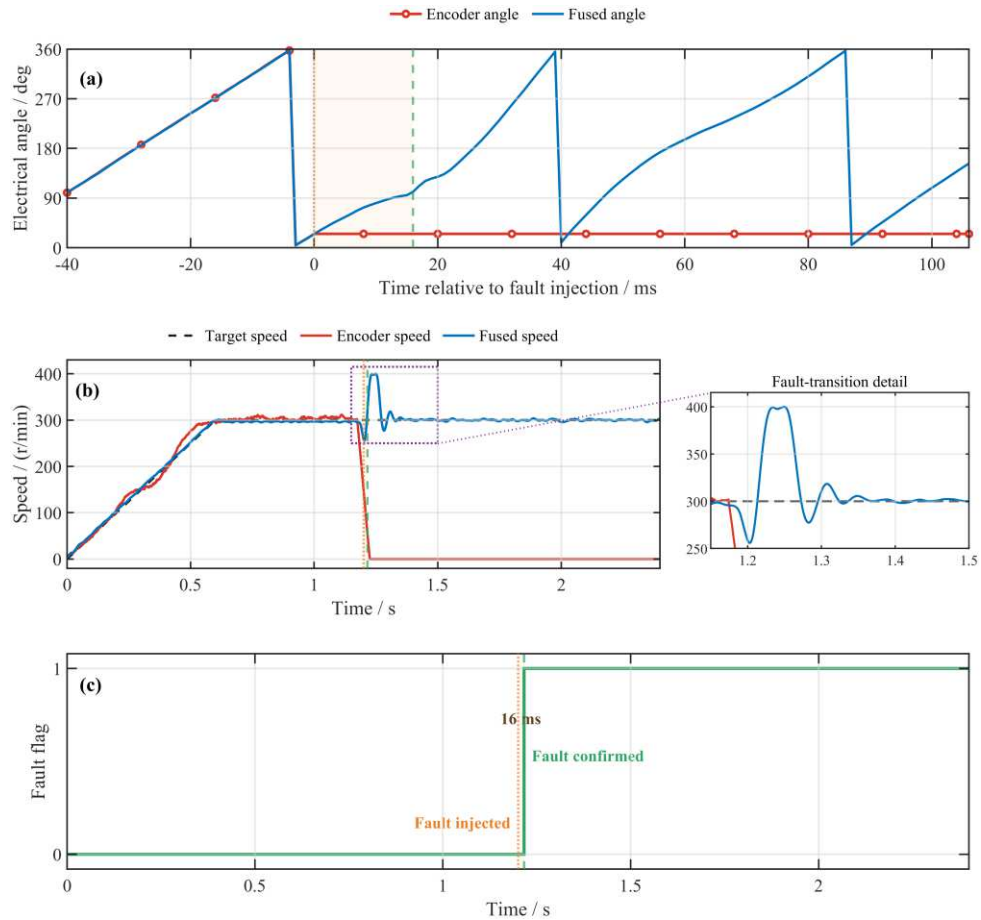


Fig. 10 HFI takeover under a 300 r/min stuck-output fault: (a) electrical angles, (b) speed response, and (c) fault flag

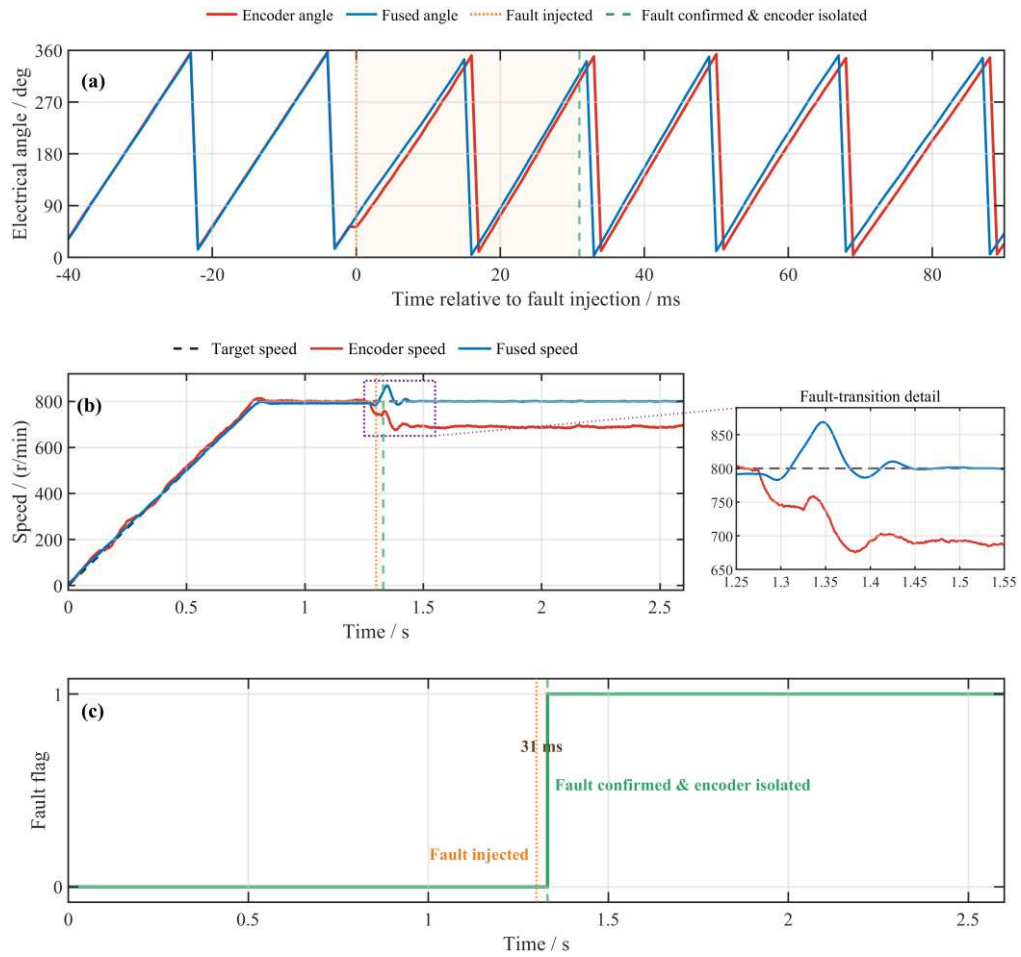


Fig. 11 Fused-feedback takeover under an 800 r/min pulse-loss-equivalent fault: (a) electrical angles, (b) speed response, and (c) fault flag

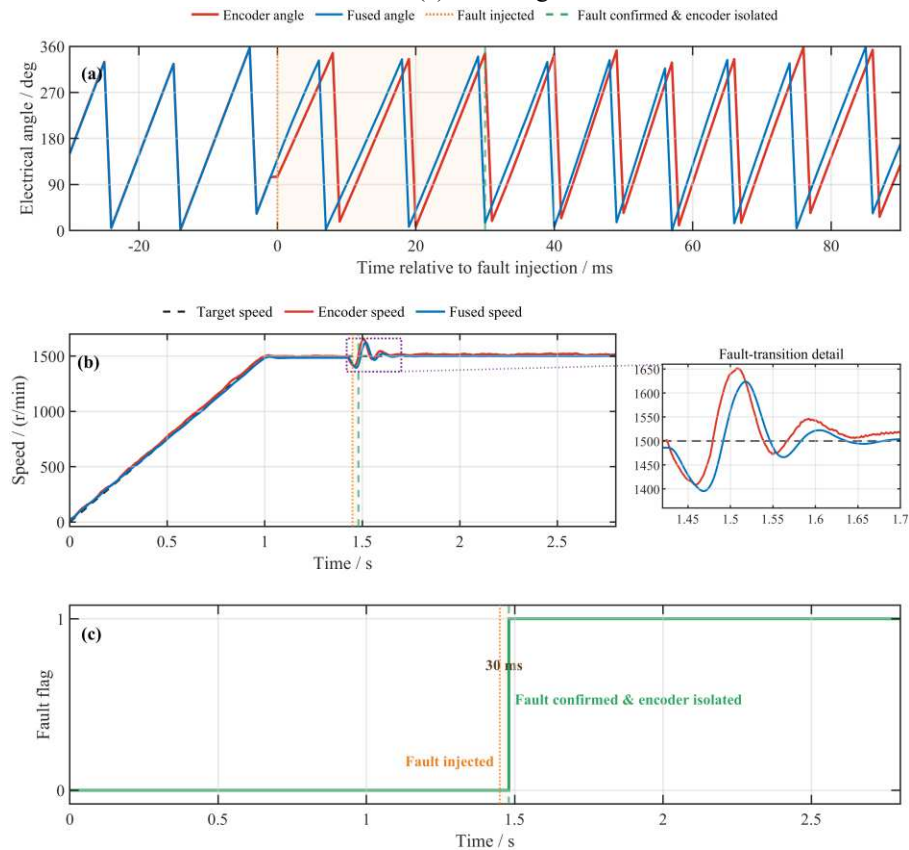


Fig. 12 SMO takeover under a 1500 r/min abrupt angle-bias fault: (a) electrical angles, (b) speed response, and (c) fault flag

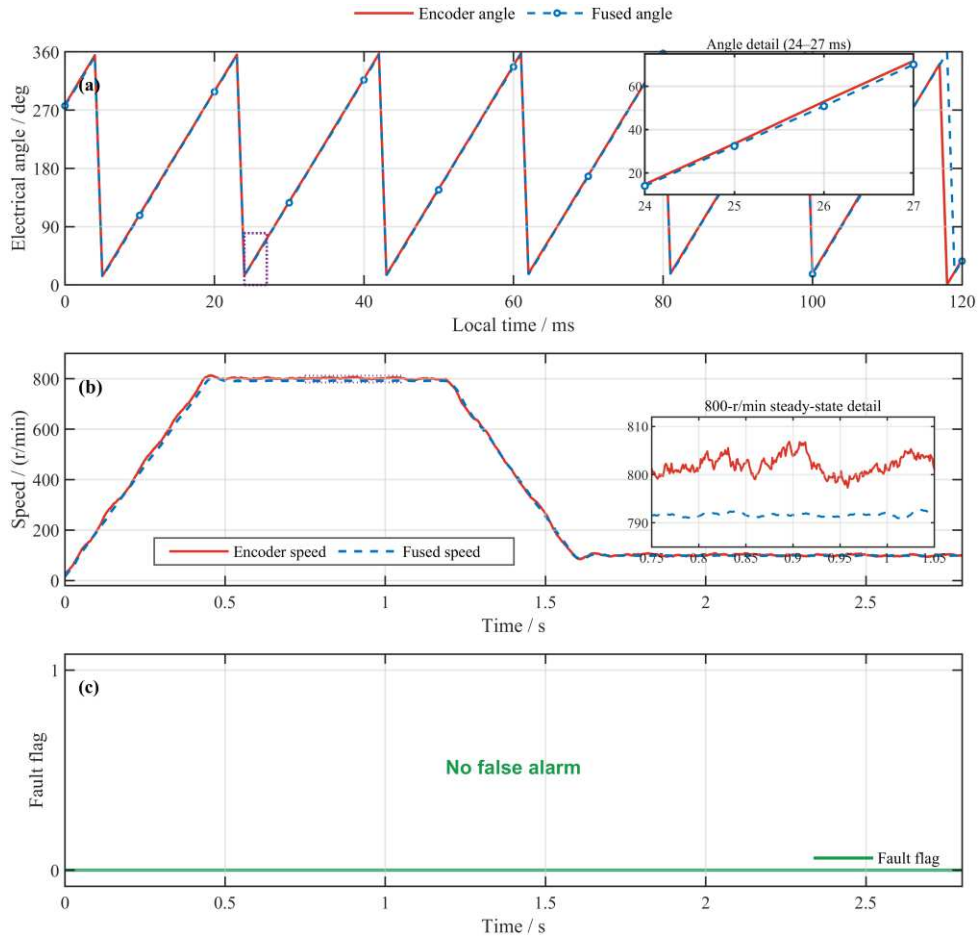


Fig. 13 Fault-free acceleration and deceleration: (a) electrical angles, (b) speed response, and (c) fault flag

At 1500 r/min in the SMO-only region, a -35° angle bias is confirmed after 30 ms. The maximum speed deviation during the complete takeover is 137.08 r/min, and the speed re-enters the $\pm 2\%$ band approximately 113 ms after confirmation, as shown in Fig. 12. Under fault-free acceleration from 0 to 800 r/min and deceleration to 100 r/min, the maximum angle residual is 4.15° , below the 15° entry threshold, and the speed residual never satisfies the confirmation criterion. The fault flag remains zero throughout this normal transient, as shown in Fig. 13.

Table 4 summarizes the closed-loop results. For the pre-startup bias, the encoder admission or isolation decision is made at the end of the 120 ms simulation observation window. Faults occurring during operation are confirmed within 16–31 ms. Across the five fault cases, the control-angle RMS error ranges from 0.363° to 1.526° , the RMS speed-tracking error from 0.92 to 9.49 r/min, and the peak of the 10 ms moving-averaged q-axis current envelope from 0.256 to 0.739 A. No false alarm occurs during the healthy startup self-check or the fault-free acceleration/deceleration case.

Table 4 Closed-Loop Results for Startup Self-Check and Encoder-Fault Cases

Case	Fault setting	Decision time (ms)	Control-angle RMS ($^\circ$)	Speed-tracking error RMS (r/min)	Maximum speed deviation in evaluation window (r/min)	q-axis current envelope peak (A)	Result
Healthy startup self-check	None	—	—	1.18	2.55	0.263	No false alarm
Pre-startup zero-speed bias	40°	120	0.363	0.92	2.57	0.256	Stable
100 r/min abrupt-bias fault	$+30^\circ$	30	0.392	1.38	10.20	0.235	Stable
300 r/min stuck-output fault	Stuck	16	0.589	3.02	14.30	0.348	Stable

Case	Fault setting	Decision time (ms)	Control-angle RMS (°)	Speed-tracking error RMS (r/min)	Maximum speed deviation in evaluation window (r/min)	q-axis current envelope peak (A)	Result
800 r/min pulse-loss-equivalent fault	-20°/-120 r/min	31	1.526	3.05	17.19	0.448	Stable
1500 r/min abrupt-bias fault	-35°	30	1.475	9.49	42.16	0.739	Stable

Note: For the pre-startup bias, decision time is the end of the 120 ms observation window. For running faults, it is the time at which either persistence criterion is met. Maximum speed deviation is evaluated after compensation fade-out for running faults and over the post-startup window for startup cases. The q-axis current peak uses a 10 ms moving average.

5 Experimental Validation

To evaluate the implementation of the proposed method on a real-time controller, a PMSM test platform with cascaded speed and current control loops is established. Four operating cases are considered: fault-free operation from 0 to 3000 r/min, a zero-speed encoder stuck-output fault, an abrupt-bias fault at 800 r/min, and a pulse-loss-equivalent fault at 3000 r/min. These cases evaluate full-speed-range parallel estimation, pre-startup fault isolation, takeover in the HFI/SMO fusion region, and high-speed takeover, respectively. Encoder faults are injected through the internal feedback channels of the controller. The experiments evaluate encoder fault diagnosis, feedback isolation, and continued closed-loop operation after takeover. The experimental cases were selected to cover startup, fusion-region, and high-speed takeover, whereas the simulation study provides a controlled comparison across the three signal-level equivalent fault models.

5.1 Experimental Setup and Control Implementation

The experimental system consists of a 24 V dc supply, a three-phase inverter, a PMSM, an incremental encoder, a TI C2000 real-time control microcontroller (TMS320F280049M), and a host computer. The motor parameters are listed in Table 3. The Simulink model is converted to executable code using Embedded Coder and deployed on the TMS320F280049M. The speed loop, current loops, HFI, SMO, fusion scheduling, and fault diagnosis are executed in a fixed-period interrupt routine. Magnetic-polarity identification before startup is also implemented in the experimental controller. The experimental platform is shown in Fig. 14.

The control and estimation periods are both 100 μ s, and the pulse-width modulation (PWM) frequency is 10 kHz. The HFI frequency is 500 Hz with a low-speed peak injection voltage of 3 V; high-frequency injection is disabled at 1000 r/min and above. Experimental data are acquired through VOFA+ using the JustFloat protocol. The main implementation parameters are listed in Table 5. The fusion schedule follows Table 2, while the diagnostic criteria and temporary-compensation parameters are those defined in Section 3.4.

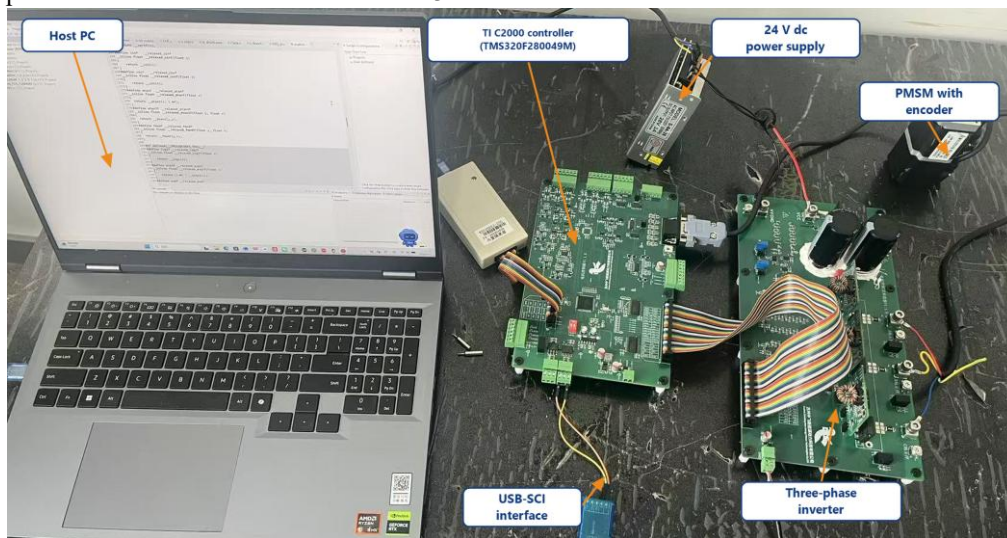


Fig. 14 Experimental platform

Table 5 Main Experimental Implementation Parameters

Parameter	Value	Parameter	Value
Controller	TI TMS320F280049M	DC-link voltage	24 V
PWM frequency	10 kHz	Control/estimation period	100 μ s

Parameter	Value	Parameter	Value
HFI signal	d-axis sinusoidal voltage	HFI frequency	500 Hz
Low-speed peak injection voltage	3 V	HFI disable speed	1000 r/min

All faults are injected through the controller feedback channels. An abrupt bias is introduced as a constant angle offset, and a stuck output holds the last encoder angle before fault injection. The pulse-loss-equivalent fault combines an angle jump with a speed decrease. This signal-level injection supports repeatable testing but does not reproduce physical A/B/Z pulse interruption or counter overflow. After fault confirmation, both encoder angle and speed feedback are removed from the closed loop.

5.2 Full-Speed-Range Parallel Fusion Estimation with a Healthy Encoder

The healthy encoder remains the closed-loop feedback source, while the HFI/SMO fused estimates run in parallel and do not participate in the Park transformation or speed-control loop. The motor is accelerated from 0 to 3000 r/min while the encoder speed and fused speed estimate are recorded. Electrical angles are then compared in time windows near 0, 800, 1500, 2500, and 3000 r/min; the zero-speed result is obtained from a separate standstill record. This experiment evaluates the continuity of parallel fusion estimation under healthy-encoder closed-loop operation. Fig. 15 shows the speed response over the full operating range.

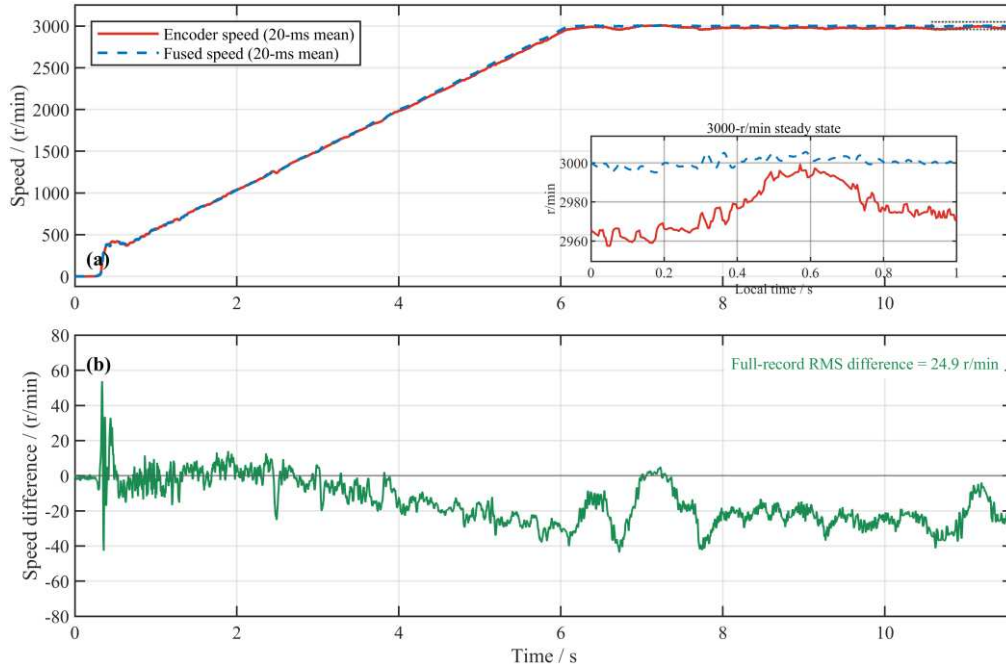


Fig. 15 Parallel speed estimation from 0 to 3000 r/min: (a) complete speed response and (b) encoder–fused speed deviation

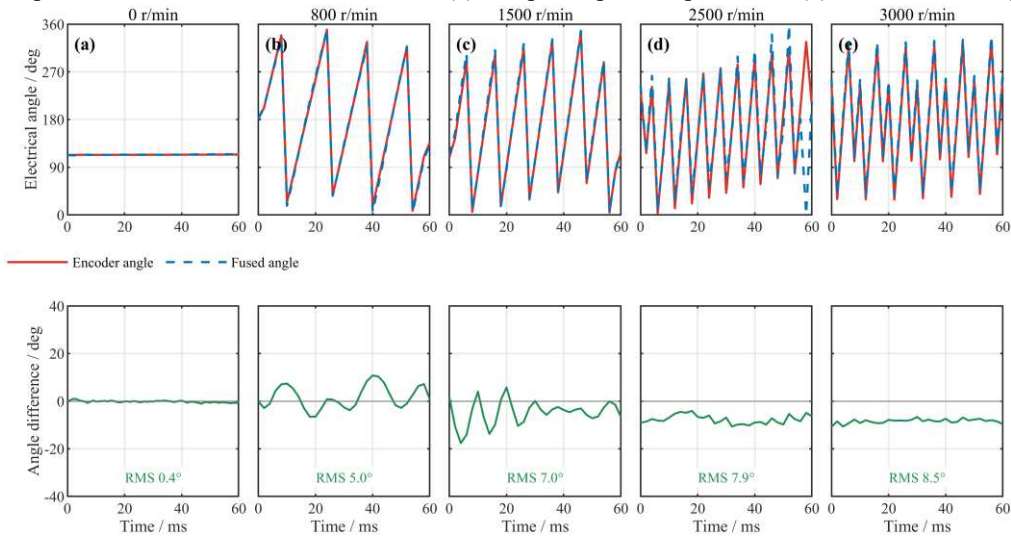


Fig. 16 Encoder and fused-angle estimates at five speeds: (a) 0, (b) 800, (c) 1500, (d) 2500, and (e) 3000 r/min

During acceleration from 0 to 3000 r/min, the fused speed estimate follows the encoder speed. The RMS deviation over the complete record is 24.9 r/min. Fig. 16 covers the HFI-dominant, HFI/SMO fusion, and SMO-dominant regions. At 0, 800, 1500, 2500, and 3000 r/min, the RMS deviations between the encoder and fused electrical angles are 0.4°, 5.0°, 7.0°, 7.9°, and 8.5°, respectively. These measurements support continuity of parallel fusion estimation. Sections 5.3 to 5.5 evaluate post-fault sensorless feedback takeover.

5.3 Zero-Speed Encoder Stuck-Output Self-Check and Sensorless Startup

Before the startup self-check, HFI magnetic-polarity identification and angle correction are completed. The encoder feedback is then frozen at a fixed value differing from the corrected HFI angle by more than 15° , representing a stuck encoder output or zero-position anomaly present before startup. Once the 30 ms angle-path persistence criterion is satisfied, the startup-isolation flag is latched and the encoder remains isolated. At approximately 0.7 s, an independent hardware startup sequence enables operation, and the motor starts using HFI angle and speed estimates as feedback. In contrast, the simulation applies the encoder admission or isolation decision at the end of a 120 ms observation window.

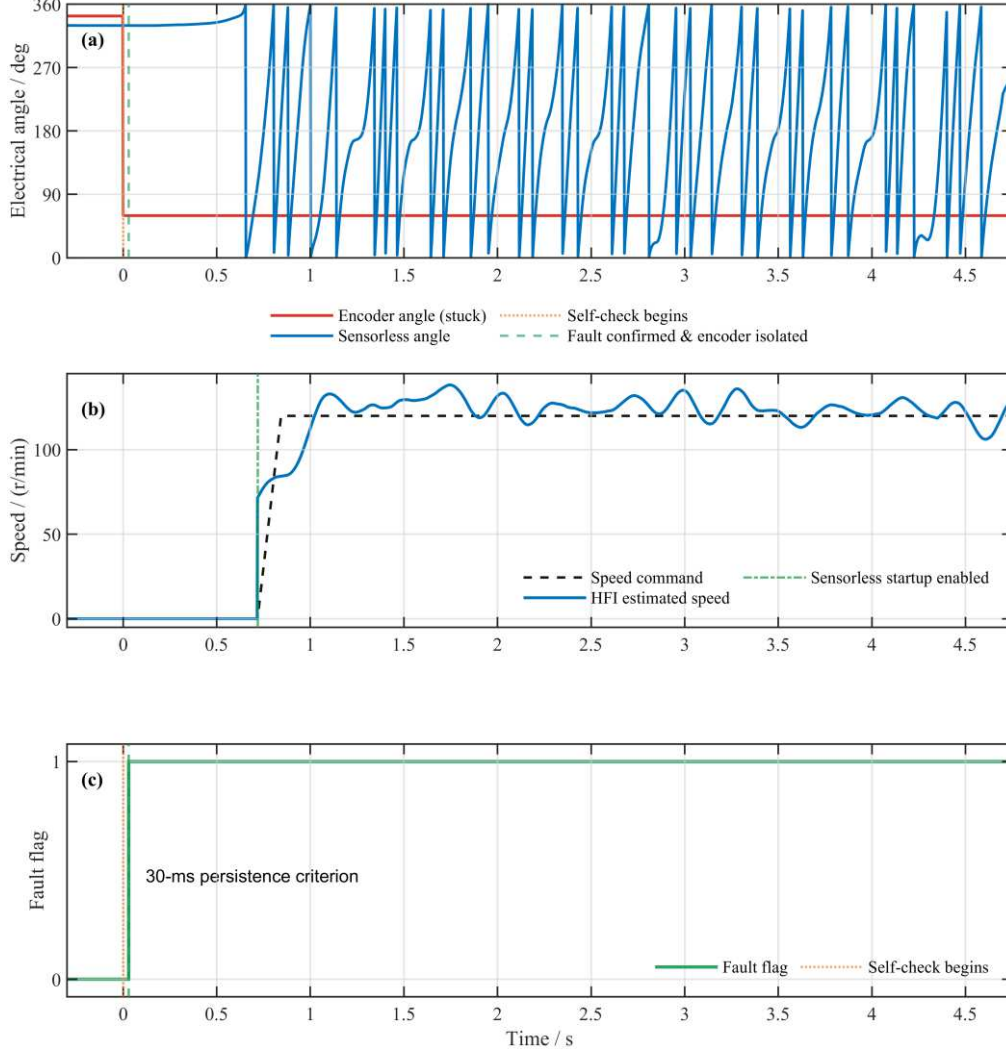


Fig. 17 Zero-speed stuck-output self-check and HFI startup: (a) electrical angles, (b) speed response, and (c) fault flag

In Fig. 17(b), the speed command is 120 r/min and the HFI speed estimate remains near 123.2 r/min, while continuous low-speed operation is maintained after encoder isolation. Because the test platform does not include an independent speed sensor, the 123.2 r/min value is an HFI estimate and is not used as a measure of actual mechanical-speed accuracy.

5.4 Takeover under an 800 r/min Abrupt Angle-Bias Fault

At 800 r/min, an abrupt bias of approximately 40° is added to the encoder electrical-angle feedback. Over the 80 ms pre-fault and 120 ms post-fault windows, the RMS deviations between the encoder and fused electrical angles are 4.8° and 38.8° , respectively. These values are not directly comparable with the corresponding simulation errors because the two evaluations use different reference quantities and the experimental results additionally include implementation delays and hardware nonidealities. Once the angle-path persistence criterion reaches 30 ms, the encoder angle and speed feedback are isolated and the fused feedback takes over. Using a 20 ms moving average and measuring from fault confirmation, the minimum fused speed estimate is 451.7 r/min. The fused speed estimate returns to within the $\pm 3\%$ band around 800 r/min after approximately 0.642 s and remains within this band for 100 ms. Closed-loop operation is maintained, although the drop and recovery of the fused speed estimate indicate that the takeover transient in the fusion region can be further improved. In Fig. 18(a), the time axis is referenced to the angle-bias injection instant, whereas the time axes in Figs. 18(b) and 18(c) are referenced to fault confirmation.

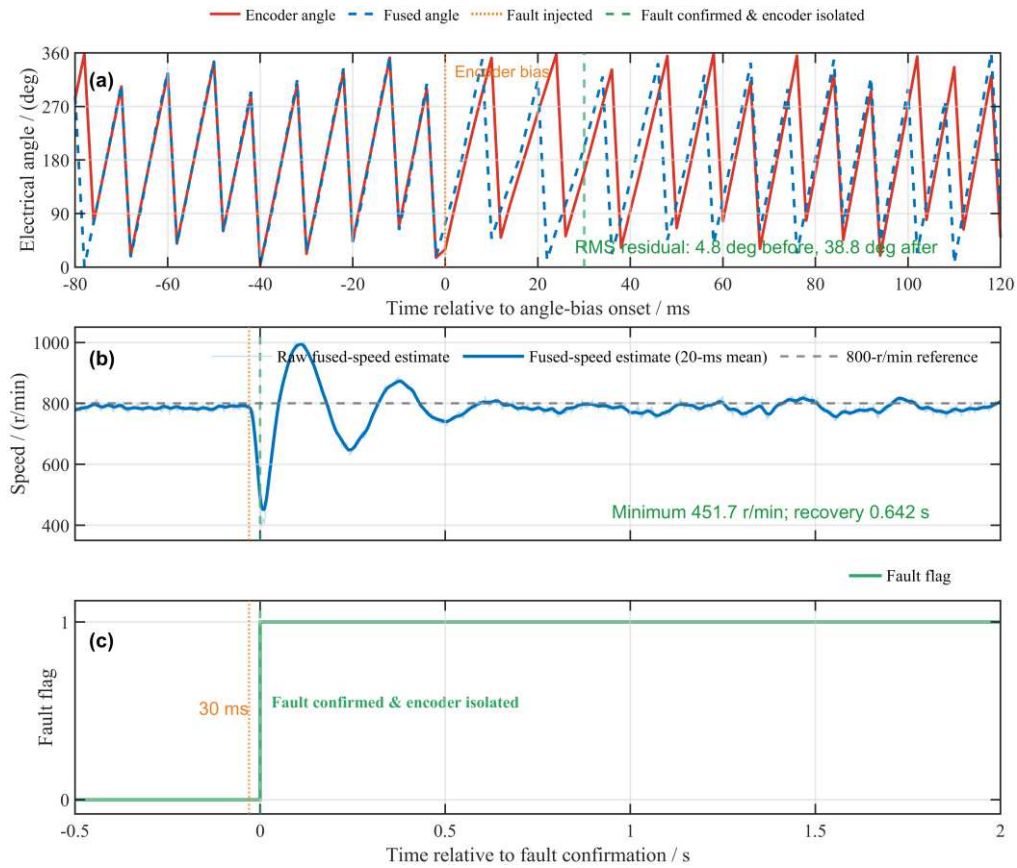


Fig. 18 Fused-feedback takeover under an 800 r/min abrupt angle-bias fault: (a) electrical angles, (b) speed response, and (c) fault flag

5.5 Takeover under a 3000 r/min Pulse-Loss-Equivalent Fault

At 3000 r/min, a -20° angle jump and an approximately 600 r/min decrease in speed are introduced into the encoder feedback to represent the accumulated angle deviation and speed anomaly associated with pulse loss. Fig. 19 shows an electrical-angle difference of approximately 20° between the faulty encoder and fused estimate. The encoder speed decreases by approximately 658.7 r/min, whereas the fused speed estimate exhibits a brief overshoot and then reconverges.

The speed-residual path confirms the fault within 15 ms. Relative to the 3000 r/min command and measured from fault confirmation, the maximum transient deviation of the fused speed estimate is 236.0 r/min. The estimate enters the $\pm 3\%$ band around 3000 r/min within 224 ms and remains there for 100 ms. Over 0.30–0.90 s after fault confirmation, the RMS deviation of the fused speed estimate from the 3000 r/min command is 11.18 r/min. The 224 ms value refers to the time required for the fused estimate to re-enter the specified band; it is not an independently measured mechanical-speed recovery time.

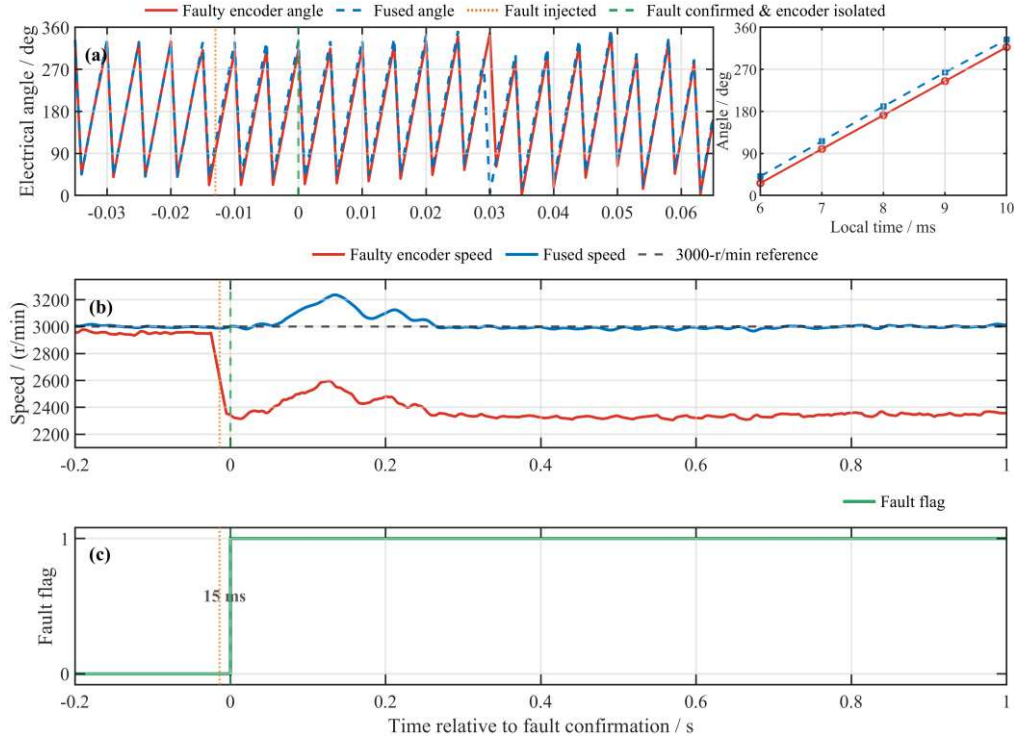


Fig. 19 Takeover under a 3000 r/min pulse-loss-equivalent fault: (a) electrical angles, (b) speed response, and (c) fault flag

6 Conclusions

This paper proposes an encoder fault diagnosis and fault-tolerant control method based on fused HFI/SMO estimates for robot-joint PMSM drives, addressing loss of position feedback, commutation-angle jumps, and degraded closed-loop stability caused by encoder faults. Under healthy conditions, the HFI and SMO channels run in parallel, and encoder status is monitored using angle and speed residuals. After fault confirmation, the encoder angle and speed feedback are isolated simultaneously, and the fused estimates reconstruct the control feedback to provide fault-tolerant closed-loop takeover.

Simulation results show that the fused estimation scheme spans zero-speed, low-speed, fusion-region, and medium- to high-speed operation. The fusion weight and HFI injection voltage are scheduled independently, and high-frequency injection is disabled at 1000 r/min and above to avoid continuous high-frequency current at higher speeds. The 50 ms temporary angle compensation reduces current and speed disturbances during the feedback-takeover transient.

For the faults occurring during operation, fault confirmation requires 16–31 ms in simulation. Across the five simulated fault cases, the post-takeover RMS control-angle error ranges from 0.363° to 1.526° , while the RMS speed-tracking error ranges from 0.92 to 9.49 r/min. Hardware experiments further demonstrate full-speed-range parallel estimation over 0–3000 r/min, zero-speed HFI sensorless startup, and encoder-fault takeover at 800 and 3000 r/min.

The hardware validation uses controller-level signal injection and does not include an independent mechanical-speed measurement. The reported hardware results therefore characterize the specified signal-level encoder faults and takeover conditions under the tested operating conditions. Physical pulse-loss faults, temperature variation, and complete robot-joint dynamics require separate experimental validation.

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Author Contributions

All authors contributed to the conception and design of the study. Material preparation, data curation, and visualization were performed by Chenxu Hu and Xuwei Shen. The first draft of the manuscript was written by Chenxu Hu. Methodology development was conducted by Xiangning Lu. Validation and supervision were provided by Xiangning Lu and Guo Ye. Resources, supervision, and manuscript review and editing were carried out by Lianchao Sheng. All authors commented on previous versions of the manuscript, read, and approved the final manuscript.

Data availability statement

The datasets generated during and/or analysed during the current study are not publicly available due to data protection and ethical considerations but are available from the corresponding author on reasonable request.

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