



Severity-Aware Anomaly Detection and Mitigation in a Permanent Magnet Synchronous Motor Traction Drive

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ABSTRACT

This study examines command and feedback anomalies in a permanent magnet synchronous motor (PMSM) traction drive using a severity-aware mitigation scheme. Seven MATLAB/Simulink cases cover healthy operation and paired unmitigated and mitigated conditions for false torque commands, speed-feedback delay and sensor mismatch. Normalised current, torque and speed residuals produce a weighted score with five severity levels (L0–L4). Mitigation applies injected-torque attenuation, ideal trusted-feedback substitution and back-calculation anti-windup. Within the 2.0–3.5 s evaluation window, RMS speed error falls from 114.58 to 7.99 rpm for false torque, 81.08 to 51.72 rpm for feedback delay, and 142.71 to 8.03 rpm for sensor mismatch. These reductions correspond to 93.02%, 36.21% and 94.37%, respectively. The findings support anomaly-specific mitigation and distinguish improved drive performance from continuing anomaly indications within the simulation assumptions.

Keyword: Permanent magnet synchronous motor; Electric vehicle traction; Anomaly detection; Severity assessment; Fault mitigation; Anti-windup control

Introduction

Electric-vehicle propulsion depends on coordinated electrical and mechanical control. Within the traction drive, measured motor states influence the voltage and current commands that produce shaft torque. Permanent magnet synchronous motors (PMSMs) are widely considered for this role because of their efficiency, torque density and controllability across demanding operating conditions (Chau et al., 2008; Zhu & Howe, 2007). Their closed-loop performance is also dependent on signal accuracy and timing provided to the controller.

The command and the feedback disturbances influence various portions of this control process. An added torque command changes the requested actuation; delayed speed feedback causes the controller to respond to previous motor state and sensor gain/offset errors change the apparent tracking error. In a surface-mounted PMSM, when it is working close to the zero d-axis current, electromagnetic torque is proportional to the current through the q-axis, and proportional to the difference between the and the rotor's acceleration.

Both electromagnetic and load torque Pillay & Krishnan (1989) . These relationships provide a basis for tracing unusual signals at the electrical response and the resulting speed deviation.

Residual diagnosis is used to identify the deviations from expected system behavior and can be used to guide. The reconfiguration of control after a failure is detected (Blanke et al., 2016; Isermann, 2006). Detection Assessment of mitigation and adaptation, however, must be done separately. A diagnostic signal can persist as long as it normally shows an abnormal input even if the physical effects are corrected by control limits. The thresholds of graded indication can therefore be used to describe the observed disturbance, if the thresholds are defined for the system being studied. In this case, severity is used as a case study simulation. Indicators are the measure of mitigation, and current, torque and speed performance.

There are already several approaches that are relevant to PMSM research. Orłowska-Kowalska et al. (2022) Diagnose and fault-tolerant control of motor, converter and sensor faults. Attaianesi et al. (2022) developed an analytical technique to identify and measure the gain fault of the phase current sensor, with the aid of numerical and experimental data. Kommuri et al. (2016) use an observer based. A reconfiguration scheme for maintaining speed tracking when sensor faults occur. When the control side is, the limited predictive current control for automotive PMSM is studied by Carpiuc & Lazar (2015). These studies provide a valuable baseline for diagnosis, replacement feedback, and control.

Besides traditional sensor failures, the command path should also be considered. Sardar et al. (2025) examine the vulnerability of PMSM drives to Frequency and Gate signal manipulation, integrity attacks. Their work proves the effects of disturbed control signals on motor operation. The current study investigates selected signal-level effects using controlled anomaly injection. The false torque, feedback delay and gain-offset cases are all distinct disturbances. They're not specific to any communication protocol or attack, but rather mechanisms implementation.

This study compares the relation between a common severity measure and physical drive performance with respect to command, timing and measurement disturbances and the changing relationship between them in the case of mitigation is enabled. Its contribution is the integration of three anomaly families, explicit residual weighting and a five-level severity scale within one control-oriented simulation. Paired comparisons allow each mitigation response to be examined under the same reference profile and load as its corresponding unmitigated case. The comparison concerns the implemented mitigation package, including its anti-windup settings.

The MATLAB/Simulink model contains an outer speed controller, an inner q-axis current controller and the motor electrical and mechanical dynamics. Seven cases comprise one healthy baseline and unmitigated-mitigated pairs for the three anomaly families. Normalised current, torque and speed residuals form a weighted score classified from L0 to L4. The mitigation actions attenuate the injected torque component, select ideal trusted feedback and apply back-calculation anti-windup. Evaluation considers current and torque deviations from the healthy baseline, speed-tracking error and the severity response.

The model uses a reduced surface-mounted PMSM representation and controlled operating conditions to make these relationships explicit. Trusted feedback is supplied by simulation ground truth, and 'severity thresholds' are study-specific. The comparisons that are drawn result in establishing the performance. In this context, detailed inverter switching, full vehicle dynamics and experimental design. Implementations of these are not addressed in the present scope. The findings are interpreted within these assumptions, with particular attention to the remaining tracking error in the feedback-delay case.

Motor Model and Control Structure

The traction drive is represented by a surface-mounted PMSM with cascaded speed and q-axis current regulation. The model retains the electrical current dynamics and mechanical torque balance needed to examine command and feedback disturbances. The d-axis current is assumed to remain approximately zero, with equal d- and q-axis inductances. This reduction follows the standard rotating-frame PMSM relationships and gives a direct connection between torque-producing current and electromagnetic torque (Krishnan, 2010; Pillay & Krishnan, 1989).

Electrical and mechanical dynamics

The q-axis current evolves according to the applied voltage, stator resistance, inductance and permanent-magnet back electromotive force:

$$L_q \frac{di_q}{dt} = v_q - R_s i_q - p \omega_m \lambda_f \quad (1)$$

Here, L_q is q-axis inductance, i_q is q-axis current, v_q is the applied q-axis voltage, R_s is stator resistance, p is the number of pole pairs, ω_m is mechanical angular speed and λ_f is permanent-magnet flux linkage. Under the zero d-axis current assumption, the torque relationship becomes:

$$T_e = \frac{3}{2} p \lambda_f i_q = K_t i_q \quad (2)$$

The torque constant K_t equals 0.51 N·m/A for four pole pairs and a flux linkage of 0.085 Wb. Electromagnetic torque T_e acts against load torque T_L and viscous friction to determine rotor acceleration:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B \omega_m \quad (3)$$

J denotes equivalent inertia and B is the viscous-friction coefficient. Angular speed is converted to the rpm signal used by the outer controller through:

$$n = \frac{60 \omega_m}{2\pi} \quad (4)$$

The electrical state responds to the voltage balance, whereas the mechanical state accumulates the net accelerating torque. Retaining both states allows a disturbance to be followed from current and torque to speed. Because K_t is constant, torque provides a proportional signature of q-axis current in this model.

Table 1. Motor parameters and nominal operating conditions.

Parameter	Symbol	Value
Pole pairs	p	4
Stator resistance	R_s	0.030 Ω
d- and q-axis inductances	L_d, L_q	0.35 mH each
Permanent-magnet flux linkage	λ_f	0.085 Wb
Equivalent inertia	J	0.050 kg·m ²
Viscous-friction coefficient	B	0.001 N·m·s/rad
Torque constant	K_t	0.51 N·m/A
Nominal power parameter	P_{rated}	3.0 kW
DC-link voltage parameter	V_{dc}	48 V

Parameter	Symbol	Value
Nominal speed reference	n_{ref}	1200 rpm
Load torque	T_L	20 N·m

The steady torque required consists of the 20 N·m load torque plus the viscous torque at the nominal speed friction. Equations (2) – (4) therefore give approximately 20.13 N·m and 39.46 A. The load-only current of $20 / 0.51 = 39.2157$ A is kept separately in the severity as its residual normalizer calculation.

Cascaded speed and current regulation

The outer controller forms the speed error $e_\omega = n_{ref} - n_{fb}$, where n_{fb} is the selected speed-feedback signal. Although the subscript identifies the speed loop, this error is expressed in rpm. Severity-based speed derating is disabled in the paired comparisons, preserving the requested profile. The speed PI controller produces an unrestricted torque request u_ω :

$$u_\omega = K_{p,\omega} e_\omega + K_{i,\omega} \int e_\omega dt \quad (5)$$

The base torque command is bounded before anomaly injection:

$$T_{base} = \text{sat}(u_\omega, T_b) \quad (6)$$

The function $\text{sat}(x, b)$ limits x to the interval $[-b, b]$. The controller torque bound T_b is 120 N·m. It is a command constraint of the simulation rather than the continuous torque rating of a physical 3 kW motor. The anomaly and mitigation stages convert this base command into T_{mit} , which determines the inner-loop current reference:

$$i_q^* = \frac{T_{mit}}{K_t} \quad (7)$$

Figure 1 presents the speed PI subsystem and the saturation of its base torque command. The speed-factor input is unity in the paired comparisons.

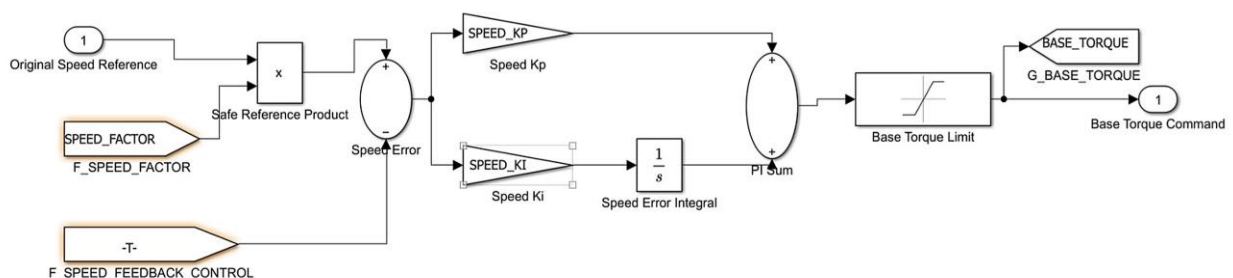


Figure 1. Speed PI controller and base torque saturation.

The current error is $e_i = i_q^* - i_q$, and the current PI controller generates the unsaturated voltage request:

$$v_{q,unsat} = K_{p,i} e_i + x_i \quad (8)$$

The current-loop error uses the actual q-axis state in the implemented plant. Perturbed sensor quantities are retained separately for the anomaly and severity paths. The controller gains are

given. The numerical values are then given after the error in rpm and the error in current (amperes) in Table 2. Gains were manually selected to provide a stable start-up and load response within the constraints imposed.

Table 2. Controller gains and imposed command limits

Setting	Symbol	Value
Speed proportional gain	$K_{p,\omega}$	0.060 N·m/rpm
Speed integral gain	$K_{i,\omega}$	0.100 N·m/(rpm·s)
Current proportional gain	$K_{p,i}$	0.350 V/A
Current integral gain	$K_{i,i}$	30.0 V/(A·s)
Back-calculation gain	K_{aw}	10.0 s ⁻¹
Base torque bound	T_b	120 N·m
q-axis voltage bound	V_b	48 V

Voltage saturation and anti-windup

The voltage saturation effect limits the current controller to follow its reference. The difference between the saturated and unrestricted outputs is fed to the anti-windup which feeds it into the integral. When the requested voltage is greater than the imposed bound Visioli (2006) , the reduction of accumulation is realized by the state. The implemented controller has the following state x_i :

$$\frac{dx_i}{dt} = K_{i,i}e_i + MK_{aw}(v_{q,sat} - v_{q,unsat}) \quad (9)$$

$$v_{q,sat} = \text{sat}(v_{q,unsat}, V_b) \quad (10)$$

$M = 0$ for health and unmitigated cases and $M = 1$ for mitigated cases. The paired comparison compares: $v_q = v_{q,sat}$. Feedback or command correction along with the enabled anti-windup branch.

The reduced voltage model is constrained by the ± 48 V bound on the q axis. It has a different style than the Modulation limit of a 48 V DC link-supplied 3-phase inverter. Other losses, such as switching losses, waveforms, inverter losses and thermal effect, don't exist here. The model thus conditions to the ones previously measured offers a controlled environment where current, torque and speed responses of the selected condition can be compared to those previously measured. The anomaly equations and the actions depending on the severity are defined in the following section.

Anomaly Models and Severity-Aware Mitigation

Three distinct anomaly families are presented, isolated from each other to discriminate bad actuation requests, stale Errors of feedback and measurement. The false torque, the speed (g_t , g_d , g_m) are selected by the binary gates, delay and sensor mismatch, respectively. A zero gate is used to keep the healthy signal active and the indicated perturbation. The following magnitudes are test settings that are under control. The measurements taken and the signals chosen for control are different throughout the calculation.

Controlled anomaly injection

The false-torque case adds a 40 N·m component to the bounded base command:

$$T_{attack} = T_{base} + g_T \Delta T, \quad \Delta T = 40 \text{ N} \cdot \text{m} \quad (11)$$

The command presented to the anomaly-monitoring path just prior to attenuation is called T_{attack} . To mitigate the injected component, the load-carrying command is still T_{base} separately. For the speed-delay case, the perturbed measurement is:

$$n_{bad}(t) = (1 - g_d)n_{actual}(t) + g_d n_{actual}(t - \tau) \quad (12)$$

The delay τ is 0.080 s. When $g_d = 1$, speed-feedback path gains the motor speed from 80 ms earlier. Sensor mismatch applies simultaneous gain and offset changes to speed and current:

$$n_{bad} = (1 - g_m)n_{actual} + g_m(1.10n_{actual} + 30) \quad (13)$$

$$i_{q,bad} = (1 - g_m)i_q + g_m(1.12i_q + 2) \quad (14)$$

The offsets are 30 rpm and 2 A respectively and the physical speed is n_{actual} and mechanically obtained, n_{bad} and $i_{q,bad}$ are perturbed speed and current measurements. n_{bad} is provided by the equation below, depending on the chosen anomaly family (12) or (13). The outer-loop feedback is affected by speed measurement and the perturbed current is stored for Comparative diagnosis with the real current condition.

Residual calculation and normalisation

Residuals are the relation of the imposed signal changes to the motor response. The current signature combines departure from the nominal load-only current, disagreement between the perturbed and the actual current signals:

$$r_I = |i_q - I_{nom}| + |i_{q,bad} - i_q| \quad (15)$$

The torque signature retains the difference between the attacked command and the electromagnetic torque:

$$r_T = |T_{attack} - T_e| \quad (16)$$

The speed signature combines reference-tracking error and the discrepancy between perturbed and actual feedback:

$$r_N = |n_{ref} - n_{actual}| + |n_{bad} - n_{actual}| \quad (17)$$

The current normaliser is $I_{nom} = 39.2157 \text{ A}$, corresponding to 20 N·m divided by K_t . Torque and speed normalisers are $T_{norm} = 25 \text{ N} \cdot \text{m}$ and $N_{norm} = 300 \text{ rpm}$. The residual percentages are defined as:

$$Z_I = \frac{100r_I}{I_{nom}}, \quad Z_T = \frac{100r_T}{T_{norm}}, \quad Z_N = \frac{100r_N}{N_{norm}} \quad (18)$$

Before weighting, each of the three signatures is put on a common number scale with normalization. The selected denominators are not uncertainty estimates or statistically obtained, but rather model settings. Residuals are computed on the fly, without RMS averaging, low-pass filtering or the weighted combination is located behind the clipping. Since torque is proportional to q-axis current in the reduced model, the signatures are related; the weighting defines their contribution to the score rather than implying statistical independence.

Severity classification

The raw score assigns weights of 0.40 to current and 0.30 each to torque and speed:

$$S_{raw} = 0.40z_I + 0.30z_T + 0.30z_N \quad (19)$$

A startup gate suppresses the score during the initial acceleration interval:

$$S(t) = A(t)S_{raw}(t) \quad (20)$$

$A(t)$ equals zero for $t < 1.8$ s and one thereafter. The resulting S is mapped to the five non-overlapping bands in Table 3. Normalisers, weights and band boundaries were selected manually for the controlled cases. They define severity within this model and do not constitute an externally standardised scale. The startup gate excludes initial acceleration from detection; an anomaly arising before 1.8 s is also suppressed by this logic.

Table 3. Severity bands and false-torque attenuation factors

Level	Score interval	Torque factor α
L0	$S \leq 5$	1.00
L1	$5 < S \leq 10$	1.00
L2	$10 < S \leq 20$	0.50
L3	$20 < S \leq 35$	0.25
L4	$S > 35$	0.00

Mitigation actions and control selection

The mitigation-enable signal M is set for each comparison case. When mitigation is active, the torque factor $\alpha(L)$ follows Table 3 and scales only the injected component:

$$T_{mit} = T_{base} + [1 - M + M\alpha(L)](T_{attack} - T_{base}) \quad (21)$$

For $M = 0$, the complete attacked command is retained. If $M = 1$, then the added component is halved by L2, L3 keeps one quarter, L4 takes one quarter. At all severities, the base command is available. This means that it maintains torque production for the regular load and only limits the false addition.

In the delay and mismatch cases, the selected speed feedback follows:

$$n_{fb} = (1 - M)n_{bad} + Mn_{actual} \quad (22)$$

The trusted signal is simulation ground truth. Feedback selection is enabled by the comparison-case setting M ; it is not inferred solely from a severity threshold. The inner current controller continues to use the actual q -axis state, as defined in the motor-model section. An observer could provide replacement feedback in a subsequent implementation, as demonstrated in PMSM sensor-fault control research Kommuri et al. (2016).

The same enable signal activates the back-calculation branch in Equation (9). Each mitigation-ON response therefore reflects the combined command or feedback action and the gated anti-windup correction. The detector retains T_{attack} , n_{bad} and $i_{q,bad}$ even when corrective control selects a different signal. A high score can consequently persist while the physical response improves. Severity and drive performance are reported together to distinguish continuing evidence of an injected anomaly from the effectiveness of its mitigation. Figure 2 illustrates residual normalisation, severity mapping and the available mitigation actions.

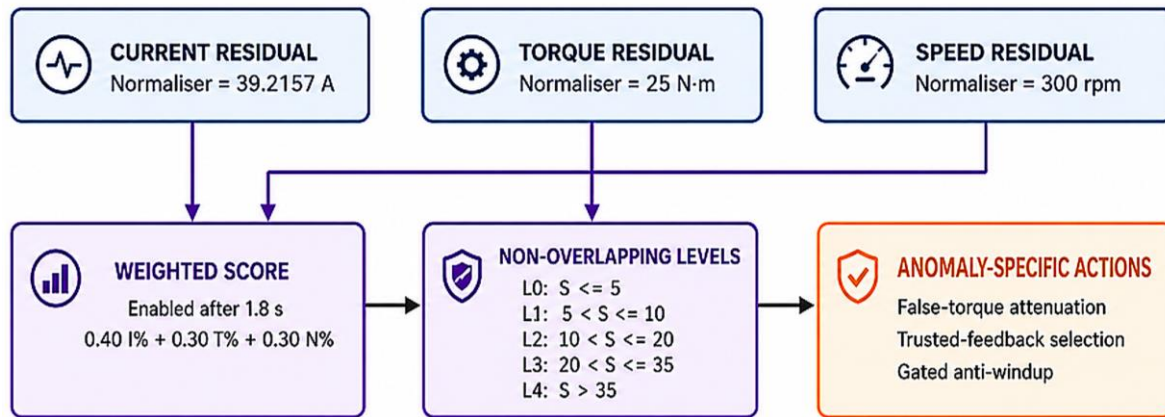


Figure 2. Residual normalisation, severity mapping and mitigation.

Simulation Protocol and Performance Evaluation

The MATLAB/Simulink R2026a evaluation uses seven simulation cases to compare nominal operation with the physical consequences of three controlled anomaly families. Motor parameters, controller gains, command limits and severity settings follow the preceding sections. Within each unmitigated–mitigated pair, the reference and load profiles and the anomaly magnitude are retained.

Case design and operating schedule

C0 is the reference for the healthy one. C1/C2 – false torque, C3/C4 – speed-feedback. A delay is introduced and C5/C6 study sensor mismatch. Mitigation is turned off in C0, C1, C3 and C5. Activated in C2, C4 and C6. Each pair of anomalies has one active family. The case assignments in Table 4 are summarized.

Table 4. Simulation cases and paired mitigation conditions

Case	Condition	Speed reference	Mitigation M
C0	Healthy baseline	1200 rpm	OFF (0)
C1	False torque, +40 N·m	1200 rpm	OFF (0)
C2	False torque, +40 N·m	1200 rpm	ON (1)
C3	Speed-feedback delay, 80 ms	1200 rpm; pulse to 1350 rpm	OFF (0)
C4	Speed-feedback delay, 80 ms	1200 rpm; pulse to 1350 rpm	ON (1)
C5	Speed/current gain-offset mismatch	1200 rpm	OFF (0)
C6	Speed/current gain-offset mismatch	1200 rpm	ON (1)

These simulations are performed over 6 s and with a solver step of 1×10^{-4} s, the maximum value allowed. The solver step upper bound is different to the fixed sampling interval. A 20 N·m load is used for the anomaly comparisons. The reference speed is 1200 rpm. The recommended anomaly range is between 2.0–3.5 s. For the delay-test program, the reference speed ramps up to 1350 rpm at 2.0 s and then back down to 1200 rpm at 2.8 s. The 4.0 s plots are used to analyze performance metrics and the 6.0 s plots the entire motor response. Input-transition time and motor-response time are considered separately. The anomaly-comparison speed plots represent the output behavior, but not the switching times as those are prescribed.

Both C3 and C4 have the same commanded speed pulse and C0 is the nominal reference. This difference is maintained when analyzing deviation from C0. The requested profile will be maintained in each pair despite a speed derating due to severity.

Evaluation window and reference quantities

The RMS metrics use $W = \{t: 2.0 \leq t \leq 3.5 \text{ s}\}$. Time Suppressor Startup 1.8 s is indications and differs from this evaluation period. They begin and conclude their shows during the entire show run. Only the samples in the range are used for the tabulated RMS metrics, while the output transients are carried out on every sample.

In case k, the current and electromagnetic torque are compared with the healthy C0 (healthy case). In the case of waveforms over W, the actual speed is compared to the reference active. RMS_W denotes the root mean square of the signal data in the data window. Current deviation is calculated as:

$$D_I(k) = 100 \frac{\text{RMS}_W[i_{q,k} - i_{q,C0}]}{\text{RMS}_W[i_{q,C0}]} \quad (23)$$

The equivalent torque deviation is:

$$D_T(k) = 100 \frac{\text{RMS}_W[T_{e,k} - T_{e,C0}]}{\text{RMS}_W[T_{e,C0}]} \quad (24)$$

Both values of D_I and D_T are percentages of the quantity of healthy RMS. They describe, as opposed to individual measures of harmonic content, differences from the healthy trajectory. The speed-tracking error is:

$$E_n(k) = \text{RMS}_W[n_{ref,k} - n_{actual,k}] \quad (25)$$

E_n is expressed in rpm, with each having the active reference used in each case. The current that is flowing relative to C0. For C3/C4, a torque deviation is composed of the commanded transition and the delayed-feedback response.

Paired improvement and severity interpretation

The relative improvement, Q is the same for any of the performance metrics listed below:

$$G_Q = 100 \frac{Q_{OFF} - Q_{ON}}{Q_{OFF}} \quad (26)$$

Q_{OFF} is the unmitigated value of D_I , D_T or E_n ; Q_{ON} is mitigated value of D_I , D_T or E_n ; G_Q is the percentage improvement of these two values. It is determined for positive Q_{OFF} , and is reported as not applicable if $Q_{OFF} = 0$. The percentages are accompanied by absolute values that reflect the rest of the error.

The current and torque deviations from the respective waveforms are expressed in terms of their normalized values, i.e., $T_e = K_t i_q$. Link and represent related results in an equal manner. Retained anomaly – severity curve, Max Levels evidence. Physical deviations measure the effectiveness of mitigation and a continuing anomaly will be recorded. Improved tracking as indication to coexist.

Results and Discussion

The seven cases are tested with the help of the healthy operating point, the paired anomaly responses and the severity trajectories. Current and torque deviations and speed-tracking error follow: Equations (23) – (25), where the performance measures constrain the range 2.0 – 3.5 s. The complete 6 seconds plot give an independent display of the transients at the start and

later. Blue and orange curves are identified as unmitigated and mitigated responses, respectively and the healthy-speed was the standard of comparison.

Healthy operating point

After acceleration, the C0 speed approaches the nominal reference speed $C0 = 1200$ rpm as shown in Figure 3. The reported steady electromagnetic torque is, around $20.13 \text{ N}\cdot\text{m}$ and the q-axis current is approximately 39.46 A . The relationship between them agrees with $K_t = 0.51 \text{ N}\cdot\text{m/A}$. The small torque viscous friction is only supplied by the increment above the $20 \text{ N}\cdot\text{m}$ load, at the nominal speed. This equilibrium builds links between the electrical and mechanical states using the motor relationships of Equations (2) and (3) in accordance with the machine modelling approach as described by Chiasson (2005).

During first interval of acceleration, the severity output is stored at L0 in the startup gate. This behavior is based on the specified detection logic and does not claim sensitivity for an anomaly. The time is introduced prior to 1.8 s . The waveform reference for the C0 is then provided by the current and torque comparisons, which are included in Table 5.

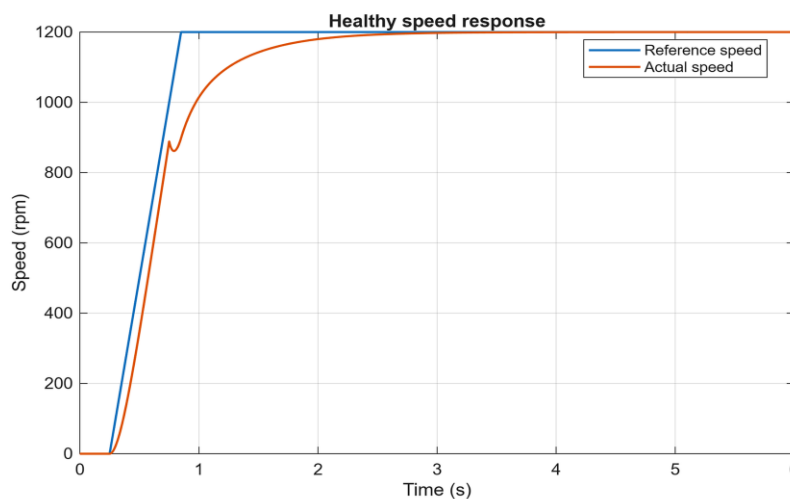


Figure 3. Healthy C0 speed response over 6 s.

Table 5. Paired performance metrics and maximum severity levels

Anomaly / case	Current and torque deviation (%)	Speed RMS error (rpm)	Maximum level
False torque / C1	21.7245	114.5810	L4
False torque / C2	0.1545	7.9938	L4
Speed delay / C3	15.5981	81.0752	L4
Speed delay / C4	8.7417	51.7174	L4
Sensor mismatch / C5	7.3124	142.7117	L4
Sensor mismatch / C6	0.0000	8.0303	L3

The equation $T_e = K_t i_q$ is satisfied if the two numbers coincide. They still remain separate physical quantities, but they do not give an idea of independent performance evidence in this mini-model.

The false-torque pair compares command-path perturbation under identical nominal reference and operating load. The unmitigated C1 trajectory is shown with a higher speed in Figure 4 and is followed by a pronounced later undershoot. The mitigated C2 path is very close to "normal" operation. The other transient is displayed for qualitative comparison and does not fall in the range of the 2.0–3.5 second RMS evaluation.

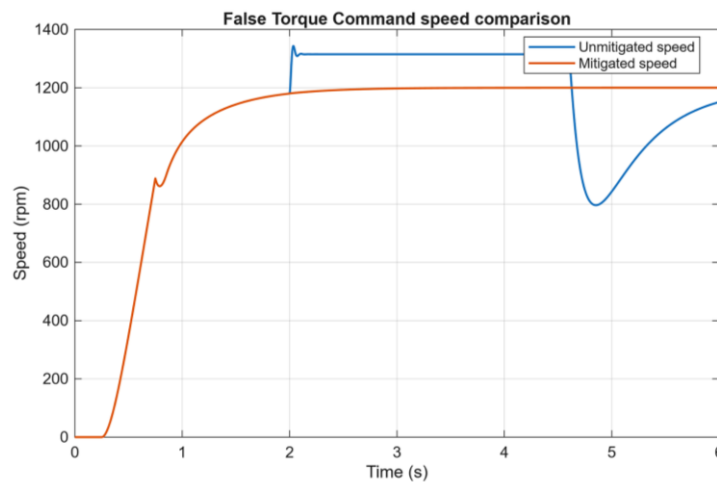


Figure 4. False-torque speed comparison, C1 versus C2.

The Current and torque deviation reduce from 21.7245% to 0.1545% and the RMS speed error reduces from 114.5810 rpm to 7.9938 rpm. The base torque request is maintained under the attenuation rule, which restricts the added component instead of removing the command required to handle the normal load. The results below are for the combined attenuation and anti-windup treatment. They do not separate their own work from the work of others when doing comparisons.

Both cases exist at L4 in Figure 5. This is the maximum retained that is compatible with the improved physical. However, the detector receives T_{attack} before attenuation, a phenomenon that is known as response. The severity output is not a direct measure of the actual speed error, but describes abnormal command evidence.

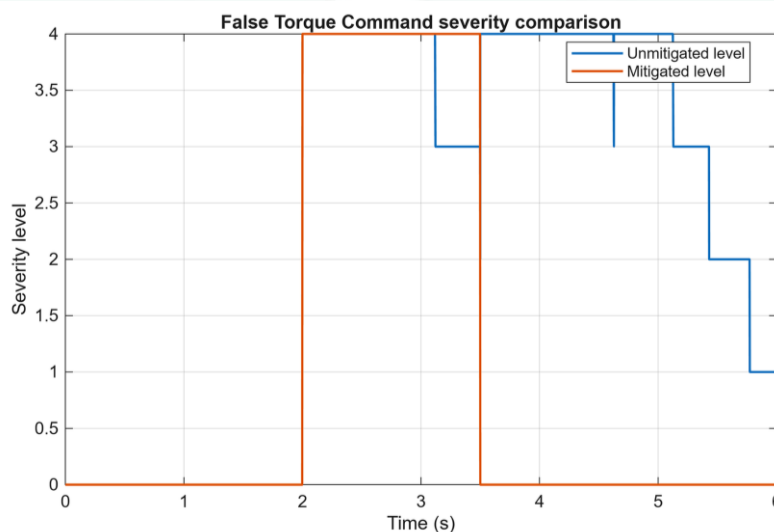


Figure 5. False-torque severity comparison.

Speed-feedback-delay response

The delay pair evaluates the temporary increase of an 80 ms feedback-delay branch, under the specified delay in speed reference. As shown in the figure 6, smaller dip in speed is observed for the mitigated C4 response, A smoother recovery than in the non-mitigated C3 response. The motor speed changes shown are not used to calculate reference-switching times. The error in the RMS speed falls from 81.0752 rpm to 51.7174 rpm, and current and torque deviate from 15.5981% to 8.7417%.

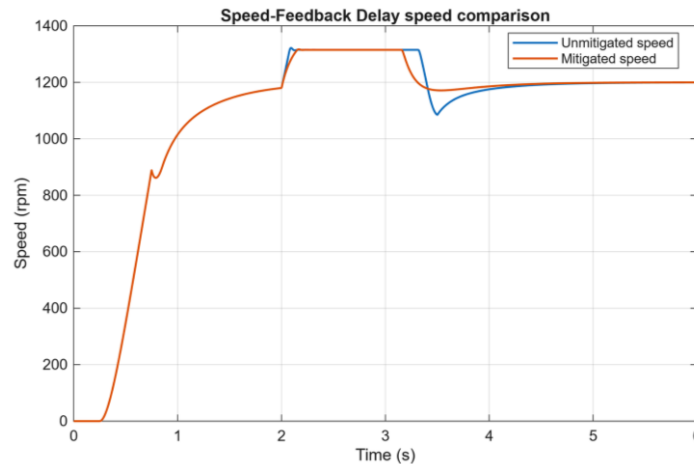


Figure 6. Speed-feedback-delay comparison, C3 versus C4.

The voltage balance is a model-based interpretation of the tracking error that is left over. At 1350, the back-electromotive-force (b_{emf}) term ($p \omega_m \lambda_f$) is about 48.1 V and is already quite close to the reference. Before considering stator resistance or current dynamics, the model can be used to cover the ± 48 V q-axis. This calculation detects a small voltage drop at the given reference speed at higher speed. Trusted feedback cancels out the delayed measurement from the active speed loop and can't make it faster. The paired comparison compares feedback reconfiguration in the presence of the imposed. The actuator is bound and won't separate an error of delay from the rest of the error.

Figure 7 indicates that both delay cases are satisfied with L4, but their levels differ over the course of the time simulated. The delayed signal is retained by the residual calculation following the feedback substitution. The shared pulse profile comparison with and without mitigation is conducted. The commanded transition is also present in the C0-relative current and torque deviations of package; its defined in the simulation protocol.

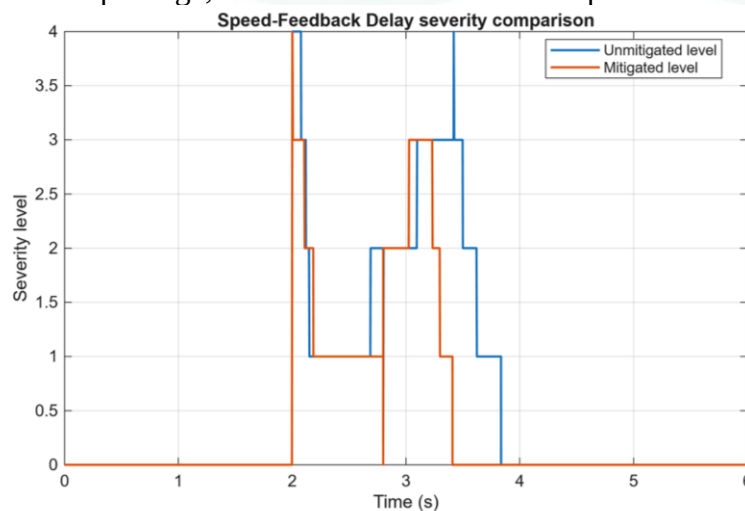


Figure 7. Speed-feedback-delay severity comparison, C3 versus C4.

Sensor-mismatch response

Gain and offset mismatch (C5) cause deformation of the measurement to the actual speed. The outer controller therefore decreases the speed command of its current, and the actual speed is lower than the nominal reference. This slowdown and the resulting recovery are illustrated in Figure 8. The largest rms speed error for unmitigated cases is due to sensor mismatch. Despite having a smaller current and torque deviation, 7.3124%, 142.7117 rpm is larger than false torque or delay.

C6 shorts out the disturbed speed measurement path in the control path but retains the path for diagnosis. The speed error of RMS is reduced to 8.0303 rpm. The current is 0.0000% deviation, and the torque is 0.0000% deviation under the C0-relative definitions. The rounded figure shows that the result is close to the healthy physical. Not that the measurement perturbation has actualized trajectories within the evaluation window, but rather that the measurement perturbation has arisen out of a collection of actualized trajectories within the evaluation window. Figure 9 shows the continued signs of anomaly, with maximum severity reducing in size from L4 to L3.

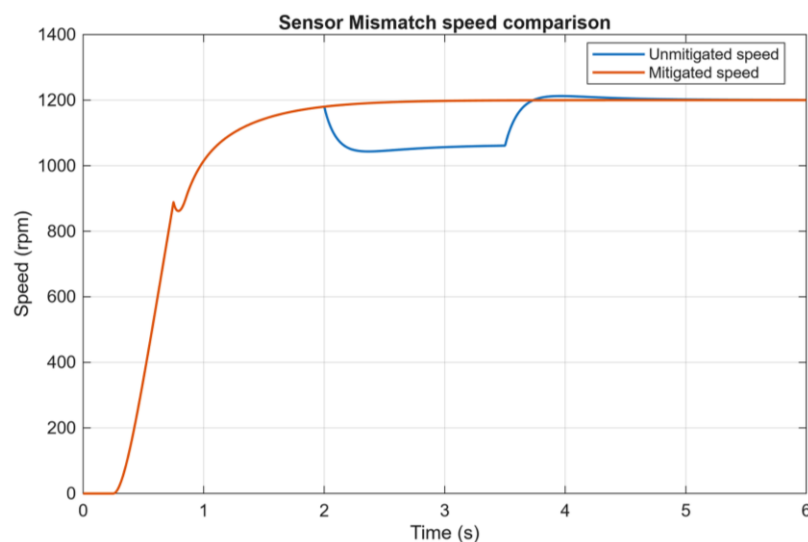


Figure 8. Sensor-mismatch speed comparison, C5 versus C6.

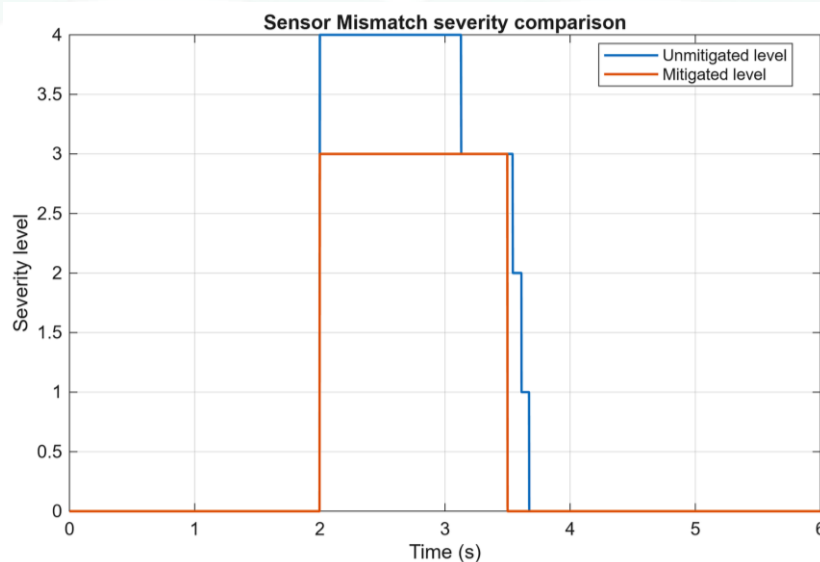


Figure 9. Sensor-mismatch severity comparison, C5 versus C6.

Comparative performance and interpretation

The efficiency of mitigation is found to be anomaly pathway dependent as seen in Table 6 and Figure 10. Delays and sensor mismatch decrease the speed error by less than 3% improves by 36.21%. Residual error: 51.7174 rpm-about 6 times lower. The errors of the other mitigated cases made up. Also, the relative improvement reported does not erase the difference between partial recovery and near-healthy tracking.

Table 6. Relative mitigation improvements from Equation (26).

Anomaly	Current and torque improvement (%)	Speed-error improvement (%)
False torque	99.29	93.02
Speed-feedback delay	43.96	36.21
Sensor mismatch	100.00	94.37

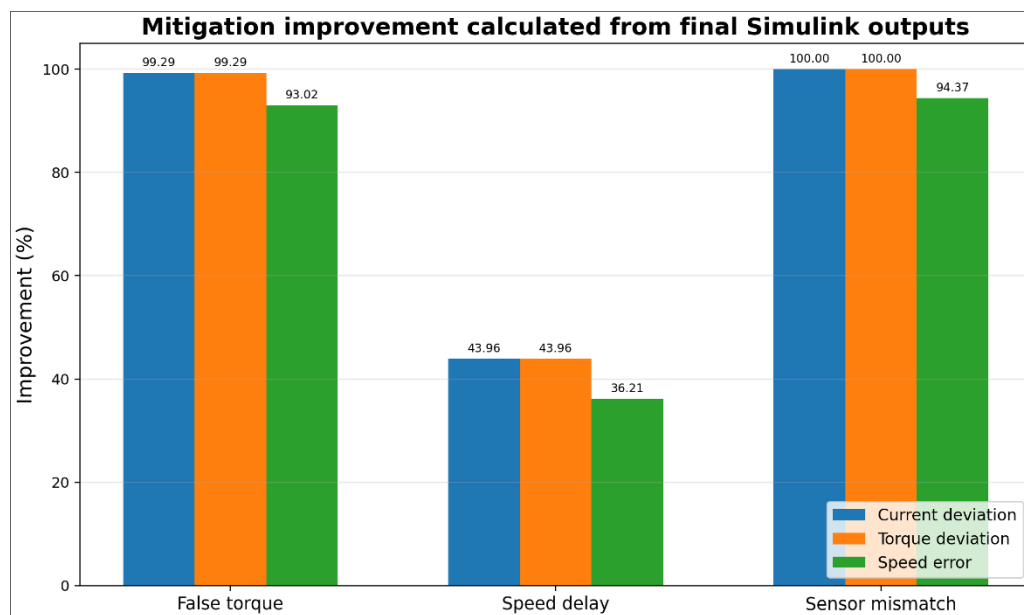


Figure 10. Relative mitigation improvements over 2.0–3.5 s.

The findings corroborate the notion of separating diagnosis from corrective control. Strong residual evidence is available to support the interpretation that, beyond the physical response is improved, successful mitigation action does not need to be restored. However, the severity output is sent straight to L0. Conversely, a lower level does not establish that the underlying perturbation has disappeared. The manually chosen bands describe the selected simulation cases; broader diagnostic performance would require tests with noise, parameter variation, different anomaly magnitudes and combined disturbances.

Practical feedback reconstruction is the principal difference between this simulation and a deployable controller. Discrete-time observer-based sensorless PMSM control provides one research direction for obtaining estimated speed instead of direct plant-state access Bernardes et al. (2014).

Vehicle-level assessment would also need to connect motor control with the energy source, power electronics and changing traction demands considered in electric-vehicle drivetrain

design Ehsani (2018). The present results exclude switching-inverter behaviour, battery-voltage variation, thermal effects and road-load variation. They establish comparative behaviour within the defined reduced model. The near-healthy false-torque and mismatch responses and the larger remaining delay error provide specific priorities for subsequent controller development and laboratory evaluation.

Conclusions and Future Work

This study evaluated anomaly detection and mitigation in a reduced PMSM traction drive. Seven cases compared healthy, unmitigated and mitigated operation. Weighted current, torque and speed residuals supplied five severity bands. The healthy model approached 1200 rpm, 20.13 N·m electromagnetic torque, and 39.46 A q-axis current, consistent with the torque constant and load balance.

Mitigation was most effective for false torque and sensor mismatch. False-torque attenuation, together with enabled anti-windup, reduced current and torque deviation by 99.29% and speed-tracking error by 93.02%. Trusted-feedback selection and anti-windup reduced the mismatch-case speed error by 94.37%, with C0-relative current and torque deviations reported as 0.0000%. The corresponding mitigated speed errors were 7.9938 rpm and 8.0303 rpm. These outcomes indicate near-healthy physical responses under the selected conditions.

The speed-delay case showed partial recovery. Current and torque deviation improved by 43.96%, and speed error improved by 36.21%, leaving a 51.7174 rpm RMS error. These results quantify the combined feedback-selection and anti-windup treatment under the imposed voltage bound. The main performance limiting condition remains the delay-test. The paired individual contributions are assessed through comparison; the performance of the combined mitigation is assessed by comparing the individual contributions. There is no separation between the selection of feedback and anti-windup and actuator constraints.

Severity and mitigation performance is complementary with inaccurate torque and delay. A maximum of L4 was retained after mitigation while mismatch went down from L4 to L3. A persistent indication may accompany a decrease in physical error as the detector is able to keep the perturbed signals. The study contrasts anomaly paths and corrective actions in one control-oriented model.

Plant-state feedback should be removed and replaced by a validated observer and predictor for further development. Delay studies can use a different latency and reference transitions. Residual weights, correct normalizers and thresholds should then be calibrated based on measured healthy ranges and tested. Parameter uncertainty, combined anomalies and sensor noise. Plant development should include switching inverters, voltage fluctuations within battery, motor losses, thermal behaviors and vehicle traction dynamics.

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