

Simple current sensor fault-tolerant control strategy for switched reluctance motors in high-reliability applications

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Abstract

Switched reluctance motors (SRMs) are considered as a potential candidate in many high-reliability demanding applications, including electrical vehicles (EVs), hybrid EVs and more electric aircrafts. For precise and stable control performance, normally an SRM drive requires one current sensor for each phase winding. Failure of any of these sensors will inevitably degrade the system's performance. The behaviour of an SRM drive under current sensor failure is investigated and a fault-tolerant control technique is proposed by changing the current sensor installation scheme without adding extra current sensors. Moreover, through the analysis of the detected currents by the phase current sensors and the dc-link sensor, a diagnostic scheme for current sensors failure is presented. The excitation current in the faulty phase under postfault conditions is reconstructed through a simple calculation without injecting a high-frequency signal or modifying the switching signals, thereby reducing the current distortion and avoiding voltage penalty issues. Motor drive can operate with satisfactory control performance even when all the phase current sensors are in fault conditions. Detailed analysis under both steady state and dynamic conditions through thorough simulations and experiments has been carried out on a three-phase 12/8 SRM. The extensive results validate the effectiveness of the proposed technique.

1 | INTRODUCTION

Switched reluctance motors (SRMs) are increasingly being used in many safety-critical industrial and automotive applications due to their advantages of low-cost, robust configuration, wide speed-torque ratio and high-reliability [1]. To further enhance the performance and reliability of SRMs, researchers have put several efforts in investigating the reliability issues [2], cost optimisation through position sensorless control schemes [3, 4] and torque ripple reduction techniques [5, 6]. Extensive research on fault identification and remediation of SRM drives was also conducted [7–10]. However, it is found that the fault diagnosis and tolerant control techniques for current sensors in SRMs are rarely reported [11].

The high-reliability applications of SRMs such as for the propulsion of more/all electric aircrafts, electric vehicles (EVs) and hybrid EVs demand high-performance control schemes, and the phase current measurement is an integral part for those control schemes. The typical control schemes for an

SRM drive such as current chopping control (CCC), single pulse control and direct torque control [12] require the accurate phase current sampling for current control and also for over-current fault protection in the drive system. Moreover, most of the fault-tolerant control (FTC) techniques for position sensor failure also mainly rely on accurate phase current sampling [13].

In a standard SRM drive, a hall-effect current sensor is normally placed in each phase leg to measure the phase winding currents, and a dc-link current sensor is utilised for fault protection [14]. However, a hall-effect current sensor has a certain probability of failure. The failure probability of the current sensors is in the same order of the probability that may appear in the motor bearings and stator windings [15]. The faults can be classified as zero-output, incorrect gain and dc-offset [16]. The failure of the current sensor (s) will inevitably degrade the control performance and even cause breakdown of the drive system. Therefore, the fault diagnosis and tolerant control schemes for current sensors deserve special attention

from both the research community and the industry [17]. While the positive and negative dc-offsets in a current sensor can be adjusted online as discussed in [18], handling of the zero-output fault needs more efforts.

Recently, several fault detection (FD) and FTC schemes for current sensors utilised in current controlled converters and AC motor drives have been reported in [19–39]. The fault identification approaches, in general, can be categorised as model based and signal based [19]. The model-based FD techniques require accurate mathematical model of the machine being studied for estimation of the measured signals and residuals generation. The generated residuals are compared to certain thresholds for fault identification. This method's accuracy will be largely affected by the variation of the machine parameters, making it less reliable for real-time implementations. Two observer-based offline FD and isolation methods by estimating the d - and q -phase currents of a permanent magnet synchronous motors (PMSM) drive system are proposed in [20]. A sliding mode observer for current sensors fault identification in a PMSM drive was reported in [21]. Luenberger observer was investigated for current sensors fault diagnosis in doubly fed induction generator in [22, 23]. An adaptive observer was used for current sensor FD in induction motor drives in [24]. This method can also estimate the rotor resistance. Another FD strategy for current sensors in PMSM drives by using extended Kalman filter was proposed in [25]. However, the performance of this method was largely affected by the variation of machine parameters. An FD scheme for insulated-gate bipolar transistors (IGBTs) and current sensors fault in a PMSM drive based on an observer was presented in [26].

On the other hand, in signal-based methods, the fault features are extracted from the measured signals, which can be obtained without installing additional devices. Moreover, they do not require system parameters and hence are suitable for online FD. A robust diagnostic strategy for power switch open-circuit faults and current sensors failure is reported in [27–29]. The faults were effectively detected and located through the analysis of stator currents. A similar FD scheme for three-phase grid tied inverters was recently reported in [30], which can effectively detect both the IGBT open-circuit faults and current sensors faults in inverter mode and rectifier mode. However, this method can only handle single IGBT open-circuit fault or current sensor fault. A current sensors FD scheme was implemented on an FPGA in [31] by analysing the error vector locus of the measured current. However, this method was mainly applied to the hysteresis current controller and was not suitable for the widely used field oriented control scheme. A diagnostic technique with two additional current sensors for a three-phase PMSM was discussed in [32]. The signal-based detection method using the average normalised currents developed for PMSM in [28], was also applied to a permanent magnetic synchronous generator in [33], which proved to be a reliable and cost-effective scheme for implementation in real-time control system.

Once the fault is detected, there are mainly two typical approaches for the current sensor FTC. In the first approach,

the drive topology is altered when the fault is detected, and typically changes the system from a closed loop to an open loop [34]. In the second approach, the faulty current signal is replaced with the estimated one without altering the drive system [35]. However, the first approach ends up with a degraded performance, while the second approach suffers from accuracy and reliability issues as discussed in [36, 37]. In [38], a current and a speed compensation technique for current and speed sensors faults, respectively, was investigated to achieve uninterrupted operation under faulty conditions. An FTC scheme for current, voltage and speed sensors of an interior PMSM drive was developed in [39] by introducing three independent observers to estimate the speed, dc-link voltage and currents of the motor. The machine operation was maintained by acquiring the estimated signals from the observers and replacing them with the faulty signals.

Since the motor configuration, converter topologies and their working principle of SRM systems are completely different from other AC drives, the fault signatures for FD, and tolerant schemes will also be different. No FD schemes for current sensors in SRM drives have been reported so far [11], while some advanced phase current reconstruction schemes by using fewer sensors have been published recently to reduce the cost of the system [40–44]. For instance, a single-current sensor-based scheme was initially introduced in [40] using complex logic circuits, however, it leads to sampling inaccuracy and as a result will reduce the system reliability. A phase shifted double high-frequency (HF) signal injection-based approach was proposed in [41] to reconstruct phase currents from a single dc-link current sensor. The phase shifted HF pulse injection will inevitably cause current distortion and decrease the measurement accuracy. A specially designed converter topology with reduced sensors was developed in [42], this converter topology is only applicable to a four-phase SRM drive. Dual-current sensors-based phase current measurement approaches for multiphase SRMs are explored in [43], where the current measurement for five-and six-phase SRMs are achieved through HF pulse injections. A minimal current sensing strategy with two current sensors for a four-phase SRM was reported in [44], where the FD of power switches was also analysed. Another phase current reconstruction scheme using two cross-winding sensors was proposed in [18]. Online calibration of dc-offsets was also discussed in this method.

These phase current reconstruction strategies are effective for cost reduction. However, in safety-critical applications, reducing the number of current sensors will inevitably compromise the overall system reliability. On the other hand, redundant current sensors could be installed to increase reliability, but higher system costs will result.

In this context, the techniques that can enhance the reliability of an SRM drive using the same number of current sensors as a standard SRM drive, become attractive. For this aim, a fault diagnosis and tolerant control scheme under current sensor failure in an SRM drive is crucial for its postfault operation. A method for this purpose is hence proposed in this manuscript.

This simple method makes full use of the dc-link current sensor in the lower dc-bus of a standard asymmetric power converter, which serves for both over-current fault protection and for current sensor tolerant control. Moreover, the diagnosis of the current sensors is also achieved by using the detected currents through the same sensors. Compared with most of the FD techniques in the literature for AC drives, this method can effectively diagnose and discriminate open-circuit and current sensor faults. Moreover, the proposed FD and remediation scheme is independent of the machine parameters allowing for real-time implementation in safety-critical applications.

2 | PROPOSED CURRENT DETECTION SCHEME

2.1 | SRM drive system

Figure 1 shows the most widely used converter topology in SRM drives known as the asymmetrical-half bridge converter with standard current sensing strategy. Two power switches and two freewheeling diodes independently control each phase leg. A single current sensor is usually installed in each phase leg to measure the motor's phase currents for closed operation. The installed sensors are represented by S_a , S_b , S_c in Figure 1. In addition, a dc-link current sensor is mostly used for over-current protection in the drive system denoted as S_{dc} in the figure. Each phase of an asymmetric converter is independent of each other, which adds good stability and fault-tolerance capability to the drive system. The converter topology has three typical modes of operations, namely magnetisation, freewheeling and demagnetisation. These working modes with current paths are shown in Figure 2.

A soft-switching strategy is normally adopted to reduce the torque ripple and switching losses. In this switching mode, the upper switches chop while the lower switches remain closed during the phase turn-on region. Once the turn-off angle is reached, both the power switches are turned-off and the phase works in demagnetisation mode as shown in Figure 2(c).

2.2 | Proposed postfault current measurement scheme

For SRMs, the maximum turn-on period for each phase, considering a positive torque generation, is a half of the phase inductance region [45]. The relation is shown as:

$$\theta_{on} = \frac{360}{2Nr} \quad (1)$$

where θ_{on} is the maximum excitation angle of a phase and N_r represents the number of rotor poles. For a 12/8 SRM, the maximum excitation angle is 22.5 degree. The relationship between the phase currents and the inductance curves for a 12/8 SRM is shown in Figure 3. θ_1 to θ_4 divide the turn-on regions of phase A, where θ_1 and θ_4 are the turn-on and turn-

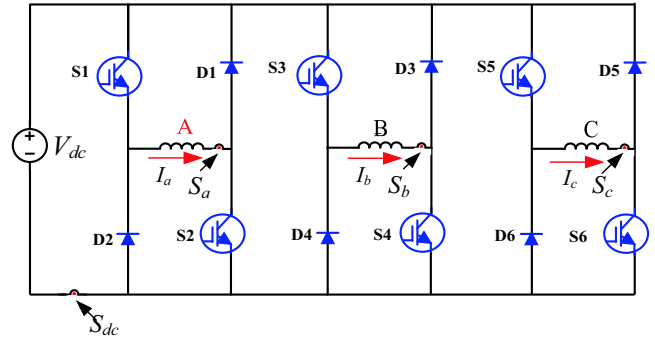


FIGURE 1 Three-phase asymmetric power converter with standard current sensor installation

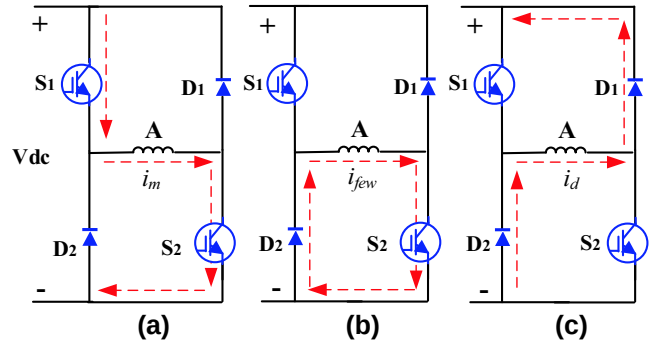


FIGURE 2 Typical operation modes of the asymmetric converter topology: (a) magnetisation, (b) freewheeling and (c) demagnetisation

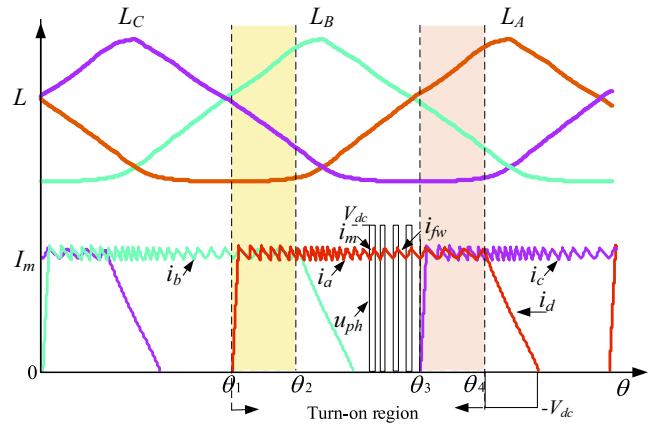


FIGURE 3 Relationship between the inductance (L) and phase currents (I_m) associated with the rotor angle (θ)

off angles of phase A, respectively. During the phase turn-on region, when the upper and the lower power switches (S1 and S2) are turned-on simultaneously, a phase voltage, u_{ph} , equivalent to V_{dc} magnetises the phase winding.

Subsequently, the magnetisation current, i_m , rises reaching the upper threshold of the hysteresis controller. The controller, then, turns off the upper switch and the current, i_{few} free-wheels through the lower switch and lower diode. The block diagram of the typical CCC scheme is shown in Figure 4. When the rotor position reaches the turn-off angle, the power

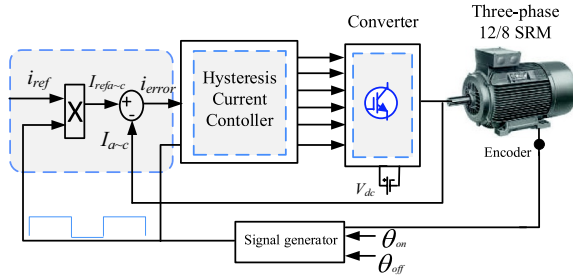


FIGURE 4 Current chopping control block diagram

switches are turned off and the phase winding is demagnetised by applying a $-V_{dc}$. The demagnetisation current, i_d flows back to the power source.

From the above analysis, it can be observed that in the phase turn-on region, the excitation current mainly includes the magnetisation current, i_m , and freewheeling current, i_{fw} , while the demagnetisation current, i_d is not included for current control. Since the switching signals for the upper switches are generated based on the error between the reference current and measured in the phase turn-on region, the demagnetisation current, i_d can be excluded from the current measurement as it is not essentially required for current regulation [46]. If the demagnetisation current is omitted from the current measurement, there will be only two phase currents overlapping in the commutation regions (i.e. $\theta_1 < \theta \leq \theta_2$) in a two-phase excitation mode that needs to be measured.

Similarly, during the single active region (i.e. $\theta_2 < \theta \leq \theta_3$), the tail current of the demagnetising phase can be ignored for the current control. Considering this fact, a current reconstruction scheme for post current-sensor fault-tolerance by sampling the dc-link current sensor is proposed. The scheme's current sensor installation with a slight change to Figure 1 is shown in Figure 5.

With the new sensor installation scheme, the magnetisation and the lower freewheeling current will flow through the dc-link sensor, while the demagnetisation current will not flow through it. During the commutation regions, both the incoming and the outgoing phase currents will flow through the dc-link current sensor simultaneously. Figure 6 shows the phase currents without demagnetisation current, the current detected by the dc-link current sensor and the associated switching signals based on soft-switching mode under the CCC. In the Figure, I_{abc} and I_{ft} represent the three-phase currents and the dc-link current, respectively. S2, S4 and S6 show the switching signals for the lower switches of phase A, B and C, respectively. θ_1 and θ_3 are the turn-on angles of phase A and phase C, respectively, and θ_2 and θ_4 are the turn-off angles of phase B and phase A, respectively. One fundamental current period, given in Equation (2) in the case of eight rotor poles, is divided into six rotor position regions for current reconstruction.

$$T_p = \frac{60}{n \times 8} \quad (2)$$

where n is the SRM's rotational speed (rpm). During commutation regions, two phases are energised simultaneously and

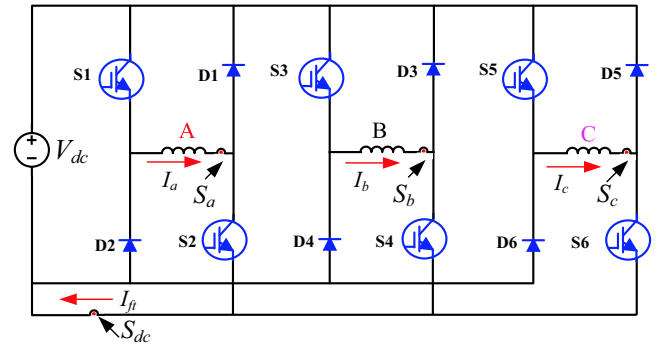


FIGURE 5 Proposed current sensor fault tolerant scheme

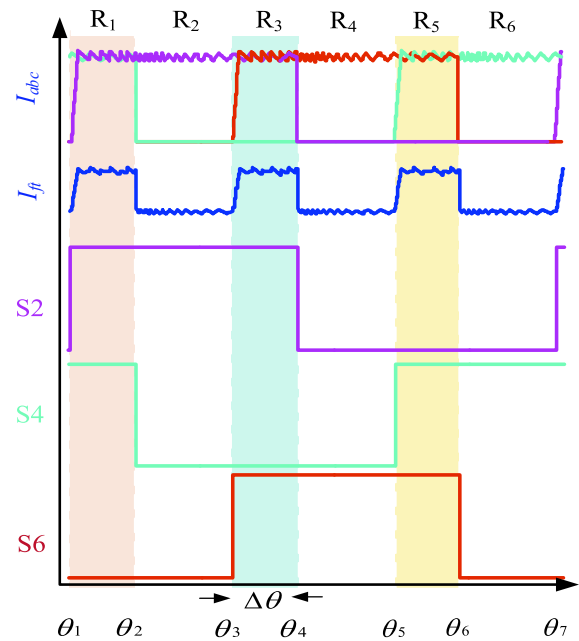


FIGURE 6 Proposed switching strategy for bus current detection

thus the detected current through the dc-link current sensor will be the sum of those currents. While during single active region there will be only one phase current in the dc-link sensor.

Taking the turn-on region of phase A as an example, the sum of currents in the whole turn-on region (i.e. θ_1 to θ_4) through the dc-link sensor can be represented as:

$$I_{ft} = \begin{cases} I_a + I_b, & \theta_1 < \theta \leq \theta_2 & R_1 \\ I_a, & \theta_2 < \theta \leq \theta_3 & R_2 \\ I_a + I_c, & \theta_3 < \theta \leq \theta_4 & R_3 \end{cases} \quad (3)$$

The cumulative bus current can be represented as:

$$I_{ft} = I_a \cdot S2 + I_b \cdot S4 + I_c \cdot S6 \quad (4)$$

The relationships between the excitation period and the detected currents through the dc-link sensor in each region are illustrated in Table 1. In a fundamental current period, T_p the

dc-link sensor contains sum of two phase currents in R_1 , R_3 and R_5 , while in R_2 , R_4 and R_6 , only single phase current flows through the sensor. Therefore, in the case of individual phase current sensor faults, only the current during commutation regions is required to be reconstructed for fault-tolerant operation.

3 | PROPOSED CURRENT SENSORS FAULT DIAGNOSIS

This study primarily focuses on the current reconstruction techniques to sustain the drive operation under current sensors failure. However, to demonstrate the feasibility of the method for fault isolation, and smooth transition from the healthy mode to the fault-tolerant mode, a fault diagnosis scheme considering the total loss of the current information that is, the zero-output case is proposed. In this case, the output of the faulty sensor will give a zero value to the SRM controller irrespective of the corresponding winding current. This erroneous information will cause catastrophe to the drive system. Particularly, in CCC scheme, the current error, i_{err} , (see Figure 4) will remain greater than the positive threshold, and the controller will keep the upper switch of the faulty phase turned on, while the lower switch is already ON due to soft switching mode. Subsequently, the faulty phase current will suddenly increase to a very large value. An open-circuit fault in a power switch or phase winding will also send a zero value to the controller. However, in this case, the faulty phase leg will be disconnected from the dc-link and the current will no longer increase. Based on these fault signatures, a fault in a current sensor will be detected and discriminated from an open-circuit fault.

Table 2 represents the detected currents by each current sensor during a current period, T_p in Equation (2) under healthy conditions. It can be observed that the dc-link current sensor during the commutation regions (R_1, R_3 and R_5) contains summation of two phase current represented by I_s . For instance, I_s in region R_1 can be represented as $I_s = I_a + I_b$. While in regions R_2, R_4 and R_6 , S_{dc} detects phase A, B and C currents, respectively.

When the controller receives a zero value from a current sensor, say S_a , in the phase turn-on region, the FD algorithm checks the updated values of the current sensor, S_a and the dc-link current sensor S_{dc} . If a current sensor, say S_a , suffers from a signal loss fault, the output of the current sensor, S_a , will be a zero value, and output status of the dc-link sensor, S_{dc} will be I_s , I_a and I_s in S_a regions R_1 , R_2 and R_3 , respectively, as depicted in Table 3. However, if a zero-output of the current sensor is caused by an open-circuit fault, the dc-link current sensor will have $0.5I_s$ (i.e., $I_s = 0 + I_b$) in R_1 and ($I_s = 0 + I_c$) in R_3 , while there will be no current in R_2 as illustrated in Table 4. It is worth noting that a current sensor fault will be detected and located within a few sampling periods, allowing the implementation of a fast fault-tolerant procedure.

TABLE 1 Relationship between switching states and measured dc-bus currents

S2	S4	S6	I_{ft}	Regions
1	1	0	$I_{b+} I_a$	R_1
1	0	0	I_a	R_2
1	0	1	$I_a + I_c$	R_3
0	0	1	I_c	R_4
0	1	1	$I_{c+} I_b$	R_5
0	1	0	I_b	R_6

TABLE 2 Detected currents through the sensors under normal conditions

Current sensors	Detected currents in a current period					
	R_1	R_2	R_3	R_4	R_5	R_6
S_a	I_a	I_a	I_a	0	0	0
S_b	I_b	0	0	0	I_b	I_b
S_c	0	0	I_c	I_c	I_c	0
S_{dc}	I_s	I_a	I_s	I_c	I_s	I_b

TABLE 3 Detected currents through the sensors under a fault in phase A current sensor, S_a

Current sensors	Detected currents in a current period					
	R_1	R_2	R_3	R_4	R_5	R_6
S_a	0	0	0	0	0	0
S_b	I_b	0	0	0	I_b	I_b
S_c	0	0	I_c	I_c	I_c	0
S_{dc}	$> = I_s$	I_a	$> = I_s$	I_c	I_s	I_b

TABLE 4 Detected currents through the sensors under an open-circuit fault in phase A

Current sensors	Detected currents in a current period					
	R_1	R_2	R_3	R_4	R_5	R_6
S_a	0	0	0	0	0	0
S_b	I_b	0	0	0	I_b	I_b
S_c	0	0	I_c	I_c	I_c	0
S_{dc}	$0.5I_s$	0	$0.5I_s$	I_c	I_s	I_b

4 | PROPOSED FAULT-TOLERANCE SCHEME FOR CURRENT SENSORS

An effective FTC scheme requires the information on the exact fault location. Therefore, the fault diagnosis and tolerant control schemes are considered as two cascaded processes. The FTC scheme in this study is further classified into the following three modes.

4.1 | Single current sensor fault tolerant control

From Figure 6 and Table 1, it can be observed that, in regions R_1 , R_3 and R_5 , the incoming phase current overlaps with the outgoing phase current, while in regions R_2 , R_4 and R_6 , only an excitation current of a phase exists in the dc-bus current sensor. Therefore, when a current sensor is faulted, the faulty phase excitation current can be accurately reconstructed. For instance, assuming phase A current sensor is diagnosed with a fault, from Figure 6 the maximum turn-on region of phase A is $\theta_1 < \theta \leq \theta_4$, which starts from R_1 and ends in R_3 , phase A's current can be reconstructed as:

$$I_{arec} = \begin{cases} (I_{fi} - I_b).S2, & R_1 \\ I_{fi}.S2, & R_2 \\ (I_{fi} - I_c).S2, & R_3 \end{cases} \quad (5)$$

where I_{arec} represents the reconstructed phase A current, I_b and I_c are the currents of phase B and phase C, respectively. Moreover, I_{fi} and $S2$ represent the detected dc-link current and turn-on signal for phase A, respectively. Clearly, in region R_1 , I_{fi} is the sum of phase A and phase B currents. Therefore, by subtracting the phase B current from I_{fi} , we can obtain the excitation current of the faulty phase (i.e., A) in this region. In region R_2 , the dc-link sensor contains only phase A current, while in region R_3 , the excitation current of phase A is decoupled by subtracting the phase C current from the dc-link current I_{fi} .

Similarly, if only phase B's current sensor is faulted, the expression for the current reconstruction is given by:

$$I_{brec} = \begin{cases} (I_{fi} - I_c).S4, & R_5 \\ I_{fi}.S4, & R_6 \\ (I_{fi} - I_a).S4, & R_1 \end{cases} \quad (6)$$

Likewise, when phase C current sensor alone is faulted, the reconstructed current I_{crec} is calculated as:

$$I_{crec} = \begin{cases} (I_{fi} - I_a).S6, & R_3 \\ I_{fi}.S6, & R_4 \\ (I_{fi} - I_b).S6, & R_5 \end{cases} \quad (7)$$

4.2 | Dual current sensors fault tolerant control

When two current sensors associated to two phases are faulted successively or simultaneously, the excitation current of the outgoing phase in a commutation region is calculated using an averaging algorithm as shown in Table 5. For example, if both the current sensors of phase A and B are in fault conditions,

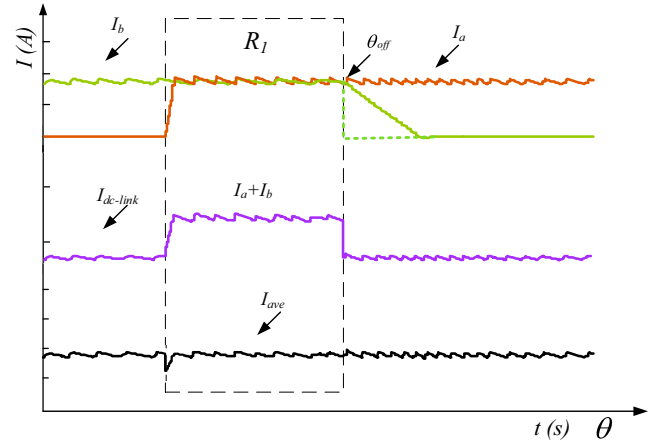


FIGURE 7 Proposed arithmetic averaging method in a commutation region

phase B's reconstructed current, which is the outgoing phase, in region R_1 is obtained by taking an average of the dc-link current. As the detected current through the dc-link sensor is the sum of the currents in phase A and B in this region as illustrated in Figure 7. The phase A current can be estimated by subtracting the phase B's reconstructed current from dc-link current, as calculated in the case of a single sensor fault. The arithmetic average of the two phase currents in commutation regions are calculated as:

$$I_{ave} = \begin{cases} \left(\frac{I_{fi}}{2}\right).S2.S4, & R_1 \\ \left(\frac{I_{fi}}{2}\right).S2.S6, & R_3 \\ \left(\frac{I_{fi}}{2}\right).S4.S6, & R_5 \end{cases} \quad (8)$$

where I_{ave} is the arithmetic average of the two simultaneously excited currents in each commutation regions of a fundamental current period. The algorithm is further illustrated in Table 2.

The expressions for phase current estimation during dual sensors (A and B) fault are given as:

$$I_{arec} = \begin{cases} (I_{fi} - I_{brec}).S2, & R_1 \\ I_{fi}.S2, & R_2 \\ (I_{fi} - I_c).S2, & R_3 \end{cases} \quad (9)$$

$$I_{brec} = \begin{cases} (I_{fi} - I_c).S4, & R_5 \\ I_{fi}.S4, & R_6 \\ (I_{fi} - I_{ave}).S4, & R_1 \end{cases} \quad (10)$$

Same method can be applied to other combination of dual current sensor faults.

4.3 | All current sensors fault tolerant control

Finally, consider the worse situation in which all the phase current sensors are faulted successively or simultaneously. In this scenario, the reconstructed current of each phase is again obtained using the averaging method in their respective commutation regions. As illustrated in Figure 7, the two currents in the commutation regions are almost equal in magnitude and hence an average of the two currents can be obtained using Equation (8). The reconstructed currents I_{arec} , I_{brec} and I_{crec} are given as:

$$I_{arec} = \begin{cases} (I_{fi} - I_{ave}).S2, & R_1 \\ I_{fi}.S2, & R_2 \\ (I_{fi} - I_{ave}).S2, & R_3 \end{cases} \quad (11)$$

$$I_{brec} = \begin{cases} (I_{fi} - I_{ave}).S4, & R_5 \\ I_{fi}.S4, & R_6 \\ (I_{fi} - I_{ave}).S4, & R_1 \end{cases} \quad (12)$$

$$I_{crec} = \begin{cases} (I_{fi} - I_{ave}).S6, & R_3 \\ I_{fi}.S6, & R_4 \\ (I_{fi} - I_{ave}).S6, & R_5 \end{cases} \quad (13)$$

5 | SIMULATION RESULTS

The feasibility of the proposed current sensor FTC technique was verified through extensive simulations in Matlab/Simulink by using a 12/8-pole SRM model. The current sampling frequency was 20 kHz. The rated parameters of the SRM model are listed in Table 6. Simulations under single, dual and all current sensor fault conditions at both low and high speeds were performed, and the results are discussed as below.

5.1 | Current sensors fault detection

Firstly, the effectiveness of the FD scheme was verified as in Figures 8–10. Figure 8 shows that the current sensor S_a suffered from a zero-output fault at $t = 0.199$ s. Subsequently, the faulty sensor S_a output a zero value and the current controller continuously received a zero-value from the faulty sensor. This erroneous information misled the current controller (see Figure 4) and the controller turned on the upper switch of the faulty phase, while the lower switch was already closed due to the soft-switching mode. The continuous conduction of the both switches caused rapid increase in the current amplitude in the faulty phase as shown in R_2 , and R_3 of the I_{fi} in Figure 8. By using the fault signatures illustrated in Table 3, the faulty current sensor is identified.

Since a signal loss fault in a current sensor and an open-circuit fault in a power switch or stator winding produce similar fault signatures. For instance, in both cases, the controller receives a zero-value from the faulty phase.

TABLE 5 Arithmetic averaging method during commutation regions

S2	S4	S6	I_{ave}	Regions
1	1	0	$\frac{I_a+I_b}{2}$	R_1
1	0	1	$\frac{I_a+I_c}{2}$	R_3
0	1	1	$\frac{I_c+I_b}{2}$	R_5

TABLE 6 Rated parameters of the 12/8 SRM

Parameters	Values
Voltage (V_{dc})	48 V
Power	400 W
Torque	1 Nm
Speed	3800 rpm
Current	10 A

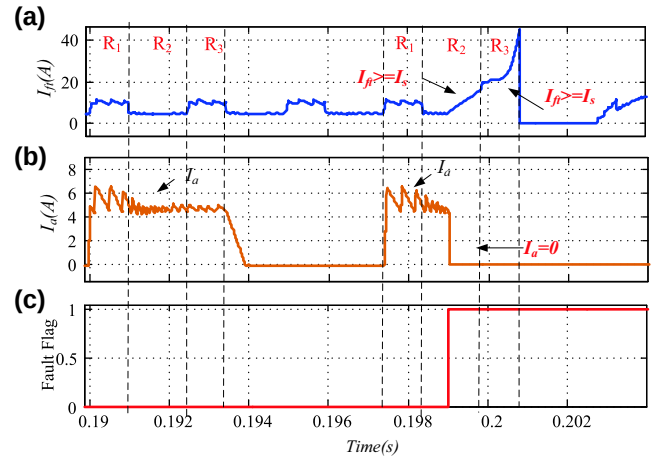


FIGURE 8 Fault diagnosis in a current sensor: (a) dc-link current (A), (b) current through current sensor S_a and (c) fault flag

Therefore, the FD algorithm should be able to accurately discriminate the two cases. Figure 9 shows that at $t = 0.199$ s (the same instance at which a current sensor appeared) the output of the current sensor S_a started to decay, while at the same time, the dc-link current, I_{fi} also decayed to zero. It means that according to Table 4, an open-circuit fault has appeared in the system as the faulty phase can no longer magnetise due to the open-circuit fault.

Figure 10 shows the fault diagnosis and tolerant control under a fault in a current sensor S_a at 1000 rpm. This case was particularly simulated to show the feasibility of smooth transition from normal to FTC mode. Similar to Figures 8 and 9, a current sensor fault was introduced in S_a at $t = 0.199$ s, the fault was detected and isolated within two sampling periods by using the fault features illustrated in Tables 3 and 4. The faulty sensor's current was replaced by the reconstructed current, using Equation (5), immediately to continue the machine operation without performance degradation.

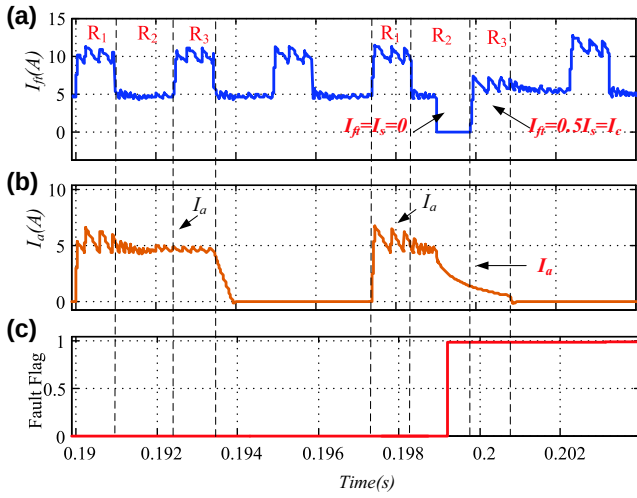


FIGURE 9 Fault diagnosis in a power switch: (a) dc-link current(A), (b) current through current sensor S_a and (c) fault flag

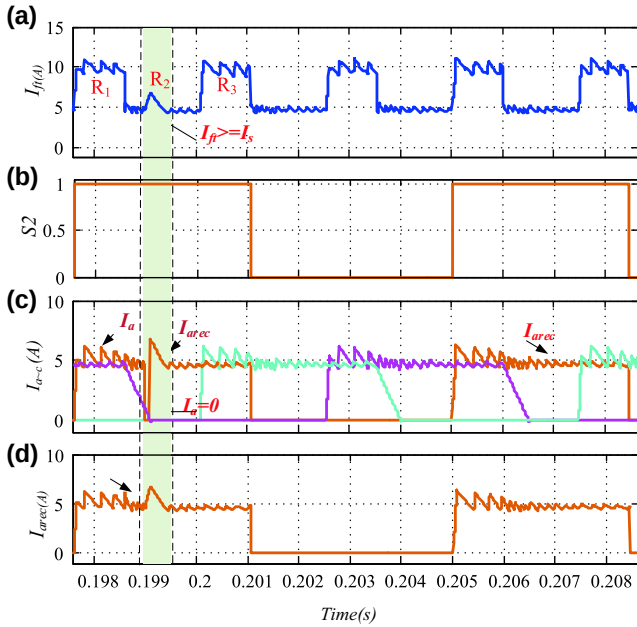


FIGURE 10 Fault diagnosis and tolerant control under a current sensor fault at 1000 rpm: (a) dc-link current (A), (b) switching signal, S_2 , (c) measured and reconstructed currents and (d) reconstructed excitation current of phase A

An FD and remediation scenario for dual sensors simultaneous fault occurrence in rotor position region R_3 , are illustrated in Figure 11. A signal loss fault was introduced at $t = 0.1916$ s in current sensors S_a and S_b , simultaneously. It can be observed that the phase currents I_a and I_b rapidly decayed to zero, while a current rise in the dc-link sensor can also be observed. The current sensors fault was effectively detected according to Tables 3 and 4, and it was immediately remediated by replacing the reconstructed currents using Equations (8) to (10). Moreover, the current ripple in the dc-link current and phase currents under normal and fault

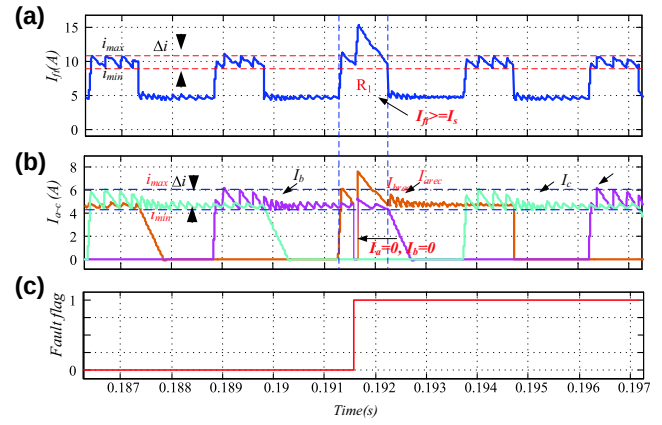


FIGURE 11 Fault diagnosis and tolerant control under dual-current sensor failure: (a) dc-link current (A), (b) phase currents (A) and (c) fault flag

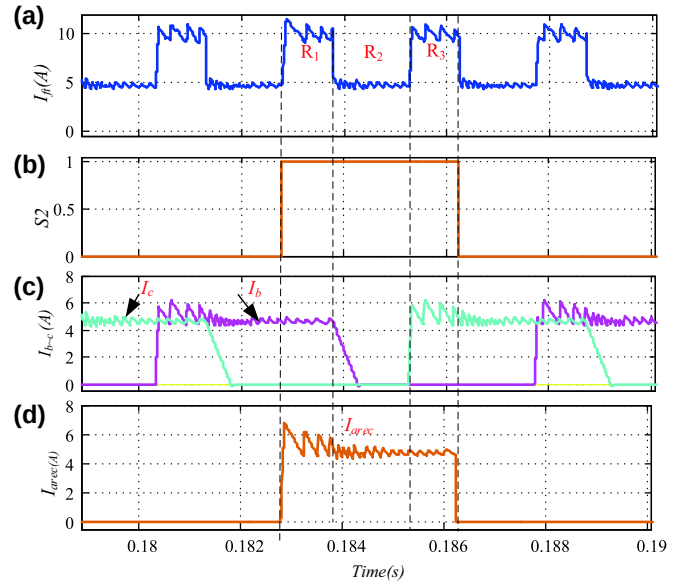


FIGURE 12 Fault-tolerant control at 1000 rpm when S_a is in faulty condition: (a) dc-link current (A), (b) position signals for lower switches of phase A, (c) measured currents of phase B and C and (d) reconstructed excitation currents of phase A

tolerant conditions can also be noticed. There is almost no ripple increase in the phase current under fault-tolerant situations.

Now, from the above analysis it is clear that a fault in a current sensor can effectively be identified and discriminated from open-circuit faults. Moreover, a smooth transition from normal to fault-tolerant mode can be achieved.

5.2 | Current reconstruction under postfault conditions

This study further mainly discusses the current reconstruction of the a faulty phase at different rotor position regions by using the equations discussed in Section 4 under single, dual and all

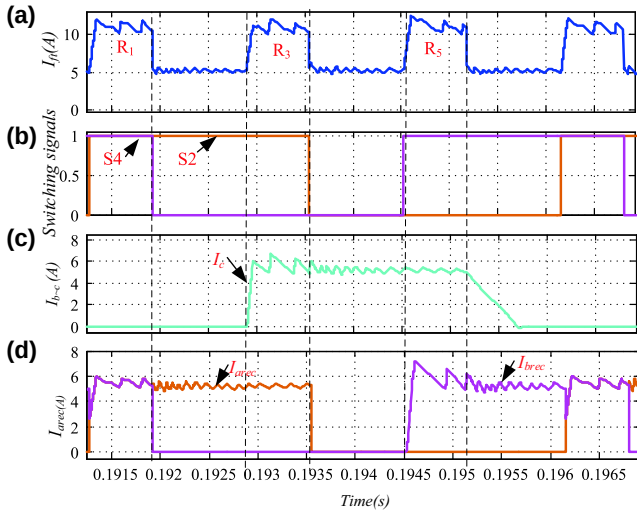


FIGURE 13 Fault-tolerant control at 1500 rpm when current sensors A and C both are faulted: (a) dc-link current (A), (b) position signals for lower switches of phase A (S2) and C (S6), (c) phase B's measured current and (d) reconstructed excitation currents of phase A and phase C

sensor failures. Figure 12 shows the fault-tolerant phase current reconstruction process considering a fault in phase A's current sensor. Since the current sensors associated to phase B and C were healthy, the excitation current of phase A was reconstructed by using Equation (5). Clearly, phase A current during regions R_1 and R_3 was accurately reconstructed without introducing current ripples.

Similarly, Figure 13 shows the FTC operation under a dual-sensor failure, where phase C current was assumed to be healthy, and phase A's and B's current sensors were subjected to a zero-output fault. The reconstructed currents of phases A and B were obtained using Equations (9) and (10), respectively. In region R_1 , both faulty phases were simultaneously conducting, therefore, in this region, the average current obtained by using Equation (8) was subtracted from the dc-link current to get the reconstructed fault-tolerant currents in this region.

The worst case, when all the current sensors were faulted, was simulated at 2000 rpm as shown in Figure 14. In this case, as explained earlier, the arithmetic average of the dc-link current in commutation regions was estimated and the averaged current was subtracted from the dc-link current in each commutation region as explained in Equations, (11), (12) and (13). Clearly, it can be observed that the currents of all phases were controlled accurately using the estimated excitation currents.

5.3 | Current error analysis

Comparisons of the reconstructed current with a measured current through the individual phase current sensor are shown in Figures 15 and 16. Figure 15 shows the comparison of the reconstructed current under single current sensor fault with the healthy current of a healthy sensor. As can be observed that the error during the magnetisation and commutation stages is

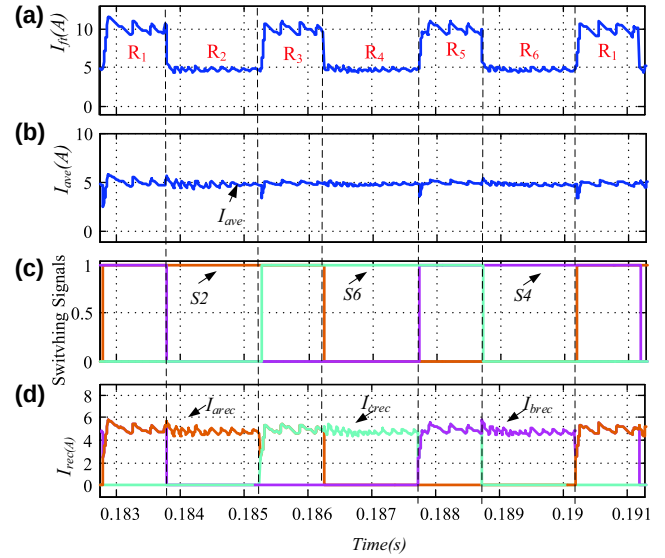


FIGURE 14 Fault-tolerant control operation at 2000 rpm when current sensors A, B and C all are faulted: (a) dc-link current (A), (b) averaged current at commutation regions (A), (c) position signals S2, S4 and S6 (d) reconstructed three-phase excitation currents (A) and (e) three-phase measured currents under healthy conditions

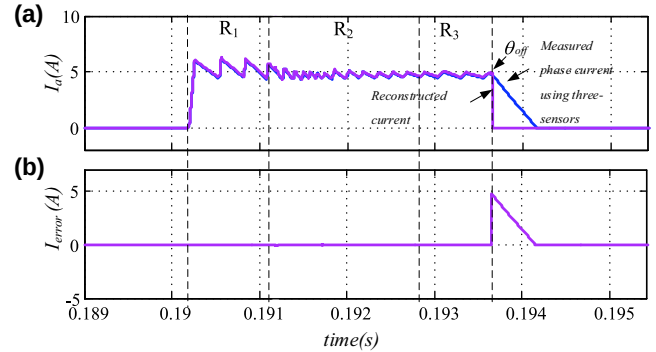


FIGURE 15 Comparison between reconstructed current and the healthy (measured) current under a faulty sensor i.e., S_a (A): (a) real and reconstructed currents of phase A and (b) currents error

nearly zero. It is evident that there was no current ripple increase under fault-tolerant mode. As mentioned previously, no current reconstruction was performed in the demagnetisation stage, and hence a large error can be seen. However, this large error did not affect the current control of the SRM drive.

Figure 16 shows the phase A's current comparison under all current sensors fault. Compared to the single/dual sensors fault, this case shows small errors during commutation regions, with a maximum error around 0.1 A. However, at the beginning of the commutation period, a small current spike in region R_3 can be seen in the outgoing phase current (phase A). This has appeared mainly because the actual current of the incoming phase started rising from zero at this instant.

However, the duration of this error is found to be short enough to influence the operation. If it is necessary, further approach to reduce this error might be implemented. For

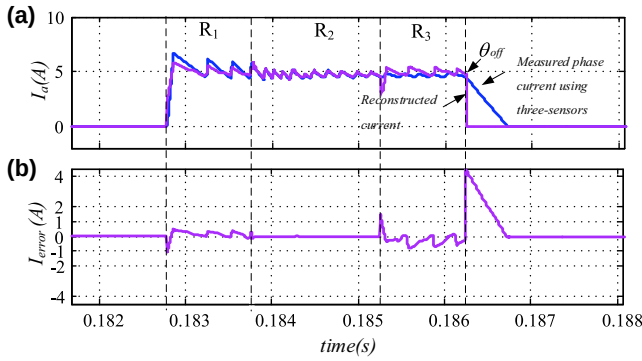


FIGURE 16 Comparison between the reconstructed current and the healthy (measured) current when all phase current sensors were faulted (A): (a) real and reconstructed currents of phase A and (b) currents error

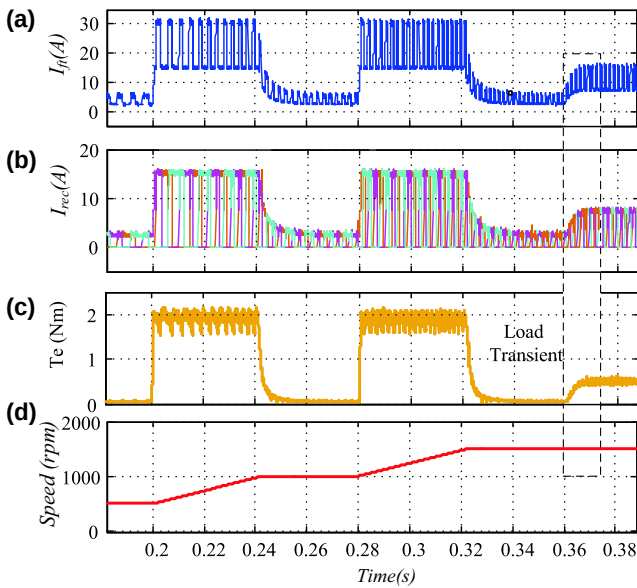


FIGURE 17 Speed and load transient response of the proposed fault tolerant scheme: (a) dc-link current (A), (b) reconstructed three-phase excitation currents (A), (c) total torque (Nm) and (d) speed of the SRM (rpm)

instance, the rising current of the incoming phase can be estimated using a simple linear estimation technique.

The dynamic response of the proposed current sensor fault-tolerant scheme was studied to verify the practicability for real-time applications. Speed and load transient conditions were simulated and the subsequent results are presented in Figure 17. For verification, the worst case i.e., all sensor faults, was considered. It can be observed that a transient speed was applied at $t = 0.2$ s from 500 rpm to 1000 rpm and another sudden speed change was applied at $t = 0.28$ s from 1000 rpm to 1500 rpm. During these speed transients a load transient was simulated at $t = 0.36$ s to verify the control performance under all current sensor fault tolerant operation. Clearly, due to the sudden load change from $T_L = 0.05$ Nm to 0.5 Nm the current amplitude has increased and quickly reached to steady state.

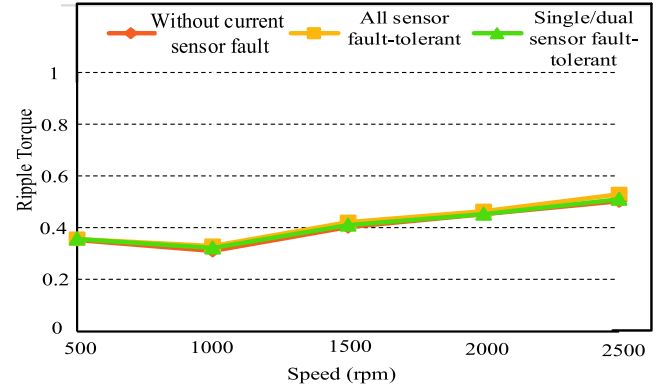


FIGURE 18 Torque ripple comparison between healthy and fault conditions

Since a phase current is a function of motor torque, a comparison on the torque ripple between the normal and postfault conditions was investigated. It is very clear from Figure 18 that no obvious torque ripple increase by using the proposed fault-tolerant scheme was registered. The ripple torque under dual sensor FTC scheme is identical to the standard individual sensor scheme. A maximum 0.7 % ripple torque increase compared to the normal condition under all current sensor fault conditions can be observed at high speeds.

6 | EXPERIMENTAL VALIDATIONS

The experimental setup to validate the proposed current sensor fault-tolerant scheme is shown in Figure 19. A three-phase asymmetric converter shown in Figure 5 was built to drive an SRM, whose parameters are tabulated in Table 6. An SC-2F load torque controller was used to control the dynamometer. A TMS320F28335 digital signal processor with code composer studio 6.1.0 was used to control the motor drive. A current sensor fault was emulated by assigning a zero value to the register associated to the current sensor. The switching and sampling frequency was 20 kHz.

As this study primarily focuses on the current reconstruction under faulty conditions, the FD scheme was mainly included to demonstrate the feasibility of the method for transition from healthy mode to the fault tolerant mode. Therefore, the practicability of the current reconstruction scheme under single, dual and all current sensors failure for a three-phase SRM is thoroughly evaluated as below.

6.1 | Phase current reconstruction under steady states

A single current sensor fault case was tested at 1000 rpm, and the corresponding waveforms are shown in Figure 20. The current sensor associated to phase A was assumed to be a faulty one and the excitation current of phase A in the rotor

FIGURE 19 Experimental test rig for the 12/8 SRM

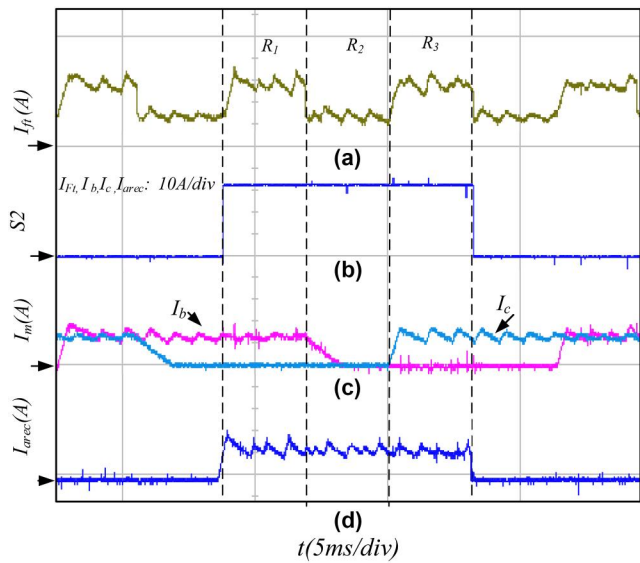
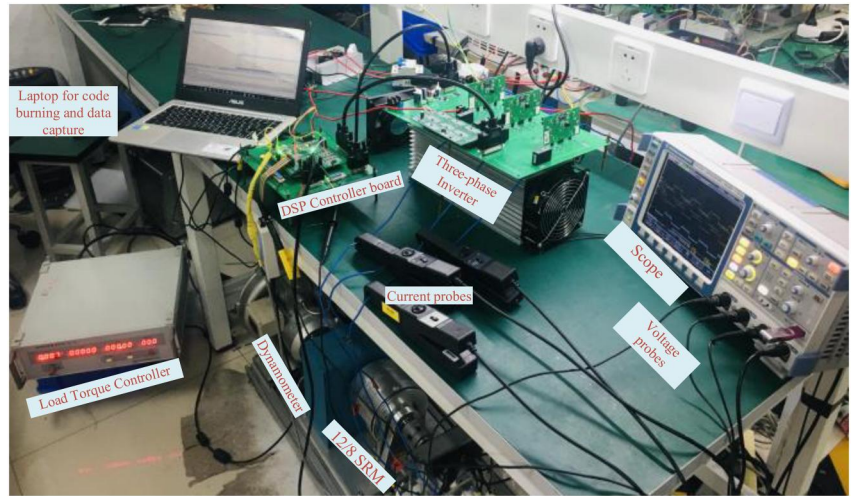


FIGURE 20 Single sensor fault-tolerant operation at 1000 rpm and 0.1 Nm: (a) dc-link current (A), (b) phase A's lower switch signal, (c) measured currents of phase B and C (A) and (d) reconstructed excitation current of phase A (A)

position regions R_1 , R_2 and R_3 were reconstructed by utilising the Equation (5) explained in Section 4. It can be observed that the phase A current precisely estimated and in close agreement with that of the simulated one shown in Figure 12.

Similarly, a test on the dual-sensor fault case was conducted at 1500 rpm. The results are shown in Figure 21. The faulty phase currents that is, phase C and phase A were built in all rotor position regions by using the detected currents through the dc-link sensor and the healthy sensor based on Equations (8) to (10). Clearly, the phase currents were precisely rebuilt under postfault conditions preventing the machine from performance degradations for safety-critical applications.

The reconstructed three-phase currents using the averaging method in the case of all sensors fault are shown in

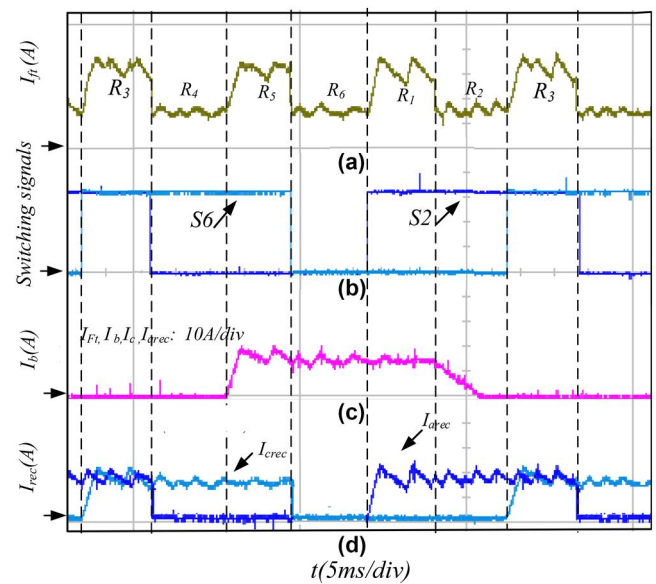


FIGURE 21 Dual-sensor fault-tolerant control under CCC at 1500 rpm and 0.12 Nm: (a) dc-link current (A), (b) switching signals S2 and S6, (c) measured currents of phase B and (d) reconstructed excitation current of phase A and phase C

Figure 22. It is worth noting that the phase currents were rebuilt in all regions by using the Equations (11) to (13) without distortions at a high speed condition (i.e., 2000 rpm). As can be seen, in commutation regions, both the incoming and the outgoing phases share the same averaged current amplitude for control. Motor drive was controlled well without degraded performance despite the fault in all phase current sensors. The turn-on and turn-off angles were 0 and 21, respectively in all cases.

Furthermore, to demonstrate the accuracy of the reconstructed currents and quantify the current ripples before and after fault occurrence, the reconstructed currents were output through the Digital to Analog Converter of the Digital Signal Processor and compared with measured currents through the

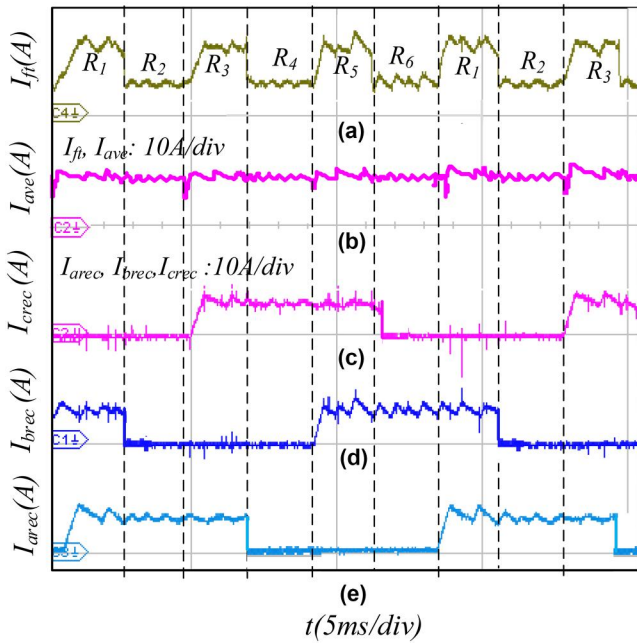


FIGURE 22 Fault-tolerant control operation at 2000 rpm when current sensors A, B and C all were faulted: (a) dc-link current (A), (b) averaged current at commutation regions (A), (c) switching signals S2, S4 and S6 (V) and (d) three-phase reconstructed currents (A)

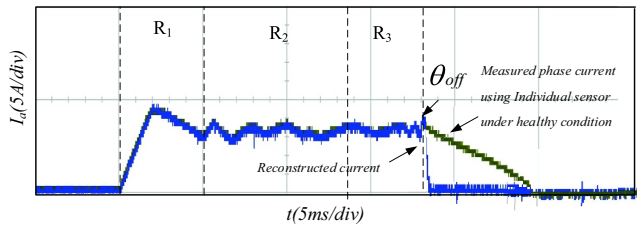


FIGURE 23 Comparison between reconstructed current and measured (real) current under dual sensors fault at 2500 rpm

individual current probes. The comparisons are established as shown in Figures 23 and 24. Figure 23 shows comparison of the currents recorded at 2500 rpm under dual sensors fault tolerant condition. The waveform with demagnetisation current represents the phase current measured through the healthy sensor (that is, S_a), while the waveform without demagnetisation current is the reconstructed current assuming a fault in current sensor, S_a . The currents comparison under the worse scenario that is, all sensors are fault-tolerant as shown in Figure 24. In this case, the current was recorded at 2000 rpm.

In the typical CCC, the switching signals are generated based on the current error comparison with thresholds, i_{max} , i_{min} as shown in Figure 24. In both simulation and experiments, the thresholds were $\pm 0.4A$. For the precise control, the current should be well within the error bands. If the current goes above or below the positive and negative thresholds, it will be counted as increase in current ripple. However, it should be noted that the CCC scheme demands high switching frequency and sampling frequency particularly for high speed operation. The current ripple is closely related to these

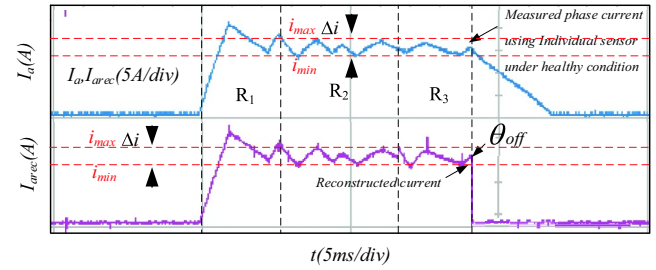


FIGURE 24 Comparison between reconstructed current and measured (real) current under dual sensors fault at 2000 rpm

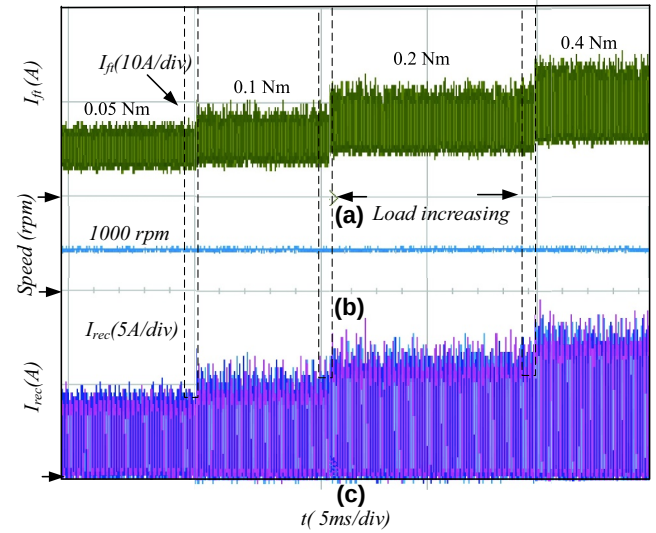


FIGURE 25 Load transient response of the proposed fault tolerant scheme: (a) dc-link current (A), (b) speed of the SRM (rpm) and (c) reconstructed three-phase excitation currents (A)

frequencies such that at lower frequencies the current ripple will be relatively high even under healthy operation. The current errors shown in Figures 23 and 24 demonstrate that there was no obvious ripple current in the reconstructed current as it was closely following the real current measured through the healthy sensors. Moreover, the three-phase currents in case of all sensor failure (Figure 24) were reconstructed from the dc-link current by using the averaging method, and the ripple in the reconstructed current reflects the ripple in the dc-link current. Hence, no additional ripple in the dc-link current appeared under the FTC operation as can be seen from Figures 20 to 24.

6.2 | Phase current reconstruction under transient states

The transient performance of the proposed current sensor fault-tolerant scheme considering the worst case i.e., all current sensor failure was evaluated experimentally. The transient responses of the closed loop system to step changes including load regulation and speed regulation are shown in Figures 25

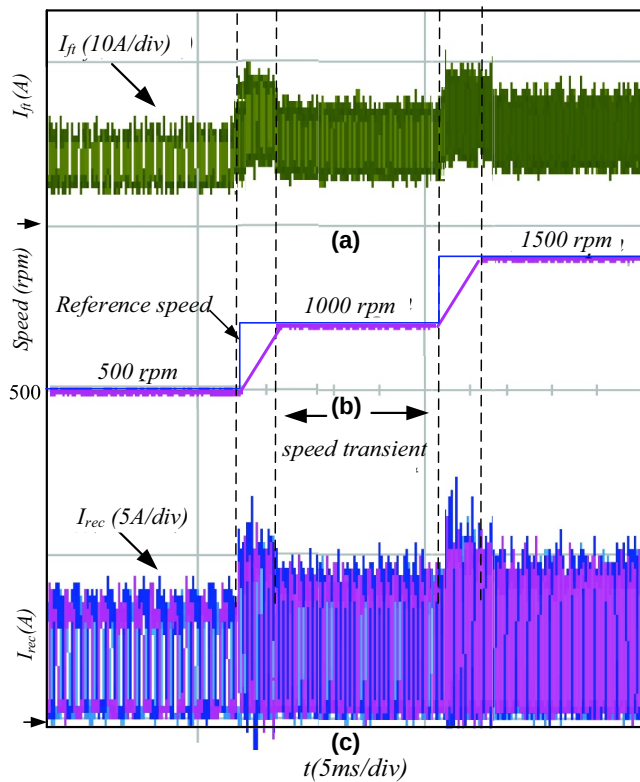


FIGURE 26 Speed transient response of the proposed fault tolerant scheme: (a) dc-link current (A), (b) speed of the SRM (rpm) and (c) reconstructed three-phase excitation currents (A)

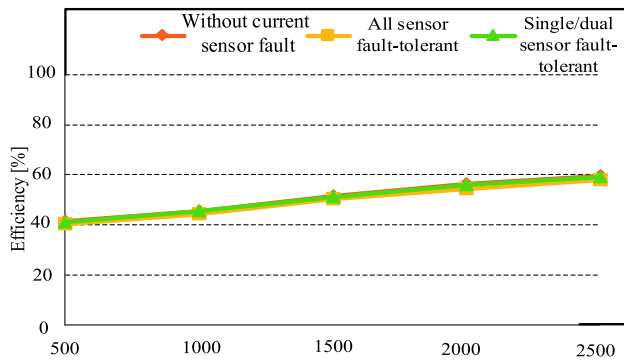


FIGURE 27 Comparison on efficiency of the SRM drive system without and with the current sensor faults

and 26, respectively. When the load was increased from 0.05 to 0.1 Nm, 0.1 to 0.2 Nm and 0.2 to 0.4 Nm, the speed was stabilised very quickly and the phase currents showed no obvious ripples, as illustrated in Figure 25. Moreover, as shown in Figure 26, when step speeds were applied from 500 to 1000 rpm and 1000 rpm to 1500 rpm, the instantaneous speed followed the reference speeds well and the reconstructed three-phase currents reached a steady state without introducing obvious current distortions during the transients.

As the phase currents, rotational speed and load torque are closely related to the efficiency of the SRM, the output

efficiency of the SRM under normal and post-fault conditions was evaluated experimentally at 0.4 Nm at different speeds. Figure 27 demonstrates that no obvious efficiency decrease by using the proposed fault-tolerant scheme was observed, which further validates the effectiveness of the proposed fault-tolerant scheme for practical applications.

7 | DISCUSSION AND CONCLUSION

The main contributions and advantages compared to the existing methods are listed as:

1. Compared to the existing current reconstruction schemes, the excitation currents were obtained by using a single dc-link current sensor, which is normally installed for current protection in the system. No HF signal injection or the switching pattern modification is needed, thereby reducing the current distortion and torque ripples.
2. In terms of complexity, compared to the existing single-sensor-based reconstruction schemes, this method does not require the phase currents to be sampled at specific sampling instants, therefore, the proposed scheme is simple and less complex for implementation. Moreover, it does not depend upon the parameters of the machine, which makes it suitable for real-time implementation.
3. Compared to the similar fault diagnosis and tolerant control schemes for other AC drives, this method does not require motor parameters and can also effectively detect and differentiate the current sensor and open-switch faults.
4. Based on the rigorous simulations and experimental results, it can be concluded that in high-performance and high-reliability applications, the proposed current reconstruction scheme can provide a simple, reliable and cost-effective fault-tolerant scheme for individual phase sensor faults.
5. The proposed current reconstruction scheme based on the dc-link current and the arithmetic average of the dc-link current during commutation regions can be an independent alternative for traditional individual current sensors in low-cost applications.
6. Finally, compared to most of the existing techniques, it can be observed that the proposed fault-tolerant scheme could be a universal scheme as it can easily be extended to SRMs with different number of phases.

As a conclusion, this study has investigated a simple and cost-effective current sensor fault diagnosis and fault tolerant scheme for an SRM drive for safety-critical applications. A dc-link current sensor which is normally used for current protection in the system is used to reconstruct the excitation currents. The faulty phase's excitation current was reconstructed by using a simple estimation technique based on the dc-link current and a healthy phase current in the case of a single or dual sensor faults. An arithmetic averaging method was utilised in the commutation regions when all the phase current sensors are faulted. The proposed method has been fully verified under both steady state and dynamic conditions.

The theoretical analysis supported by the extensive simulations and experimental results demonstrate that the extreme fault-tolerance can be achieved even when all the current sensors are in a fault condition. However, if the dc-link current sensor is also faulted together with phase current sensor(s), the excitation current of the faulty phase(s) during the single-active region cannot be reconstructed using the proposed method. It should be noted that the authors presented the FTC method by avoiding the parameter dependency of the existing methods for other AC drives. When all phase current sensors fail together with the dc-link sensor, the excitation current can only be estimated through the intelligent methods using the machine parameters, which remain to be investigated in the near future.

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