

Position Sensor Fault Detection of IPMSM Using Single DC-Bus Current Sensor with Accuracy Uncertainty

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Abstract—This paper proposes a position sensor fault detection scheme using single DC-bus current sensor for interior permanent magnet synchronous motor (IPMSM) drives. The three-phase current values are derived from the only DC-bus current sensor, and the accuracy uncertainty of the current sensor is also considered. The six active vectors are divided into three groups for the purpose of sensor calibration purposes. Then, the proposed DC-bus current sensor offset error calibration method is implemented by setting two opposite basic vectors together simultaneously and measuring the two current values on both sides of the junction point for in the same time interval. If the sum of the two sampled current values is not zero, it indicates that the offset error of the DC-bus current sensor can be detected exists and compensated. Therefore, a corresponding compensation method is proposed. Meanwhile, the DC-bus current slopes under different switching states are closely related to the rotor position, which are utilized for position sensor error detection. Finally, the effectiveness of the proposed scheme is verified by experimental results on a 5-kW IPMSM motor prototype.

Index Terms—Accuracy uncertainty, error compensation, fault detection, fault tolerant control, interior permanent magnet synchronous motor (IPMSM).

I. INTRODUCTION

INTERIOR permanent magnet synchronous motors (IPMSMs) are now widely used in industrial applications due to the outstanding features and excellent controlling performances [1]–[4]. Usually, an IPMSM drive system contains several kinds of sensors, of which the most important are position sensor and current sensors are of paramount significance [5]. Thanks to these high-precision sensors, the advantages of IPMSM can be achieved revealed. However, after a long time of use, especially near the end of its life-span period, or works under a harsh working condition, the accuracy of these sensors will decrease. A bad result followed by this is that in this case, the controlling performances of the drive system will be compromised, leading to such as speed fluctuations, torque ripple, and unbalanced three-phase currents [6]–[11].

Take ageing and temperature drift for into consideration, the accuracy of both the current and position sensors in the drive

system is degraded. For current sensors, the main types of errors are offset error and scaling errors [5], which cause periodic speed ripples of with one and two times the fundamental current frequency respectively [9]. The influence of current measurement error on the system performance are is analyzed detailedly in detail in [5], and the compensation strategies are proposed for current and speed sensor errors. However, the proposed scheme will become invalid if there is no healthy current sensor in the drive system. Papers [6] and [10] propose methods to compensate the offset and scaling errors separately without any additional hardware, while but using the commanded voltage reference of the current controller is applied. However, several additional digital signal filters have to be added in the method, which increases the amount of computation computational burden and system complexity. For some special applications such as EVs, emergency parking is not the best way to solve of dealing with the current sensor failures [8]. Therefore [NK1], control strategies are proposed in the event of current sensor failure [8], [11], [12].

For position sensors, the commonly occurred faults are pulse loss and periodic signal interference, which cause undesired speed fluctuation, torque ripple, and unbalanced three-phase currents. The hall-effect position sensor fault detection, identification, and compensation strategy is are discussed detailedly in [13] [NK2]. The information of the estimated rotor position and speed information, which are is used as the criterion for under the situation of the hardware fault, have uncertain error limits according to the operation status and system parameters. Therefore [NK3], an observer based position sensor fault detection method with adaptive threshold is proposed in [14]. Two active fault-tolerant control schemes for EV or HEV applications are proposed in [15]. The sensorless control technologies have been are proposed and studied for decades [16]–[21], which have achieved good precise estimation results. Whereas, the accuracy of the proposed methods is guaranteed by depends on the accuracy of the current sensors.

In [5], the speed sensor fault detection and compensation method is proposed by considering current sensor errors. However, if no accurate current sensor exists in the system, the proposed strategy will become invalid. An adaptive position and current estimators are proposed in [22], which are robust to

motor parameters change. However, the proposed method relies on the search coil, which requires special ~~changes~~ ~~modifications~~ in the motor structure. [NK4] Detection [NK5] and isolation strategies of both position and current sensor faults are proposed in [23], [24].

The phase current reconstruction strategies are researched in [25]–[29]. However, the current sensor errors are not taken into consideration in these literatures. The DC offset error is compensated in [30], whereas the proposed strategy utilizes digital filters and a proportional-integral (PI) controller which ~~is makes the circuit structure~~ complicated.

As illustrated in Fig. 1, for cost efficiency and fault-tolerance capability considerations, a single DC-bus current sensor is applied in the system with no phase current sensors installed. The three-phase currents are reconstructed from the DC-bus current values (in Fig. 1, block “Recon.”). If no error exists in the DC-bus current sensor, the accurate three-phase currents can be obtained continuously. And the position sensor fault detection and calibration strategy can be well implemented (in Fig. 1, block “Calibration”). However, if the accuracy uncertainty of the DC-bus current sensor is taken into consideration as shown in Fig. 1, the ~~utilization-method~~ of ~~utilizing~~ the DC-bus current information for detecting and calibrating ~~of~~ the position sensor fault ~~will be affected or even may become~~ invalid. Also, ~~undesired errors are encountered in~~ the reconstructed three-phase currents ~~will show undesired errors. All of these consequences will have a bad effect on the system.~~

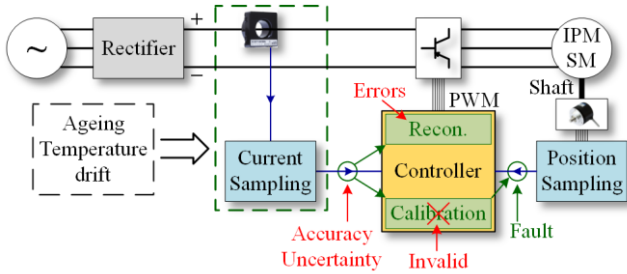


Fig. 1. Influence of DC-bus current sensor accuracy uncertainty on system performance.

In this paper, the position sensor fault detection strategy using single DC-bus current sensor with accuracy uncertainty is proposed, where the three-phase current values are also obtained in the current reconstruction process. The proposed DC-bus offset error calibration method is implemented by setting two opposite basic vectors ~~together-simultaneously~~ and measuring the two current values on both sides of the junction point ~~for-in~~ the same time interval. Under this circumstance, the sum of the two current values should be zero. However, if the value is not zero, the offset error of the DC-bus current sensor will be detected, which can be calculated as the average value of the two sampled currents. The DC-bus current slopes under different switching states are closely related to the rotor position, which can be used for position sensor error detection.

This paper is organized as follows. In Section II, the DC-bus offset error calibration strategy is illustrated. In Section III, the position sensor fault detection strategy using DC-bus current

slope measurement is proposed and the effect of scaling error in the DC-bus current sensor on the position sensor fault detection is analyzed accordingly. In Section IV, the PWM synthesis method and the overall control strategies are proposed and discussed. In Section V, experimental results are presented. ~~Finally, The-the~~ conclusion is given ~~finally~~.

II. PROPOSED DC-BUS CURRENT SENSOR OFFSET ERROR CALIBRATION METHOD

The mathematical model of IPMSM is given by [20]

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = R \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} L_0 + L_2 \cos 2\theta & L_2 \sin 2\theta \\ L_2 \sin 2\theta & L_0 - L_2 \cos 2\theta \end{bmatrix} \times \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{d\theta}{dt} \left(2L_2 \begin{bmatrix} -\sin 2\theta & \cos 2\theta \\ \cos 2\theta & \sin 2\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \psi_f \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} \right) \quad (1)$$

$$\begin{bmatrix} L_0 \\ L_2 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} L_d \\ L_q \end{bmatrix} \quad (2)$$

where $u_{\alpha,\beta}$ and $i_{\alpha,\beta}$ are the motor voltages and currents in the α - β axis-reference frame, respectively; R is the winding resistance; $L_{d,q}$ denotes the winding inductances in the d-q axis-reference frame; θ is the rotor electrical angle; ψ_f is the permanent magnet (PM) flux linkage.

The input voltage vector is usually synthesized by the six basic active vectors (V_{100} , V_{110} , V_{010} , V_{011} , V_{001} , V_{101}) and two basic zero vectors (V_{000} and V_{111}). When analyzing the model excited by different basic active vectors in (1), the current derivative values in the three-phase static reference frame can be simplified as [3]

$$\frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \frac{2}{3L_d L_q} \cdot \mathbf{X} \cdot \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \quad (3)$$

$$\mathbf{X} = \begin{bmatrix} a & -\frac{a}{2} + \frac{\sqrt{3}c}{2} & -\frac{a}{2} - \frac{\sqrt{3}c}{2} \\ -\frac{a}{2} + \frac{\sqrt{3}c}{2} & \frac{a}{4} - \frac{\sqrt{3}c}{2} + \frac{3b}{4} & \frac{a}{4} - \frac{3b}{4} \\ -\frac{a}{2} - \frac{\sqrt{3}c}{2} & \frac{a}{4} - \frac{3b}{4} & \frac{a}{4} + \frac{\sqrt{3}c}{2} + \frac{3b}{4} \end{bmatrix} \quad (4)$$

$$\begin{cases} a = L_0 - L_2 \cos 2\theta \\ b = L_0 - L_2 \cos 2\theta \\ c = L_2 \sin 2\theta \end{cases} \quad (5)$$

where $u_{A,B,C}$ and $di_{A,B,C}/dt$ are the input voltages and output current derivative values in the A-B-C axis-reference frame, respectively.

In (3), $u_{A,B,C}$ varies with ~~different-the~~ switching states as shown in Table I. In the table U_{DC} represents the input DC-bus

voltage, V_{000} , V_{100} , V_{110} , V_{010} , V_{011} , V_{001} , V_{101} and V_{111} are defined as V_0 , V_1 , V_2 , V_3 , V_4 , V_5 , V_6 and V_7 , respectively. By combining Table I and (3)-(5), $di_{A,B,C}/dt$ can be calculated as shown in Table II.

TABLE I
THREE-PHASE VOLTAGES UNDER DIFFERENT BASIC ACTION VECTORS.

Vector	u_A	u_B	u_C
$V_{000} (V_0)$	0	0	0
$V_{100} (V_1)$	$2U_{DC}/3$	$-U_{DC}/3$	$-U_{DC}/3$
$V_{110} (V_2)$	$U_{DC}/3$	$U_{DC}/3$	$-2U_{DC}/3$
$V_{010} (V_3)$	$-U_{DC}/3$	$2U_{DC}/3$	$-U_{DC}/3$
$V_{011} (V_4)$	$-2U_{DC}/3$	$U_{DC}/3$	$U_{DC}/3$
$V_{001} (V_5)$	$-U_{DC}/3$	$-U_{DC}/3$	$2U_{DC}/3$
$V_{101} (V_6)$	$U_{DC}/3$	$-2U_{DC}/3$	$U_{DC}/3$
$V_{111} (V_7)$	0	0	0

TABLE II
DC-BUS CURRENT AND THREE-PHASE CURRENT DERIVATIVE VALUES
UNDER DIFFERENT BASIC ACTION VECTORS.

Vector	V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7
di_A/dt	0	P_1	$-P_5$	P_4	$-P_1$	P_5	$-P_4$	0
di_B/dt	0	P_4	P_6	P_2	$-P_4$	$-P_6$	$-P_2$	0
di_C/dt	0	P_5	$-P_3$	$-P_6$	$-P_5$	P_3	P_6	0
i_{DC}	0	i_A	$-i_C$	i_B	$-i_A$	i_C	$-i_B$	0
di_{DC}/dt	0	P_1	P_3	P_2	P_1	P_3	P_2	0
P_1	$k[L_0-L_2\cos 2\theta]$			P_4	$k[-L_0/2-L_2\sin(2\theta-\pi/6)]$			
P_2	$k[L_0+L_2\sin(2\theta+\pi/6)]$			P_5	$k[-L_0/2+L_2\sin(2\theta+\pi/6)]$			
P_3	$k[L_0-L_2\sin(2\theta-\pi/6)]$			P_6	$k[L_0/2+L_2\cos 2\theta]$			

$$k=2U_{DC}/(3L_dL_q)$$

In Table II, i_{DC} is the DC-bus current, which ~~is equal to different phase current values~~ has the same value as that of ~~certain phase current~~ according to when applying a specific action vectors. P_1, \dots, P_6 represent ~~the~~ intermediate variables that indicate current derivative values. From Table II, it can be seen that i_{DC} has two mutually opposite values and the same derivative under opposite basic vectors [NK6], which can be illustrated in Fig.2.

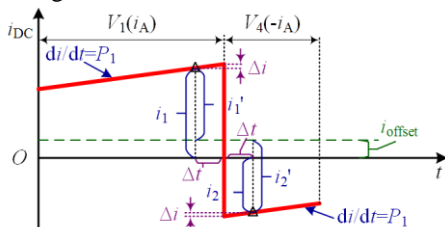


Fig. 2. The DC-bus current under two opposite basic vectors.

In Fig.2, i_1 and i_2 are the two actual current values ~~two sampled currents~~ under two opposite vectors. ~~If~~ When the offset error, i_{offset} , does not exist in the DC-bus current sensor, the two sampled currents are expressed as i_1' and i_2' , respectively. Theoretically, i_2' is the ~~negative value~~ opposite number of i_1' . ~~For t~~ The two actual sampled current values i_1 and i_2 , ~~the offset error i_{offset} are equal~~ is added to the ideal values i_1' and i_2' ~~plus offset error i_{offset}~~ , respectively. Therefore, i_{offset} can be calculated as the average value of the two actual ~~sampled~~ current values.

By applying the proposed strategy, the DC-bus offset error i_{offset} can be detected and compensated. It can be seen that ~~the proposed method needs~~ only one addition operation and one right shift operation are required in the proposed method (in microprocessors, a one-bit right shift operation is the same as the operation of division by 2), which is very simple. Neither digital filters nor complicated operations are required.

III. PRINCIPLE OF POSITION SENSOR FAULT DETECTION USING SINGLE DC-BUS CURRENT SENSOR

As displayed in Table II, the DC-bus current derivative (di_{DC}/dt) only ~~have~~ has three values (P_1 , P_2 and P_3) under different basic vectors. The three derivative values have different relationships with the rotor position. Vectors V_1 and V_4 are ~~defined as~~ classified into “Group-1” because the DC-bus current derivative values are the same (P_1) ~~under-when~~ applying ~~NK71~~ these two vectors. Similarly, vectors V_3 and V_6 are ~~classified into~~ defined as “Group-2”, and vectors V_5 and V_2 are ~~classified into~~ defined as “Group-3”. Therefore, it is possible to realize position sensor fault detection through DC-bus current slope measurement. By calculation, the rotor position can be obtained by the measured three different DC-bus current derivative values

$$\theta = \left[\arctan 2 \left(\sqrt{3} (P_2 - P_3), (-2P_1 + P_2 + P_3) \right) \right] / 2 \quad (6)$$

In (6), to obtain the estimated rotor position in a signal-single DC-bus current sensor based IPMSM drive system, the three different derivative values of DC-bus current in Table II (P_1 , P_2 , and P_3) need to be measured within one PWM cycle.

As the offset error of DC-bus current sensor has been calibrated previously, only the effect of scaling error on the position sensor fault detection will be analyzed. The scaling error can be described by the magnification factor k' . Because the scaling error not only affect the DC-bus current i_{DC} , but also affect the reconstructed three-phase currents i_A , i_B , and i_C . [NK8] The magnification factors of all the three-phase currents are the same with that of the DC-bus current factor k' . Therefore, coefficients P_1 , P_2 , and P_3 also share the same magnification factor k' . In (6), it can be seen that through arctangent-2 function, the impact of scaling error on position calculation is eliminated.

In Fig.3, the overall scheme of calibration and fault detection for sensors are illustrated. The red dashed line marked with '1' denotes the calibration of the DC-bus current sensor. Whereas the blue dotted line marked with '2' represents the fault detection of the position sensor, where R is the detection result. The calibration of the DC-bus current sensor utilizes/relies on the sampled current values and the corresponding switching states, which are also utilized to obtain the position/speed estimation results θ^n/n . The speed ~~information~~ n' , which is obtained from the position sensor, are also involved in the position sensor fault detection process together with the position signal θ' . The speed ~~information~~ is only utilized as one of the criteria of ~~judgment when~~ judging if the sensor fault is ~~recovered or~~ removed. Whereas the position ~~information~~ is

applied as the criteria of judgment of both the sensor fault detection and removal.

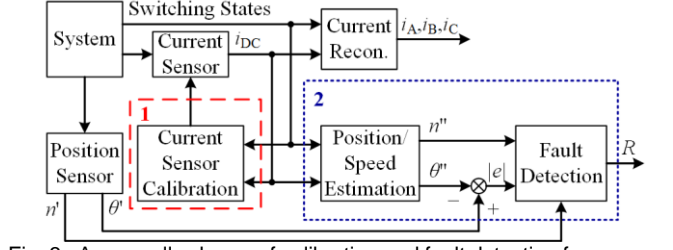


Fig. 3. An overall scheme of calibration and fault detection for sensors.

IV. PROPOSED CONTROL STRATEGIES

A. An Overall Control Scheme

In order to implement the proposed position sensor fault detection scheme using only one DC-bus current sensor with accuracy uncertainty, at least three basic vectors from each of the three defined Groups are required within one PWM cycle. Additionally, an opposite vector of one of the three required basic vectors is also needed for implementing the current sensor accuracy uncertainty calibration strategy. A simple diagram of the proposed control strategy and current sampling method are illustrated in Fig. 4. In the figure, “Vector Group-a/b/c” represents the three defined vector groups in Section III, respectively. It is worth noting that the opposite vector “- V_a ” in the figure can be either “- V_b ” or “- V_c ” according to specific sectors. T_{min} is the minimum period required for precise current measurement after switching the vector. $S_{a1}, S_{a2}, S_{b1}, S_{b2}, S_{c1}, S_{c2}$ and $i_{a1}, i_{a2}, i_{b1}, i_{b2}, i_{c1}, i_{c2}$ are the current sampling points and sampled values which—that are used for current slope measurement, respectively. In addition, $S_{a2}, S_{a2'}$ and $i_{a2}, i_{a2'}$ are the two current sampling points and sampled values for DC-bus offset error calibration, respectively. As shown in Fig. 4, the actual DC-bus current during the process of switching cannot follow the ideal one, and the actual current oscillates before it reaches a steady state to track the ideal one. Therefore, a dime[NK9] delay Δt ($\Delta t < T_{min}$) is required from the switching point to the current sampling point. For accurate measurement of the current slope, the minimum period of $2T_{min}$ is set for all the three basic vectors. The sum of action time of all the four vectors reachs the switching period T_s . The equivalent zero vector is synthesized by the three basic vectors.

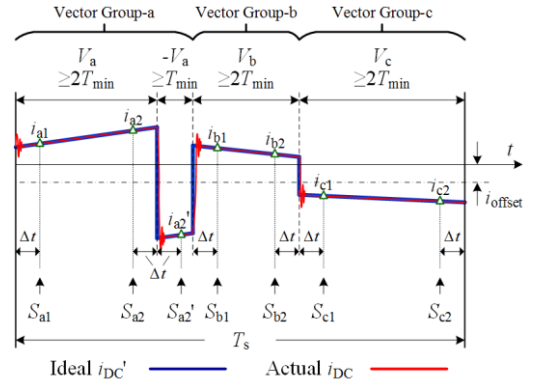


Fig. 4. Simple diagram of the proposed control strategy and current sampling method.

B. Vector Generation Method and Corresponding Sensor Calibration Strategy

As illustrated in Fig. 4, the action time of the four vectors are nois not less shorter than either T_{min} or $2T_{min}$. And the sum of the four action time is T_s . Therefore, the proposed vector generation method and output range is shown in Fig. 5.

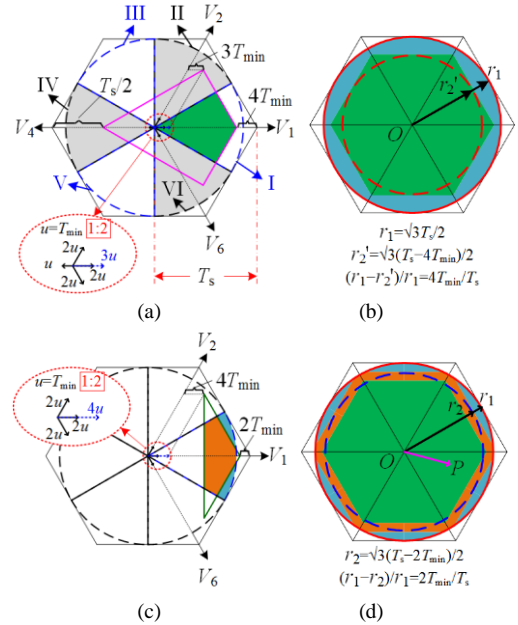


Fig. 5. The proposed vector generation method and output range (with $T_{min}/T_s=1/20$): (a) Vector generation method in defined Sector I, (b) Output voltage range in the six Sectors, (c) Method of expanding the output voltage range in Sector I, (d) Overall output voltage range.

The circular space voltage vector area is divided into six defined sectors in this paper, which are illustrated in Fig. 5 (a). The defined six sectors are marked out with roman numerals “I”, “II”, ..., “VI”. The side length of the hexagon is the switching period T_s . [NK10] In Sector I, the four vectors V_1, V_2, V_4 and V_6 are utilized. The action time of vectors V_1, V_2 and V_6 (defined as T_{V1}, T_{V2} and T_{V6} , respectively) areis not less shorter [NK11] than $2T_{min}$ and the action time of vector V_4 (defined as T_{V4}) is less than T_{min} . The initial voltage synthesis result is shown in the red dotted circle in the middle, which is magnified by 2 to the red dotted ellipse down to the left-hand

side. As shown in the area, ~~a $3T_{\min}$ the~~ action time of V_1 is ~~$3T_{\min}$ obtained~~. The remaining action time of the switching period is $T_s - 7T_{\min}$. ~~By applying Distributing~~ the remaining action time to ~~each of~~ the four vectors yields the final voltage output range, which is surrounded by the pink quadrangle. It can be seen that the ~~range of~~ voltage output ~~range covers the~~ most ~~part range of~~ Sector I ~~which that are is~~ indicated by the green shaded part.

By extending the proposed vector synthesis method to the six defined sectors, the whole output voltage range is shown in the green hexagon in Fig.5 (b). The vector synthesis ~~strategy~~ ~~strategies~~ in the other five sectors are displayed in Table III (Normal Area). As illustrated in Fig.5 (b), the output voltage range (red dashed circle, radius r_2') is minished by $4T_{\min}/T_s$ compared to ~~the output rangethat~~ of the normal voltage synthesis method (red solid circle, radius r_1).

TABLE III
VECTOR SYNTHESIS METHOD IN DEFINED SIX SECTORS.

Action time (\geq)		T_1	T_2	T_3	T_4	T_5	T_6
Sector							
Normal Area	I	$2T_{\min}$	$2T_{\min}$	0 ^a	T_{\min}	0	$2T_{\min}$
	II	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0	T_{\min}	0
	III	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0	T_{\min}
	IV	T_{\min}	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0
	V	0	T_{\min}	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$
	VI	$2T_{\min}$	0	T_{\min}	0	$2T_{\min}$	$2T_{\min}$
Extended Area	I	$2T_{\min}$	$2T_{\min}$	0	0	0	$2T_{\min}$
	II	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0	0	0
	III	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0	0
	IV	0	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$	0
	V	0	0	0	$2T_{\min}$	$2T_{\min}$	$2T_{\min}$
	VI	$2T_{\min}$	0	0	0	$2T_{\min}$	$2T_{\min}$

^a0 does not mean that the minimum action time of the corresponding vector is zero but represents that the vector has no action time in such condition.

In order to further extend the output voltage range, in Sector I, the three vectors V_1 , V_2 and V_6 are utilized in the area beyond the green hexagon in Fig.5 (b). T_{V1} , T_{V2} and T_{V6} are all set ~~to the~~ ~~values not less smaller~~ than $2T_{\min}$, ~~as shown~~ in Fig.5 (c). The initial voltage synthesis result is the part shown in the red dotted circle in the middle, which is magnified by 2 to the red dotted ellipse up to the left-hand side. As shown in the area, ~~a~~ ~~$4T_{\min}$ the~~ action time of ~~$4T_{\min}$ is obtained for~~ V_1 ~~is obtained~~. ~~Therefore, The the~~ remaining action time of the switching period is $T_s - 6T_{\min}$. The final output voltage range is surrounded by the green triangle. ~~Moreover, The the~~ output voltage range ~~which that~~ is indicated by the orange-colored shaded part covers most ~~range-part~~ of Sector I, where the "Normal Area" cannot reach.

By extending the proposed vector synthesis method to the six defined sectors, the whole output voltage range is shown in the orange-colored shaded part in Fig.5 (d). The vector synthesis ~~strategy~~ ~~strategies~~ in the other five sectors are displayed in Table III (Extended Area). As illustrated in Fig.5 (d), the output voltage range (blue dashed circle, radius r_2) is minished by $2T_{\min}/T_s$ compared to the output range of the normal voltage synthesis method in Fig.5 (b) (red solid circle, radius r_1).

~~Furthermore, The the reduction amount of the~~ output voltage range is reduced by $1 - (r_1 - r_2)/(r_1 - r_2') = 50\%$.

It is worth noting that the position sensor fault detection strategy can be achieved in both the normal ~~area~~ ~~the~~ extended ~~areaone~~, whereas the DC-bus current sensor calibration strategy can only be realized in the normal area. Although it is a pity to lose the current sensor calibration capability in the extended area, the area is very small, which ~~will hardly have has~~ a great impact on the performance of the system. Besides, as far as the circular output range is considered, the non-extended vector synthesis method will always be used near the center line of each defined sector, making it acceptable for the current sensor calibration strategy ~~which that is does not have~~ extremely high ~~in~~ real-time requirements.

The ~~judging condition~~ ~~judgment~~ of ~~whether~~ the output voltage $OP(x_0, y_0)$ in Fig.5 (d) ~~falling falls into~~ the normal area ($r = r_2'$) or the extended area ($r = r_2$) is given below

$$\begin{cases} \sqrt{3}x_0 + y_0 \leq 2r & \sqrt{3}|x_0| \geq |y_0| \& x_0 \cdot y_0 \geq 0 \\ \sqrt{3}x_0 - y_0 \leq 2r & \sqrt{3}|x_0| \geq |y_0| \& x_0 \cdot y_0 < 0 \\ |y_0| \leq r & \sqrt{3}|x_0| < |y_0| \end{cases} \quad (7)$$

V. EXPERIMENTAL RESULTS

In order to verify the correctness of the proposed DC-bus current sensor offset error calibration strategy and the position fault detection method, an experimental platform is developed as shown in Fig.6. The parameters of the IPMSM used in ~~the~~ experiment are given in Table IV. The drive system is powered by a 380 V three-phase AC voltage source. A rectifier is installed to provide the DC voltage (540 V) for the inverter-an intelligent power module (IPM) (Mitsubishi PM75RLA120), ~~who which~~ served as the PWM voltage source inverter (VSI) with the frequency of 5 kHz ($T_s = 200 \mu s$). Also, a ~~multiple~~ ~~multi-level~~ DC output power converter is installed to provide the power for the low voltage devices. An isolated hall-effect current sensor (HS01-100, Max sample rate 100 kHz) is used as the DC-bus current sensor. The offset error value of the DC-bus current sensor is set ~~within in~~ the software of a DSP, TMS320F2812, ~~who which~~ is also utilized to sample the DC-bus current, generate the PWM signals and ~~to~~ implement the proposed sensor calibration strategy, etc. The current clamps are installed for comparison of the currents. A MAGTROL 30 kW dynamometer is utilized for load test. In this paper, T_{\min} is set ~~with as~~ 10 μs , and Δt is set ~~with as~~ 8 μs .

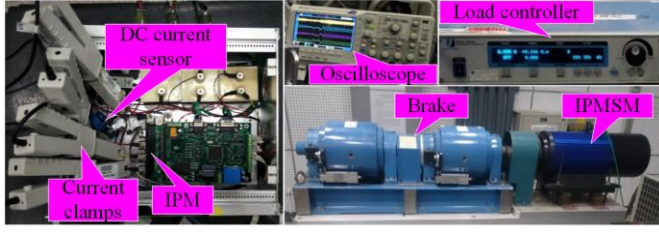


Fig. 6. Experimental setup.

TABLE IV
MAIN PARAMETERS OF IPMSM USED IN EXPERIMENT.

Parameter	Value	Parameter	Value
Rated power	5 kW	Pole pairs	3
Inverter DC voltage	540 V	d-axis Inductance	4.2 mH
Rated voltage	380 V	q-axis Inductance	10.1 mH
Rated current	8.5 A	Phase resistance	0.18 Ω
Efficiency	0.9	Maximum speed	3000 r/min
Rated torque	15 N m		

In Fig.7, the experimental results of the proposed DC-bus current sensor offset error calibration strategy is illustrated (here, Sector II). In the figure, i_{DC} , i_A , i_B , and i_C are the DC-bus and the actual three-phase currents, i_A' , i_B' , and i_C' denote the reconstructed three-phase currents, and i_{offset} is artificially added with-by -2 A in the controller. The sampled DC-bus current values are displayed in Table V. Therefore, the offset error of the DC-bus current sensor can be calculated as the average of i_{c2} and i_{c2}' , which is $i_{offset}' = -1.95$ A. After the calibration of the DC-bus offset error, the reconstructed three-phase current values can also be obtained as displayed in Table V and illustrated in Fig.7. The reconstructed three-phase currents without calibration of the DC-bus current sensor offset error (i_A'' , i_B'' , and i_C'') are also given for comparison. It can be seen that the unexpected offset errors in the reconstructed three-phase currents are compensated after calibration of the DC-bus current sensor offset error.

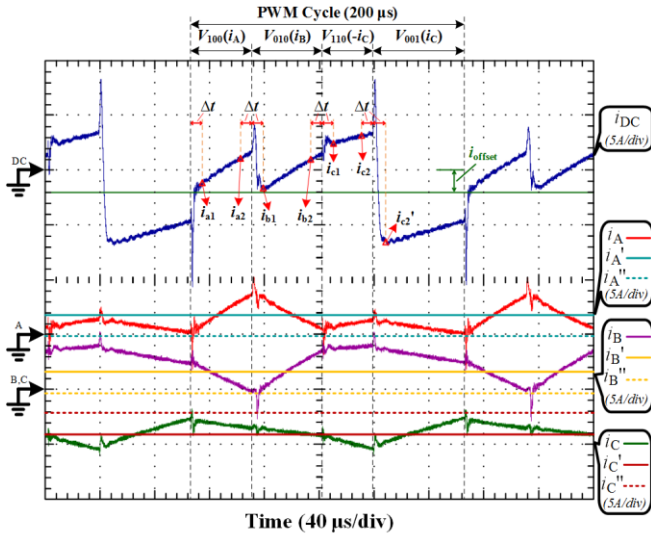
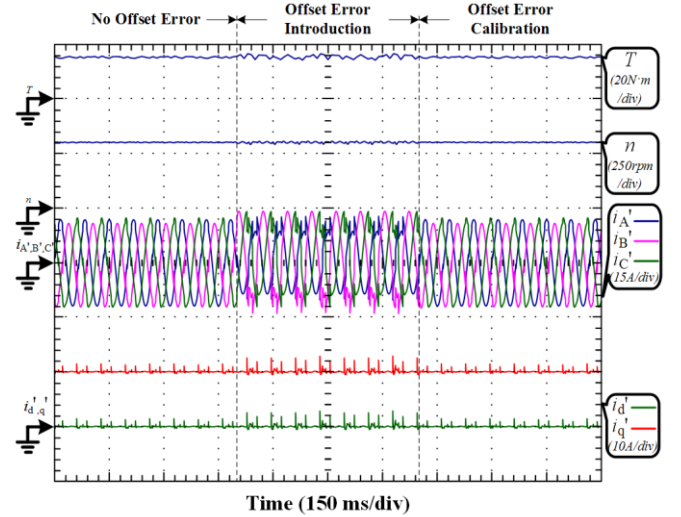


Fig. 7. Experimental results of proposed DC-bus current sensor offset error calibration strategy (here, Sector II).

TABLE V
SAMPLED DC-BUS CURRENT VALUES.

Current	Value (A)	Current	Value (A)
i_{a1}	-1.35	i_{a2}	1.05
i_{b1}	-1.60	i_{b2}	0.95
i_{c1}	2.25	i_{c2}	3.00
i_{c2}'	-6.90		
i_{offset}'	$(i_{c2}+i_{c2}')/2=-1.95$	i_A'	$(i_{a1}+i_{a2})/2-i_{offset}'=1.80$
i_B'	$(i_{b1}+i_{b2})/2-i_{offset}'=1.63$	i_C'	$-[(i_{c1}+i_{c2})/2-i_{offset}]=-4.58$
i_A''	$(i_{a1}+i_{a2})/2=-0.15$	i_B''	$(i_{b1}+i_{b2})/2=-0.33$
i_C''	$-(i_{c1}+i_{c2})/2=-2.63$		

Fig.8 illustrates the experimental results of the system performance before and after calibration of the DC-bus current sensor offset error (here, $i_{offset}=-4$ A), which is artificially added to the system by software. In the figure, T and n denote the motor output torque and speed, respectively. i_d and i_q are the d- and q-axis motor currents calculated by i_A' , i_B' , and i_C' , respectively. It can be seen that after introduction of the DC-bus current sensor offset error, both the motor output torque and speed fluctuates. The error in the reconstructed three-phase current value has more complex kinds of error, which is not only a simple offset error of the current waveform, but also rather the contains uncertainty of the error. This unexpected error in the reconstructed three-phase currents eventually leads to the fluctuation of the d- and q-axis currents. However, After after the calibration of the DC-bus offset error, all these the unfavorable phenomena have disappeared.

Fig. 8. Experimental results of the system performance before and after calibration of the DC-bus current sensor offset error ($i_{offset}=-4$ A).

The experimental results of the total harmonic distortion (THD) of the actual three-phase currents are displayed in Fig.9. Although the THD level of the proposed method is slightly larger-higher than that of the traditional space vector pulse width modulation (SVPWM) method, it is better than or reaches the same level as those of many other PWM synthesis methods [29], [31]. Also, the slightly increased THD does not have a serious-significant impact on those large inductive loads [29].

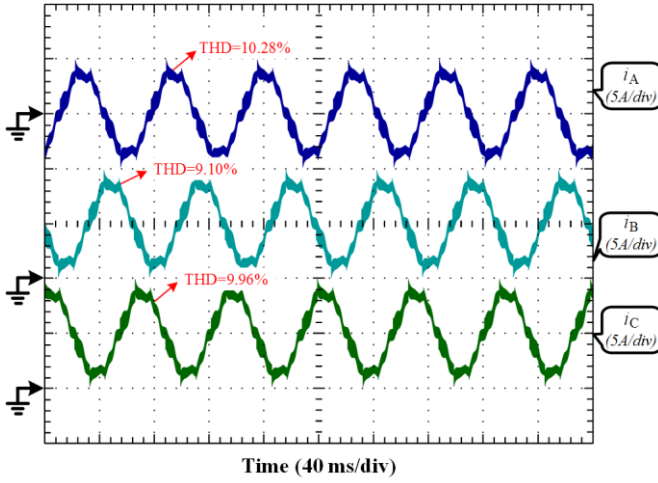


Fig. 9. Experimental results of THD of actual three-phase currents.

Fig.10 shows the experimental results of the system performance at 300rpm and 15 N m. In Fig.10 (a), the reconstructed three-phase currents track the actual ones accurately. It can be seen that the current fluctuation of both the actual and reconstructed three-phase currents vanished after calibration of the DC-bus current sensor offset error. In Fig.10 (b), θ and θ'_{Re} are the actual and estimated rotor positions, $\Delta\theta'_{Re}$ is the estimation error. The estimation error is controlled within ± 0.2 rad in the steady state. Although the error ~~are-is~~ not small enough for ~~the~~ sensorless control, it is still sufficient for ~~the purpose of~~ position fault detection ~~purposes~~ for a drive system with position sensor installed.

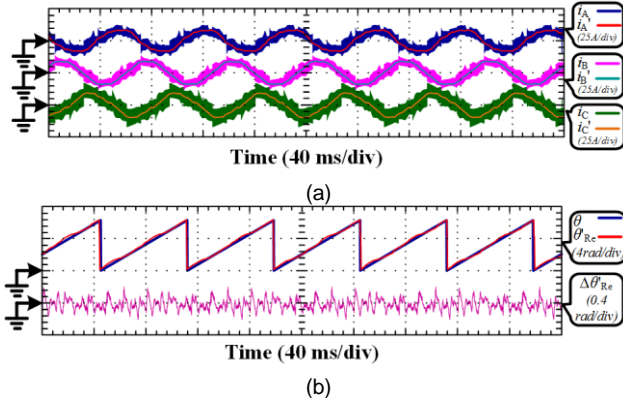


Fig. 10. Experimental results of system performance at 300 rpm and 15 N m: (a) actual and reconstructed three-phase currents, (b) actual and estimated rotor position.

In Fig.11, the system performance in the starting process ~~are~~ is displayed. It can be seen that during the dynamic process of starting, the reconstructed three-phase currents track the actual ones accurately. Besides, The-the position estimation error is controlled within ± 0.3 rad in the dynamic process. In Fig.11 (c), the waveforms of the actual and estimated rotor speeds are also given. The estimated rotor speed are calculated using-according to the estimated position information. A simple digital low-pass filter is also set as shown in (8) in order to filter out the speed clutters. The estimated rotor speed ~~estimated-error~~ are-is controlled with ± 10 rpm.

$$n[k+1] = Q \cdot n[k] + (1-Q) \cdot \frac{\theta'_{Re}[k+1] - \theta'_{Re}[k]}{T_s} \cdot \frac{30}{\pi p} \quad (8)$$

where $n[k+1]$, $n[k]$, $\theta'_{Re}[k+1]$ and $\theta'_{Re}[k]$, ($k=1, 2, \dots$) are the discrete estimated speed and position signals; Q is the filter coefficient; p denotes the rotor pole pairs.

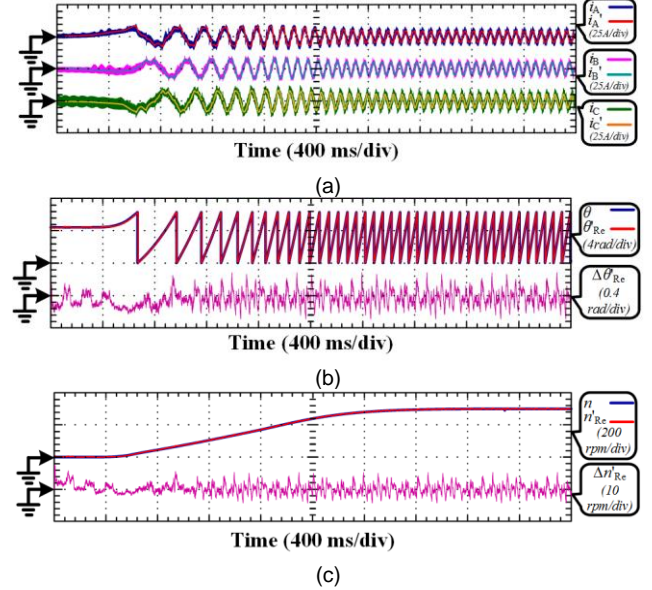


Fig. 11. Experimental results of system performance in the starting process: (a) actual and reconstructed three-phase currents, (b) actual and estimated rotor position, (c) rotor speed.

The system performance in the fast dynamic process (reversing) ~~are-is~~ also displayed in Fig.12. The reconstructed three-phase currents track the actual ones accurately. In addition, The-the estimated rotor position and speed match the actual ones with an acceptable estimation error.

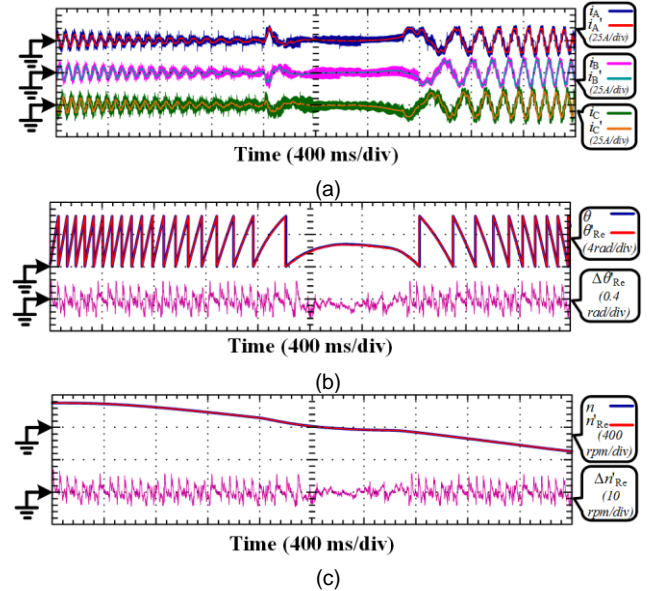


Fig. 12. Experimental results of system performance in the reversing process: (a) actual and reconstructed three-phase currents, (b) actual and estimated rotor position, (c) rotor speed.

The experimental results of the position sensor fault

detection are displayed in Fig.13. In the figure, θ and θ' are the actual rotor positions before and after introduction of the fault signal, respectively. θ'' is the estimated rotor position obtained from the DC-bus current sensor. n' and n'' denote the speed information calculated from θ' and θ'' , respectively. The position sensor fault ~~are-is~~ artificially added to the system by software ~~in-at~~ point 1 marked with a red arrow. ~~Until point 2,~~ ~~the~~ The fault signal is ~~not~~ detected ~~until reaching point 2,~~ with the value of $|\theta'' - \theta'|$ exceeding the preset threshold value (0.4 rad). Upon the detection of the fault signal, depending on the specific requirements of the system, further actions such as fault reporting or sensor isolation and sensorless control switching will be taken. With the ~~rotating-rotation of the~~ rotor, the value of $|\theta'' - \theta'|$ ~~will-be-becomes~~ smaller than the preset threshold value again (0.4 rad), whilst the sensor fault has not ~~been~~ removed from the system yet. As shown in point 3, the estimated rotor position passed ~~by~~ the actual position with fault signal (θ'). While actually, at point 3 the sensor fault signal still exists, ~~therefore~~ Therefore, the speed information calculated ~~from-according to~~ θ' and θ'' ~~are-is~~ utilized to dispel the wrong judgment. In this paper, ~~there are two conditions for~~ the judgment of ~~the~~ sensor fault recovery ~~has two conditions~~: (1) The absolute difference between the detected position signal and the estimated value is within the threshold value (0.4 rad) for 10 consecutive cycles, (2) The difference ~~value-of-between~~ the speed values calculated by the detected and the estimated position signals is within ~~another-the~~ threshold value (~~of~~ 10 rpm). ~~In-At~~ point 4, the sensor fault is removed from the system by software, ~~until point 5 and~~ both the two conditions are satisfied ~~when reaching point 5.~~ At point 5 the sensor isolation is shut off, and the position ~~information~~ is therefore applied in the system again.

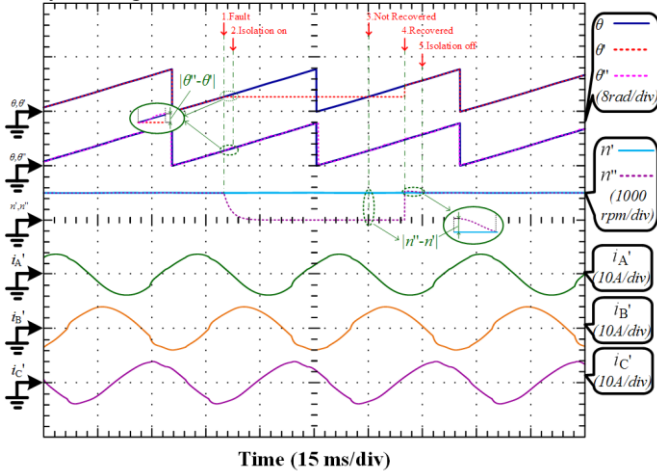


Fig. 13. Experimental results of position sensor fault detection.

VI. CONCLUSION

A position sensor fault detection method using a single DC-bus current sensor with accuracy uncertainty in an IPMSM drive system is proposed in this paper. The main contribution of this paper is that the current sensor offset error calibration method and the three-phase current reconstruction process

together with the position sensor fault detection strategy are all realized within one single PWM cycle. To accomplish this ~~purpose-task~~, the vector generation method is redesigned. The output voltage range is divided into six sectors to ensure the minimum action time of the basic vectors ~~is obtained~~. Meanwhile, a method of expanding the output voltage range is also developed. Afterwards, two opposite basic vectors are always set together in the non-extended areas to achieve the detection of the DC-bus current sensor offset error. Then the position sensor fault detection strategy is realized by detecting the DC-bus current slopes ~~under-when~~ different action vectors ~~are employed~~. Finally, the effectiveness of the proposed position sensor fault detection method together with the DC-bus current sensor offset error calibration strategy ~~are-is~~ verified by the experimental results on a 5-kW IPMSM prototype.

- 1) The ~~self-calibration-detection~~ and ~~self-calibration the detection~~ of the position sensor fault are ~~all-both~~ realized by a single DC-bus current sensor.
- 2) With modulation of the PWM generating method, the DC-bus current sensor offset error calibration strategy, the three-phase current reconstruction process and the position fault detection method can all be achieved by a few current sampling points within one PWM cycle.
- 3) The DC-bus current sensor offset error calibration method does not need any complicated observers or digital filters, ~~and~~ only the sampled current values are needed.
- 4) The proposed DC-bus current sensor offset error calibration strategy is applicable but not limited to the IPMSM drive system, ~~and~~ it is widely effective for the motor drive systems ~~which-that~~ are driven by PWM based inverters.

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