Position Fault Detection for UAM Motor with Seamless Transition

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ABSTRACT A strict fault tolerance is required in urban air mobility (UAM). The motor position sensor is one of the monitoring targets in UAMs, because it is in a harsh environment such as rain, ice, dust, vibration, etc. In this work, a resolver-based sensor method and a sensorless algorithm are fused in cooperative mode. Under normal conditions, the sensored angle and the sensorless angle are weighted equally. However, in case of sensor failure, only the sensorless method is selected. In other cases, only the sensored angle is fully respected. It is assumed here that the sensored method as well as the sensorless method may fail. To determine which of the two methods is faulty, the measured current is used as a reference. The virtual current is obtained by numerically solving the permanent magnet synchronous motor (PMSM) model in the stationary frame using the rotor angles. The position fault is then detected by comparing the virtual current to the measured current. Sigmoid functions with a step at zero are used for fault detection and fusion method robust against sudden error fluctuations or noise. Convincing performance and robustness are demonstrated by simulation and experimental results.

INDEX TERMS Urban air mobility, Fault-tolerant control, Permanent magnet synchronous motors, motor control, Runge-Kutta 4th.

I. INTRODUCTION Electric urban air mobility (UAM) envisions a safe, sustainable, and accessible air transportation system for passenger mobility within traversing metropolitan [1]. UAM is gaining increasing attention with advances in battery energy density and fuel cell batteries. In the near future, UAMs will become the main short-haul aircraft due to the convenience of vertical takeoff and landing. Fig. 1 shows the conceptual design of a UAM equipped with four propulsion electric motors. PMSMs are primarily used in UAMs due to their high power density. In PMSM speed control, field-oriented control has an absolute advantage, which requires rotor position [2]. Since high reliability is strongly demanded in aerial vehicle, sensor fault tolerance is also important. The resolver is most widely used in PMSMs since they are robust and provide absolute position [3], [4]. It also provides more accurate angle information by compensating the resolver angle error [5], [6].

Many safety critical systems use multi-sensors in parallel, fusion, and backup to increase fault tolerance. Sensorless methods were often used as a backup for sensor failure in the high reliability system [7]- [13]. Kai et al. [7] detected position sensor fault by monitoring the difference between measured and estimated values. G. Foo et al. [8] conducted a similar study using the extended Kalman filter (EKF). In [9], a robust fault detection method was proposed using an adaptive EKF with varying covariance. H. Berriri [10] proposed a fault detection method based on parity space that is less affected by parameter changes. A fault detection method was proposed with a failover scheme by using extended back electromotive (EMF) force [11]. A transition method was considered based on the adaptive threshold angle to avoid unnecessary switching between sensored and sensor-
less modes [12], [13]. J. Liu et al. [14] also proposed a soft transition method by adjusting the linear weights.

Because sensor failure or sensor error was detected based on the sensorless output, previous work is limited in determining the error or estimating the error. Note that sensorless angle estimation is not always correct because there are uncertainties in inductance [15], [16], back EMF coefficient [17], and temperature-related stator coil resistance [18]. The accuracy is also affected strongly by the uncertainty of the voltage drop over semiconductor switches [19], [20].

In this work, currents are used to determine the accuracy of angles. It employs two virtual PMSM models inside a controller. One is utilizing the sensored angle and the other the sensorless angle for the reference frame. The virtual currents are obtained as the model outputs and they are compared with the measured current. Any value closer to the measured current is considered more accurate. Then, the accurate angle is weighted more than the other. Further sigmoid functions are used in fault detection and determining the weights to enhance the robustness and seamless transition.

This paper is organized as follows: The mathematical PMSM model is stated in the stationary frame and the fault detection method is derived in Section II. A position angle fusing method is developed using the current comparison method is derived in Section II. A position angle estimation is not always correct because there are angle errors in the measured current. We use the sensored angle for a model with the measured current. Any value closer to the measured current is considered more accurate. Then, the accurate angle is weighted more than the other. Further sigmoid functions are used in fault detection and determining the weights to enhance the robustness and seamless transition.

This paper is organized as follows: The mathematical PMSM model is stated in the stationary frame and the fault detection method is derived in Section II. A position angle fusing method is developed using the current comparison and relative angle difference in Section III. Simulation results are shown along with failsafe control block diagram in Section IV. Finally, the experimental results are analyzed.

II. PMSM MODEL AND FAULT DETECTION METHOD

Interior PMSM is modeled in the stationary $\alpha \beta$ frame as [17]

$$\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} = \begin{bmatrix} \frac{d}{dt} i_{\alpha} \\ \frac{d}{dt} i_{\beta} \end{bmatrix} = r_{s} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} + \begin{bmatrix} L_{S} + L_{d} \cos 2\theta_{e} & L_{d} \sin 2\theta_{e} \\ L_{d} \sin 2\theta_{e} & L_{S} - L_{d} \cos 2\theta_{e} \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} + \begin{bmatrix} \omega_{e} \psi_{m} & -\omega_{e} \psi_{m} \end{bmatrix} \begin{bmatrix} \sin \theta_{e} \\ \cos \theta_{e} \end{bmatrix}$$

(1)

Then, it is derived in an ordinary differential equation (ODE) form such that

$$\begin{bmatrix} \frac{d}{dt} i_{\alpha} \\ \frac{d}{dt} i_{\beta} \end{bmatrix} = \frac{1}{L_{d} L_{q}} \begin{bmatrix} L_{S} - L_{d} \cos 2\theta_{e} & -L_{d} \sin 2\theta_{e} \\ -L_{d} \sin 2\theta_{e} & L_{S} + L_{d} \cos 2\theta_{e} \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} - \frac{d}{dt} \begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} = 2\omega_{e} L_{d} \begin{bmatrix} -\sin \theta_{e} \\ \cos \theta_{e} \end{bmatrix}$$

(2)

where $v_{\alpha}, v_{\beta}$ and $i_{\alpha}, i_{\beta}$ are the $\alpha \beta$-axis voltages and currents. $r_{s}$ is the stator resistance, $L_{S} = \frac{L_{d} + L_{q}}{2}$ and $L_{d} = \frac{L_{d} - L_{q}}{2}$ are the average and difference inductances, respectively. Note that if $L_{d} = 0$, it becomes an surface PMSM model. $\psi_{m}$ is the PM flux linkage, and $\theta_{e}$ and $\omega_{e}$ are the electrical angle and speed of the rotor. Fig. 2 shows a PMSM block diagram in the stationary frame.

A. TWO SENSED ANGLES FROM SENSED AND SENSORLESS METHOD

Fig. 3 shows the resolver and its signal processing diagram. It is similar to transformer in structure. It has three winding sets: one is for field excitation and the other two are for signal pickup. The pickup coils are 90° apart, they are called sine and cosine coils. Since the rotor has a flower shape the airgap is nonuniform. Thereby, the carrier is modulated depending on the rotor position. To detect the rotor position, demodulation is necessary. The detection process contains normally the quadrature PLL [3], [4].

In recent decades, sensorless method of PMSM has been studied [21], [22]. These self-sensing controls include back EMF [23], [24], [25], active flux [26], State observer type [27] etc. In particular, the sensorless control shows good performance in the medium speed range. Thus, sensorless method has been used in parallel, fusion, and backup to prepare for fault tolerance in the high-reliability system [13].

Under normal circumstances, the sensored method is regarded more accurate than the sensorless method. However, the sensor may breakdown under harsh environments. Even if the sensor does not fail completely, it may operate with a partial failure. In such a situation, the use of sensorless method would be better. On the other hand, the sensorless method may also not work properly. It is assumed here that the sensored method as well as the sensorless method may fail. Therefore, we need a criterion to judge which method is more accurate than the other.

B. PROPOSED FAULT DETECTION METHOD

In this study, we propose to use the motor current as a reference to determine a better sensing method. To do this, we use two mathematical PMSM models and apply the same voltage to the model input as the voltage reference used for actual current control. The models (2) require the rotor angle. We use the sensored angle $\theta_{e}^{sen}$ for one model and sensorless angle $\theta_{e}^{sl}$ for the other. The motor dynamics are solved by Runge-Kutta 4th method, and the resulting currents are denoted as $i_{\alpha \beta}^{sen}$ for a model with $\theta_{e}^{sen}$ and $i_{\alpha \beta}^{sl}$ for the other model with $\theta_{e}^{sl}$.

Fig. 4 (a) shows a block diagram for fault detection. First, the measured current $i_{\alpha \beta}$ is taken cross product with the virtual currents, $i_{\alpha \beta}^{sen}$ and $i_{\alpha \beta}^{sl}$ such that

$$e_{sen} = i_{\alpha \beta} \otimes i_{\alpha \beta}^{sen}$$

$$e_{sl} = i_{\alpha \beta} \otimes i_{\alpha \beta}^{sl}$$

(3)

(4)
Circuit current is small.

If $\theta_{e}^\text{sen}$ is right, then $i_{\alpha\beta}^\text{sen}$ is parallel with $i_{\alpha\beta}$, thereby, $|e_{\text{sen}}| = 0$. If they are not parallel, $|e_{\text{sen}}| > 0$. The same is true with the sensorless angle.

Let

$$e_{rr} = \frac{||e_{\text{sen}}||^2 - ||e_{sl}||^2}{||i_{\alpha\beta}||^2} = \frac{||e_{\text{sen}}||^2}{||i_{\alpha\beta}||^2} \sin^2(\theta_e - \theta_{e}^\text{sen}) - \frac{||e_{sl}||^2}{||i_{\alpha\beta}||^2} \sin^2(\theta_e - \theta_{e}^\text{sl}).$$ (5)

In Fig. 4 (a), normalization is used to make the fault detection free from the magnitude of currents, especially when the current is small.

The fault detection rule is set using the sigmoid function $\kappa$ defined as

$$\kappa(e_{rr}) \equiv \frac{1}{1 + e^{-r(e_{rr} - d)}} - \frac{1}{1 + e^{-d(e_{rr} + d)}}.$$ (6)

where $r$ and $d$ are parameters that determine the transition rate and offset value, respectively. Fig. 4 (b) shows an example of $\kappa$ which gives 1 when the error of $\theta_{e}^\text{sen}$ is large and -1 when the error of $\theta_{e}^\text{sl}$ is large. Note that the function $\kappa$ has a step of $2d$ width at zero. Thereby, $\kappa(e_{rr}) = 0$ when both errors of $\theta_{e}^\text{sen}$ and $\theta_{e}^\text{sl}$ are small. This is because fault detection is not attempted in the area where both $\theta_{e}^\text{sen}$ and $\theta_{e}^\text{sl}$ errors are small. The reason why each corner is smoothed and the zero step is provided is to prevent chattering due to noise in fault detection. Whenever a position error occurs, a large current is generated, and since the PMSM model takes an angle as an input, a large virtual current is calculated. Therefore, there is a signature current for fault detection.

### III. FUSING METHOD BY USING WEIGHTS

Denote by $\theta_{e}^c$ the angle of a reference frame for the field oriented control. In determining $\theta_{e}^c$, both $\theta_{e}^\text{sen}$ and $\theta_{e}^\text{sl}$ are fused with weight $\rho$:

$$\theta_{e}^c \equiv \rho \theta_{e}^\text{sl} + (1 - \rho) \theta_{e}^\text{sen}, \quad 0 \leq \rho \leq 1,$$ (7)

If the weights change too quickly, change frequently, or react sensitively to small errors, it can actually impair stability. To prevent this, when changing the weights, it is necessary to smooth out the transition and provide a holding region for small errors. Let $\Delta \theta_{e} = \theta_{e}^\text{sl} - \theta_{e}^\text{sen}$. Define another sigmoid function of $\Delta \theta_{e}$ as

$$f(\Delta \theta_{e}) = \frac{1}{1 + e^{-\nu(\Delta \theta_{e} - \mu)}},$$ (8)

where $\nu$ is a coefficient determining the rate of transition and $\mu$ is a value that prevents chattering when $\Delta \theta_{e}$ is small. Fig. 5 shows $f$ for different values of $\nu$. It gives 0 and 1 for small and large $|\Delta \theta_{e}|$. Note that the holding region enlarges as $\mu$ increases, and the transition slope increases as $\nu$. Utilizing $f$, the weight is determined as

$$\rho = \frac{1}{2}(1 + \kappa(e_{rr}) f(\Delta \theta_{e}))$$ (9)

For small $|\Delta \theta_{e}|$ in the holding region, the reference angle is determined simply as the average of $\theta_{e}^\text{sen}$ and $\theta_{e}^\text{sl}$ with $\rho = \frac{1}{2}$. If $|\Delta \theta_{e}|$ is large, either sensorless or sensored angle is selected depending on the sign of $\kappa$. Specifically, one of the angle is assumed to be faulty when the relative angle difference is larger than 20°. Note that $\kappa$ is a function of current error and $f$ is a function of angle relative difference. Both of them have smooth transitions against error variation.

### A. PARAMETER DESIGN

Even if a fault does not take place, the angle difference may increase due to acceleration, deceleration, motor parameter variation, PLL delay, etc [13], [15], [28]. Therefore, fault detection should be withheld for naturally occurring errors, and only be activated when a threshold is exceeded. Let $\Delta \theta_{\text{max}}$ be the maximum allowable angle difference. When the angle difference reaches $\Delta \theta_{\text{max}}$, one angle data is considered invalid and the other is chosen alone as $f(\Delta \theta_{e}) \approx 1$. On the other hand, let $\Delta \theta_{\text{min}}$ be the boundary value of the
holding region. Then, the maximum and minimum values of the sigmoid function have the following relationship from the set values $\Delta \theta_{\text{max}}$ and $\Delta \theta_{\text{min}}$:

$$
f_{\text{max}} = 1/(1 + e^{-\nu(\Delta \theta_{\text{max}} - \mu)}), \quad (10)
$$

$$
f_{\text{min}} = 1/(1 + e^{-\nu(\Delta \theta_{\text{min}} - \mu)}), \quad (11)
$$

Then, the parameters are obtained such that

$$
\nu = \frac{\delta_{\text{max}} - \delta_{\text{min}}}{\Delta \theta_{\text{max}} - \Delta \theta_{\text{min}}},
$$

$$
\mu = \frac{\delta_{\text{max}} - \delta_{\text{min}} \Delta \theta_{\text{max}}}{\delta_{\text{max}} - \delta_{\text{min}}},
$$

where

$$
\delta_{\text{max}} = \nu(\Delta \theta_{\text{max}} - \mu) = \ln \left( \frac{f_{\text{max}}}{1 - f_{\text{max}}} \right),
$$

$$
\delta_{\text{min}} = \nu(\Delta \theta_{\text{min}} - \mu) = \ln \left( \frac{f_{\text{min}}}{1 - f_{\text{min}}} \right).
$$

**FIGURE 5.** Sigmoid function $f$ of angle difference, $\Delta \theta_{\alpha \beta}$.

### IV. SIMULATION RESULTS

Fig. 6 shows a block diagram for speed control of IPMSM. The rotor angles are obtained from a sensor attached to the shaft and from a sensorless algorithm that utilizes stationary voltage ($v_{\alpha \beta}$) and current measurements ($i_{\alpha \beta}$). In this work, all three-channel currents are used to eliminate zero-sequence currents and increase the accuracy of the $\alpha \beta$ transformed currents [29]. Note that a resolver and EEMF observer are utilized as the position sensor and the sensorless algorithm, respectively. Two copies of the same Runge-Kutta 4th IPMSM model in the stationary frame are used with the same voltage input. However, the two models use different angles, so they output different virtual currents. To estimate the amount of angle error, the cross product is taken between the virtual currents and the measured current. Based on the relative error $e_{rr}$ of the current vectors, $\kappa$ is generated, and the weight $\rho$ is obtained using $\kappa$ and the relative angle error $\Delta \theta_{e}$. Therefore, angle fusion, fault detection, and failover are possible with the proposed method. In a special case, the current could be zero in standby. To prevent unreliable fault detection when the current magnitudes is less than a noise threshold $I_{\text{snr}}$, a switch is added in Fig. 6. Therefore, the proposed method does not work in near-zero current. In Fig. 6, the input of the sigmoid function, $\Delta \theta_{e}$, is preprocessed through LPF. Therefore, it is possible to cope with sudden step angle error through LPF and sigmoid function.

Fig. 7 shows the failover performance when artificial angle errors are injected in the sensored or sensorless angle data. It is assumed that the motor runs at 1000 rpm constant speed and the currents are well controlled based on accurate angle information. However, artificial errors are added to $\hat{\theta}_{\alpha \beta}^{\text{sen}}$ and $\hat{\theta}_{\alpha \beta}^{\text{sl}}$, and applied to the Runge-Kutta 4th models. Figs. 7 (a) and (b) show altered signals by artificial errors. The relative angle difference between the two angles is shown in Fig. 7 (c). The Runge-Kutta 4th model current, $i_{\alpha \beta}^{\text{sl}}$, or $i_{\alpha \beta}^{\text{sen}}$ is not aligned with $i_{\alpha \beta}$ due to the angle error. The corresponding weight $\rho$ and control angle $\theta_{e}^{\text{sen}}$ are shown in Figs. 7 (d) and (e). Note that the sensorless signal is selected in interval II with $\rho = 1$ when there is an error in the sensored signal. Otherwise, the sensored signal is selected in interval III with $\rho = 0$ when there is an error in the sensorless signal. However, $\rho$ changes slightly as shown in interval I when the level of error is small.

Fig. 8 shows how the failover algorithm works with motor control. The motor speed is controlled at 1000 rpm. In Fig. 8 (b), the position sensor fails at $t = 2.2$, so that $\hat{\theta}_{\alpha \beta}^{\text{sen}}$ remains the previous data thereafter. Such a fault is detected and the control relies on $\hat{\theta}_{\alpha \beta}^{\text{sl}}$ by changing $\rho$ to 1. Fig. 8 (d) also shows a slight unsettling in the phase currents at the transition. Note however that $\hat{\theta}_{\alpha \beta}^{\text{sl}}$ hits the constant value $\theta_{\alpha \beta}^{\text{sen}}$ after one electrical cycle. Then, $\rho$ turns out to be $1/2$ at this point, and goes back to 1 afterwards. For this reason, slight speed ripples are shown in Fig. 8 (a) after the sensor failure with $\theta_{\alpha \beta}^{\text{sen}} = \text{constant}$.

Fig. 9 (a) shows a position fault-tolerant control at 500 rpm when the cosine resolver cable is shorted. Thus, the output signal $V_{\cos}$ is zero after the fault. Also, this causes $\theta_{\alpha \beta}^{\text{sen}}$ to be a rectangular signal. Although these periodic errors increase ripple and distortion in speed and currents, the proposed algorithm works satisfactorily. Fig. 9 (b) shows a similar result when the sine resolver cable is opened. Thus, the value of the output signal $V_{\sin}$ is not refreshed after the fault and therefore retains its previous value. In such a case, $\theta_{\alpha \beta}^{\text{sen}}$ turns out to be a sinusoidal wave. The algorithm also works satisfactorily.

Fig. 10 shows a simulation of acceleration and deceleration for 0.3 seconds. Fig. 10 (a) shows the result of accelerating from 500 rpm to 1500 rpm and then decelerating back to 500 rpm, and shows the speed difference between sensored and sensorless in the transient state. Since the sensorless method uses a PLL, acceleration/deceleration performance is poor. As shown in Fig. 10 (b), the control angle is smoothly switched to the sensored angle by weight. Similarly, when decelerating, the weights smoothly transition to zero. In Fig. 10 (c), $\rho$ becomes 0 providing a full weight to the sensored method. It is a convincing simulation result that shows the sigmoid function is tuned well in the transients.

Fig. 11 shows current errors and weight variation when the PMSM model involves parameter errors. Fig. 11 (a) shows...
the virtual current errors for the back EMF constant and $q$-axis inductance mismatch. When the inductance changes up to 50%, the sensored virtual current changes by about 32.9% and the sensorless virtual current by about 32.5%. When back EMF constant changes up to 50%, the sensored virtual current changes by about 53.2% and the sensorless virtual current by about 46.7%. The virtual current errors increase
in proportion to the parameter errors. On the other hand, the change of weight is less than 5% as shown in Fig. 11 (b). The weight variation is more sensitive to the inductance error. Detailed percent errors in $\kappa$ and $\rho$ are summarized in Table 1.

| Parameter | $\Delta L_q / L_q$ [%] | $\Delta \kappa / \kappa$ [%] | $\Delta \rho / \rho$ [%] |
|-----------|------------------------|-----------------------------|------------------------|
| $\Delta L_q / L_q$ [%] | 10 | 0.019 | 0.002 |
| $\Delta L_q / L_q$ [%] | 20 | 0.092 | 0.006 |
| $\Delta L_q / L_q$ [%] | 30 | 0.337 | 0.014 |
| $\Delta L_q / L_q$ [%] | 40 | 1.211 | 0.023 |
| $\Delta \kappa / \kappa$ [%] | 50 | 4.002 | 0.056 |

### V. EXPERIMENTAL RESULTS

Fig. 12 shows a test bench for experiments. The test motor parameters are listed in Table 2. The control board includes...
FIGURE 12. Dynamo test bench for experiments.

FIGURE 13. Experimental results of angle fusing at 1000 rpm under resolver sensor fault: (a) weight and angles, (b) speed and phase currents.

DSP TMS320F28377D and a 16-bit differential analog to digital converter (ADC). The PWM frequency is 5 kHz, whereas the current sampling frequency is 10 kHz. The deadtime is 2.5µs. The deadtime and IGBT on-drop were compensated to mitigate the inverter nonlinearity [20], [30], [31].

Fig. 13 shows a performance at 1000 rpm when the sensor signal is broken. The sensor fault is made just by stopping the resolver data refresh, thereby \( \theta_{select} \) remains constant in Fig. 13 (a). It causes a change in \( \rho \) to 1, meaning that the controller relies fully on the sensorless angle estimate. The failover algorithm is very smooth and fast, so it has almost no effect on current and speed. Note however that \( \theta_{select} \) hits the constant value \( \theta_{selec} \) after one electrical cycle. Then, \( \Delta \theta_{select} = 0 \) again, so that \( \rho \) turns out to be \( \frac{1}{2} \), and goes back to 1 afterwards. This causes a little distortion and ripple in current and speed, but stable speed control is sustainable.

FIGURE 14. Experimental results of recovery process at 1500 rpm when sensor failure is cleared.

FIGURE 15. The proposed method according to \( V_{cos} \) fault (short error) at 500 rpm: (a) angles, (b) speed and phase currents.
Fig. 14 shows a recovery process when the position sensor fault is cleared during operation. In the bottom plot of Fig. 14 (a), $\theta_{ecn}$ is back to normal from a constant. At that moment, $\rho$ is changed from 1 to $\frac{1}{2}$, since both the sensored and sensorless signals are normal. Observe from the currents that there are slight current unsettling when $\rho$ changes. It causes a little distortion in currents, but stable speed control is possible.

Fig. 15 shows a performance when the cosine resolver cable is shorted. Then, this causes $\theta_{ecn}$ to be a rectangular signal. Even with this periodic error, the proposed algorithm works satisfactorily. Fig. 16 shows a similar result when the sine resolver cable is opened. In such a case, $\theta_{ecn}$ turns out to be a sinusoidal wave. The algorithm also works satisfactorily.

The proposed algorithm is designed with the goal of operating for serious angle errors of about 15° or more. In practice, it is necessary to ensure that the algorithm does not malfunction due to load or parameter changes that may occur. Fig. 17 (a) shows the experimental results in which the resistance mismatch is changed from 20% to 50%. Because of the resistance mismatch, $\Delta \theta_e$ and sensorless angle errors increase. Fig. 17 (b), when the resistance mismatch is 50%, the angle error is 5° occurs. The algorithm does not work because it is not a value that is judged to be a severe error. Fig. 18 (a) and (b) show the experimental results in which the $q$-axis inductance mismatch is changed from 20% to 50%. Similarly, the angle error increases with the change in inductance, but it is not considered a failure. This algorithm works for angle errors greater than about 15° degrees. It is not significantly affected by parameter mismatch. Fig. 19 (a) shows the result when the step load is 100% at 1500 rpm. $\Delta \theta_e$ is about 5°. It can be confirmed that there is no malfunction of the proposed algorithm due to the load.

### VI. CONCLUSION

Sensored and sensorless methods are used in parallel to enhance the robustness of angle measurement. In the dual sensor system, there is no strict reference for detecting a fault and weighting the two angles. In this study, sensored and sensorless values are applied to the PMSM models as

### TABLE 2. Parameters of test IPMSM used in the experiment.

| Parameter                  | Value   |
|----------------------------|---------|
| Rated output power         | 1.3 kW  |
| Rated speed                | 2000 r/min |
| Rated current              | 8.7 Arms |
| Rated line to line voltage | 110Vrms |
| Numbers of poles ($P$)     | 4       |
| PM flux linkage constant ($\psi_m$) | 0.11Wb |
| d-axis inductance ($L_d$)  | 6.2mH   |
| q-axis inductance ($L_q$)  | 8.6mH   |
| Stator resistance ($r_s$)  | 0.3 Ω   |
| PWM switching frequency ($f_s$) | 5000Hz |
| Sigmoid function $f_{\text{max}}$ | 0.99   |
| Sigmoid function $f_{\text{min}}$ | 0.01  |
| Sigmoid function $\nu$     | 42.132  |
| Sigmoid function $\mu$     | 0.327   |

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the angles of the reference frame. The virtual currents are obtained as the numerical solutions and compared to the real measured current. Among the two angles, an angle that generates a current close to the measured current is judged as an angle with a small error, and a fusing algorithm that gives a greater weight to a more accurate angle was created. Here, a sigmoid function with a holding region is used to make it insensitive to noise and small error fluctuations and to make a smooth transition. Therefore, a transition was made seamlessly if it completely depended on one sensing angle due to a failure. Simulation and experiments were carried out to demonstrate the validity of the algorithm. The main idea that utilizes mathematical models in the controller can be applied to the other multi-sensor systems as well.

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