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Model based Fault Detection and Isolation for Driving Motors of a Ground Vehicle

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Abstract: This paper proposes model based current sensor and position sensor fault detection and isolation algorithm for driving motor of In-wheel independent drive electric vehicle. From low level perspective, fault diagnosis conducted and analyzed to enhance robustness and stability. Composing state equation of interior permanent magnet synchronous motor (IPMSM), current sensor fault and position sensor fault diagnosed with parity equation. Validation and usefulness of algorithm confirmed based on IPMSM fault occurrence simulation data. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Fault detection and isolation (FDI), Parity equation, Fault diagnosis, Residual, Current sensor, Position sensor, Faulty sensor.

1. Introduction

Driving motors of ground vehicle need to satisfy various requirements. Such as structural robustness, high output and torque, wide velocity, vibration, heat-proof, high efficiency driving control. IPMSM satisfy above requirements compare to SPMSM (Surface Permanent Magnet Synchronous Motor) due to structural difference. IPMSM has wider speed range by flux weakening.

IPMSM is widely used in industries in behalf of induction motor because of higher output, speed and efficiency than induction motor. Since IPMSM does not need field coil so rotor rotate same speed with stator magnetic field. IPMSM have permanent magnet inside, so there is no copper loss and provide high peak efficiency compare to induction motor. With compact construction, power to weight ratio is higher that induction motor. With development of electricity and electronics, it is possible to apply IPMSM in high performance and speed drive area.

Vector control is a way to control IPMSM precisely. Field oriented principle is used to control magnetic flux, space vector of current and voltage. Coordinate system that can separate vector to magnetic flux and torque occurrence is composed. To control magnetic flux and torque separately, it need to dissociate stator current's magnetic field and torque occurrence part and compose a rotary coordinate system connected with rotor magnetic field. This is d-q coordinate system.

To conduct vector oriented control, there are procedure to follow : measure of phase voltage and current, change measured data to 2-phase system (α,β) with Clarke transformation, calculation of vector amplitude and position angle, change stator current to d, q-coordinate with Park transformation, stator current torque and magnetic field is controlled, output stator voltage space vector is calculated using decoupling block, changing stator voltage space vector from d, q coordinate to 2-phase coordinate related with stator with iPark transformation, generation of 3-phase voltage with sine wave modulation. In this control method, information of sensor data of current and position is necessary.

Since driving motors of ground vehicle is in harsh condition and many surroundings such as physical shock, changeable temperature and humidity can cause fault in sensor. For stability of vehicle, detection and diagnosis of fault must be fast and effective.

There are two ways of fault management method. One is Hardware redundancy and another is analytic redundancy. Hardware redundancy means that using same sensor or actuator that can replace faulty part. It is easy to deal with faulty situation. However it pay more expense and require additional space. This method is used in aerospace application. On the other hand, analytic redundancy use mathematical model of plant. So it does not need additional sensor and can detect and diagnosis fault. Generally in ground vehicle, analytic redundancy is used more because of the cost. This paper is using analytic redundancy to detect and diagnosis fault.

There are 2 main approaches for fault detection. One is parity equation and the other is observer-based method. Both of them use measurable input and output signals. Structure of equations is very similar. There are difference in the way of filtering of input and output. Parity equation is intuitive approach and have advantage in arithmetic operation speed since it is simplicity and immediacy. Since it is open loop system, its accuracy is less accurate than observer-based approach. Usually, parity equation is not used in control itself because aim of control is minimizing control error. However it is different in fault detection because detecting fault is more important. In this way, it is possible to use parity equation. If situation is well understand, it is good choice to use parity equation. Observer-based approach is closed loop system so that accuracy is higher than parity equation. They use observer such as Luenberger state observers and Kalman filter. Even if there are feedback circuit in observer-based approach, it is influenced by noise and disturbance. However it is good to decrease modeling error. There are method using both of parity equation and observer-based approach. In automotive system, modeling error is not so big except with vehicle friction. Such being the case, it is possible to use parity equation in automotive system and this motor example.

In this paper, by taking situation of fault in measurement of current sensor and position sensor, we have shown that validation of model based current and position sensor fault detection and isolation algorithm. To detect and isolate the fault, modeling of the IPMSM is introduced, model based fault detection and isolation (FDI) with parity equation is proposed. To make faulty situation, types of current and position sensor faults are introduced. Finally, validation of proposed FDI algorithm was conducted with Matlab/Simulink simulation model.

2. Modeling of IPMSM

For analytical redundancy analysis, mathematical model of the target system is needed. Fig. 1 express d-q equivalent circuit of IPMSM. It can be simplified with several components. Equation (1) express voltage equation of d-q rotary coordinate system.

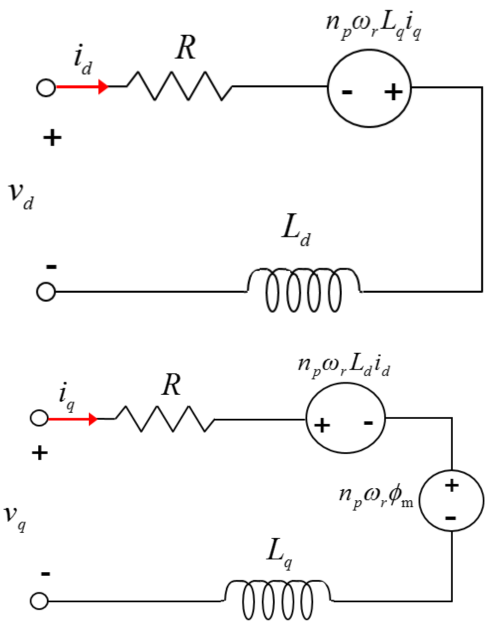


Fig. 1. D-q equivalent circuit for IPMSM.

$$\begin{aligned} v_d &= Ri_d + L_d \frac{di_d}{dt} - n_p w_r L_q i_q \\ v_q &= Ri_q + L_q \frac{di_q}{dt} + n_p w_r L_d i_d + n_p w_r \varphi_m , \end{aligned} \tag{1}$$

where v_d, v_q are the d-q axes applied voltages, i_d, i_q are the d-q axes currents, w_r is the rotor speed, R is the armature winding resistance, L_d, L_q are the d-q axes inductances, ϕ_m is the magnet flux linkage.

Equation (2) is transformation from 3-pahse fixed coordinate system to 2-pahse rotary coordinate system.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

Most cases in 3-phase motor system use 2-phase current sensor does not use 3-phase current sensor because it costs more. Using motor current equivalent $i_a + i_b + i_c = 0$, we can eliminate i_c in equation (2).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{3} & \frac{2\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{3}$$

3. Fault Detection and Isolation

3.1. Fault Detection with Parity Equations

One of way to detect the fault is to compare with process that actual behavior and model that behave nominal. The difference between the process output and model output is residual.

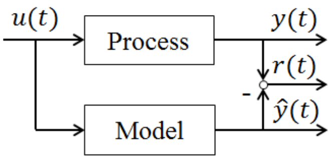


Fig. 2. Residual generation with parity equations. u(t): input, y(t): process output, $\hat{y}$(t): model output r(t): residual.

In fault free situation, residual will be close to zero if model is composed well. In faulty case, process output will be different from model output.

3.2. Current Sensor Fault Diagnosis

To compose parity equation, state space equation is given by:

$$\begin{aligned} \dot{x} &= \mathrm{A}x + \mathrm{B}u + \mathrm{E}_\mathrm{x} d \\ y &= \mathrm{C}x + \mathrm{D}u + \mathrm{E}_\mathrm{y} d + \mathrm{F}_\mathrm{y} f \end{aligned} \tag{4}$$

where x∈R^n: state vector, u ∈ R^m: the vector of measured input signals, y ∈ R^P : the vector of measured plant output signals, d ∈ R^{n_d}, f ∈ R^{n_f}: the vectors of unknown input signals, f : the faults one wishes to detect, d: unknown disturbances.

Transfer function is calculated with equation (4) and is given by:

$$\begin{aligned} y(s) &= H_{yu}(s)u(s) + H_{yx}(s)x(0) \\ &\quad + H_{yd}(s)d(s) + H_{yf}(s)f(s) \end{aligned}$$
$$\begin{cases} H_{yu}(s) = C(sI-A)^{-1}B + D \\ H_{yx}(s) = C(sI-A)^{-1} \\ H_{yd}(s) = C(sI-A)^{-1}E_x + E_y \\ H_{yf}(s) = C(sI-A)^{-1}F_x + F_y \end{cases} \tag{5}$$

By using Fig. 3's residual, equation (6) is given by:

$$\begin{aligned} r(s) &= V_{ru}(s)u(s) + V_{ry}(s)y(s) \\ &= V_{ru}(s)u(s) + V_{ry}(s)\begin{Bmatrix} H_{yu}(s)u(s) + H_{yd}(s)d(s) \\ + H_{yx}(s)x(0) + H_{yf}(s)f(s) \end{Bmatrix} \\ &= \begin{bmatrix} V_{ru}(s) + V_{ry}(s)H_{yu}(s) & V_{ry}(s)H_{yd}(s) \end{bmatrix} \begin{bmatrix} u(s) \\ d(s) \end{bmatrix} \\ &\quad + V_{ry}(s)H_{yx}(s)x(0) + V_{ry}(s)H_{yf}(s)f(s) \end{aligned} \tag{6}$$

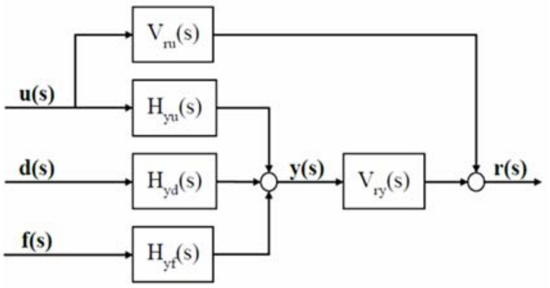


Fig. 3. Structure of residual generator using parity equation.

To be affected by only fault signals, both u(s) and d(s)'s coefficients must be 0. So it needs to find the matrix that $V_{ru}(s)$ and $V_{ry}(s)$ satisfy.

$$\begin{bmatrix} V_{ry} & V_{ru} \end{bmatrix} \begin{bmatrix} H_{yu} & H_{yd} \\ I & 0 \end{bmatrix} = 0 \tag{7}$$

Here are state space equating expressed.

$$\begin{aligned} &\dot{x} = \mathrm{A}x + \mathrm{B}u + \mathrm{E}_\mathrm{x} d \\ &y = \mathrm{C}x + \mathrm{D}u + \mathrm{E}_\mathrm{y} d + \mathrm{F}_\mathrm{y} f \\ &x = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, u = \begin{bmatrix} v_d \\ v_q - n_p\omega_r\phi_m \end{bmatrix}, y = \begin{bmatrix} i_a \\ i_b \end{bmatrix}, f = \begin{bmatrix} i_{a\_f} \\ i_{b\_f} \end{bmatrix} \\ &\mathrm{A} = \begin{bmatrix} -\dfrac{R}{L_d} & \dfrac{n_p\omega_r L_q}{L_d} \\ -\dfrac{n_p\omega_r L_d}{L_q} & -\dfrac{R}{L_q} \end{bmatrix}, \mathrm{B} = \begin{bmatrix} \dfrac{1}{L_d} & 0 \\ 0 & \dfrac{1}{L_q} \end{bmatrix} \\ &\mathrm{C} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix}, D = 0 \\ &\mathrm{F}_\mathrm{y} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix} \end{aligned} \tag{8}$$

In parity equation, it consider only sensor faults ($F_x = 0$) and suppose disturbance is neglectful ($E_x = E_y = 0$).

Let w_r is pseudo constant and change equation (8) to transfer function like equation (5).

$$\begin{aligned} &H_{yu}(s) = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \dfrac{\sqrt{3}}{3} & \dfrac{2\sqrt{3}}{3} \end{bmatrix} \frac{1}{K} \begin{bmatrix} R + sL_q & n_p\omega_r L_q \\ -n_p\omega_r L_d & R + sL_q \end{bmatrix} \\ &H_{yd}(s) = 0 \end{aligned} \tag{9}$$

where $\mathrm{K} = (\mathrm{R} + sL_d)(R + sL_q) + n_p^2 w_r^2 L_d L_q$.

Applying Equation (9) to Equation (7), $V_{ry}(s)$ and $V_{ru}(s)$ is given by:

$$\begin{aligned} &V_{ry}(s) = \begin{bmatrix} -n_p\omega_r L_d & -R - sL_q \\ -R - sL_d & n_p\omega_r L_q \end{bmatrix} \\ &V_{ru}(s) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \end{aligned} \tag{10}$$

And the residual is calucated and given by:

$$\begin{aligned} r(s) &= V_{ry}(s)y(s)+V_{ru}(s)u(s) \\ &= \begin{bmatrix} -n_p\omega_r L_d & -R-sL_q \\ -R-sL_d & n_p\omega_r L_q \end{bmatrix} y(s) + \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} u(s) \\ &= \begin{bmatrix} -n_p\omega_r L_d & -R-sL_q \\ -R-sL_d & n_p\omega_r L_q \end{bmatrix} \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{3} & \frac{2\sqrt{3}}{3} \end{bmatrix} f(s) \end{aligned} \tag{11}$$

And make a coordinate transformation to separate current sensor faults in phase a, b.

$$\begin{aligned} r'(s) &= \left(\begin{bmatrix} -n_p\omega_r L_d & -R-sL_q \\ -R-sL_d & n_p\omega_r L_q \end{bmatrix} \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\sqrt{3}}{3} & \frac{2\sqrt{3}}{3} \end{bmatrix} \right)^{-1} r(s) \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} f(s) \\ &= \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} \end{aligned} \tag{12}$$

From equation (12), the result shows that residual r_1 and r_2 affected by i_{a_f} and i_{b_f} independently.

3.3. Position Sensor Fault Diagnosis

Calculated parity equation results showed only separation of only current sensor fault and there was no additional residual that separate position sensor fault independently. To confirm separation possibility of position sensor fault, it need to analysis correlation with each sensor about residual.

From equation (11) and (12), sensor information that related with r_1 and r_2 is given by:

$$r_1 : 0 = r_1(v_d, v_q, i_a, \theta), \tag{13}$$

$$r_2 : 0 = r_2(v_d, v_q, i_b, \theta), \tag{14}$$

From equation (13) and (14), fault table is expressed in Table 1.

Table 1. Fault table of fault diagnosis residual.

	v_d	v_q	i_a	i_b	θ
r_1	X	X	X		X
r_2	X	X		X	X

X in Table 1 means that there are relations with residual $r_i(\mathrm{i} = 1,2)$ and each sensor. Otherwise blank in table is not related.

From the table, in position sensor faulty situation, it shows that both r_1 and r_2 will be affected and residual data will be change.

If we assume only single fault of the system, it is possible to separate that position sensor fault with current sensor i_a, i_b's fault through calculated r_1 and r_2.

4. Simulation Results

Suggested algorithm realized with Matlab/Simulink. Matlab/Simulink can describe motor system similar to the real IPMSM system.

IPMSM control system was selected as "AC6 - 100 kW Interior Permanent Magnet Synchronous Motor Drive" in example of Matlab/Simulink. Each parameter of motor model is expressed in Table 2.

Table 2. IPMSM model parameter.

Parameter Name	Value (Unit)
Stator resistance (R)	8.296 (mΩ)
d-axis stator inductance (L_d)	0.174 (mH)
q-axis stator inductance(L_q)	0.293 (mH)
Magnet flux linkage($\emptyset_m$)	71.115 (mV · s)
Inertia(J)	0.089 (kg · m^2)
Viscous damping(F)	0.005 (Nm · s)
Pole pairs(n_p)	4

Fig. 4 is fault command to each sensor.

From 0.5 to 0.7 s: fault signal to current sensor of phase a adding 100A offset.

From 1.0 to 1.2 s: fault signal to current sensor of phase b multiplying gain 2.

From 1.5 to 1.7 s fault signal to position sensor adding 0.1 rad offset.

Total simulation time is 2 s.

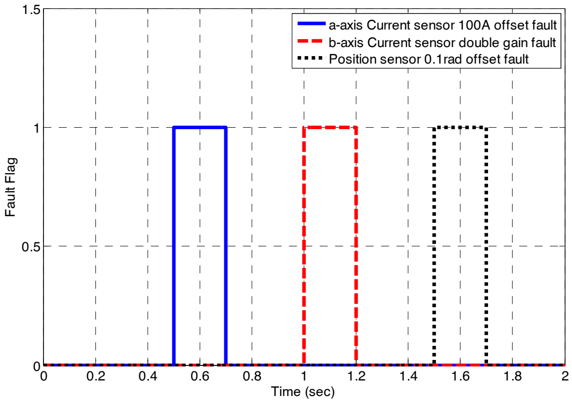
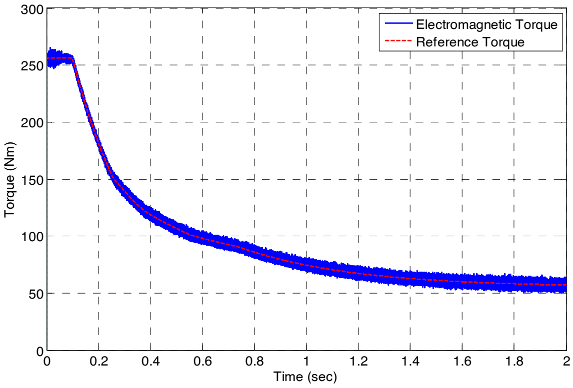


Fig. 4. Torque control simulation results (Fault flag).

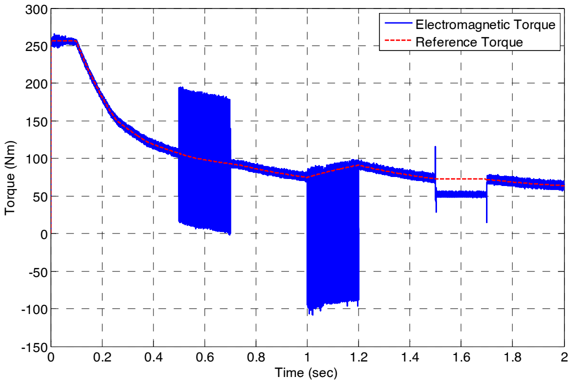
Fig. 5 shows electromagnetic torque of IPMSM control system respect to reference torque.

Fig. 5. (a) shows measeared output torque in normal state. Electromagnetic torque follows reference torque. In faulty state like Fig. 5. (b), electromagnetic torque break away from reference

torque. There are changes in each sensor fault siutation. Especially current sensor data break out a lot and looks distinguishable. It affect output torque with current sensor fualt in both phase. However it is hard to tell where the fault occurs.



(a) Output torque (Normal)



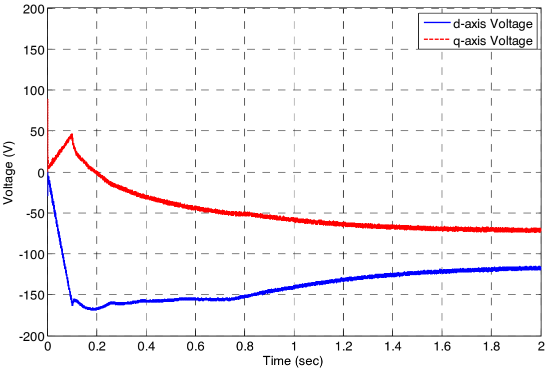
(b) Output torque (Faulty)

Fig. 5. Torque control simulation results (Output torque)

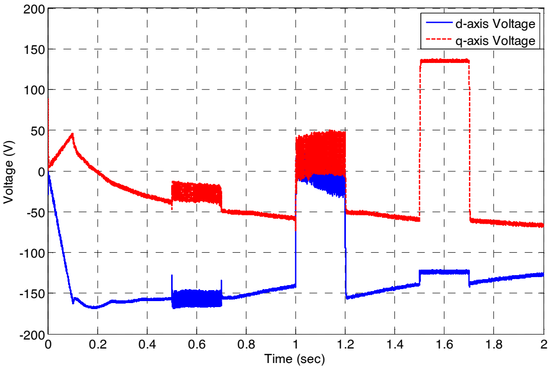
Fig. 6 shows d-q axis input voltage of IPMSM control system. Fig. 6. (a) is normal graph of rotor voltages. Fig. 6. (b) is in faulty situation in rotor voltages. Similar with Fig. 5's graph, it is hard to tell where the fault occur but we can figure out data break out in each faulty situation. Especially, current sensor fault in phase b make big change in d-q axis voltage and position sensor fault affect d-axix voltage.

Fig. 7 shows d-q axis current of IPMSM control system. Fig. 7. (a) is normal state of rotor currents. Fig. 7. (b) is faulty situation in rotor currents. As you can see, both d-axis and q-axis current are affected by each current sensor fault. On the other hand, position sensor fault affect d-axis current a lot.

From simulation results, when current and position sensor break down, it affects electromagnetic torque, input voltage and current. It can be identified that fault of one part can affect different parts in control system.

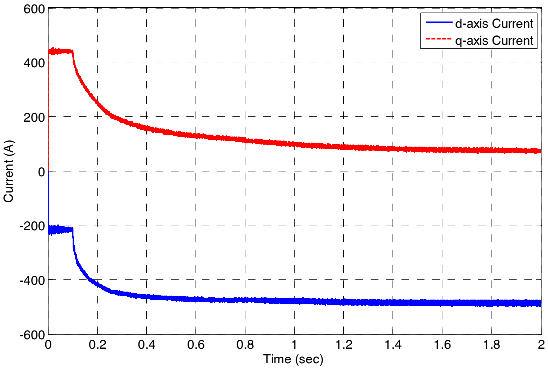


(a) Rotor voltages (Normal)

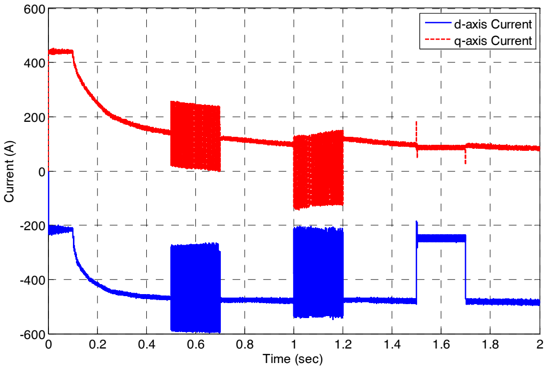


(b) Rotor voltages (Faulty)

Fig. 6. Torque control simulation results (Input voltages)



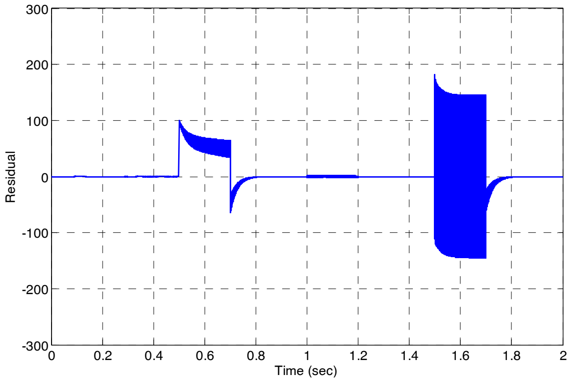
(a) Rotor currents (Normal)



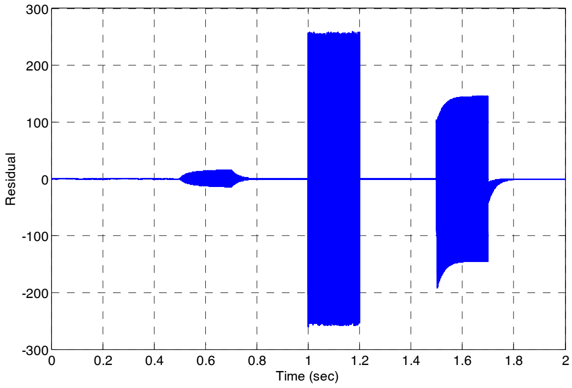
(b) Rotor currents (Faulty)

Fig. 7. Torque control simulation results (Rotor currents)

Fig. 8 shows proposed algorithm r_1 and r_2 in faulty situation. By Table 1's fault table, when current sensor of phase a breakdown, r_1 breaks away from 0 a lot and r_2 does not. When current sensor of phase b breakdown, r_2 breaks away from 0 a lot and r_1 does not. In case of position sensor breaking down, both r_1 and r_2 breaks away from 0 a lot. However if it assume only single fault like in automotive system, it can be fault diagnosis and isolation through residual r_1 and r_2.



(a) Residuals (r_1)



(b) Residuals (r_2)

Fig. 8. Torque control simulation results (Residual)

5. Conclusions

In this paper, current and position sensor fault detection and isolation algorithm with parity equation suggested and algorithm confirmed validation with Matlab/Simulink simulation results. This fault detection and diagnosis method with parity equation can be applied to driving motors of a ground vehicle but also this method is possible to apply and extend to other systems as well. We expect that proposed fault diagnosis algorithm can develop robustness and stability of electric vehicle system.

There are various algorithm that detect and diagnosis fault. The party equation is only one of that. Parity equation have a strong advantage in operation speed so it is proper to use in real time processing system such as automotive system.

In further study, we will realize this system and conduct experiment of IPMSM system. We hope that we can obtain same result with proposed fault detection and isolation algorithm with parity equations.

After that we can apply both parity equation and overseer-based approach and make stronger algorithm that detect and diagnosis of motor system.

Acknowledgements

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