

Fault-Tolerant Control of EMB Systems

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ABSTRACT

In this paper, for the fault-tolerant control of electro-mechanical brakes (EMBs), we continuously estimate several system variables and utilize these estimates to detect faulty sensor outputs. The clamping force is estimated by using the motor position and hysteresis phenomenon during clamping and releasing. Current sensor faults can be easily derived from the characteristics of a three-phase balanced circuit, and the motor position is estimated by applying different methods in low-speed and high-speed regions where a model-based approach is adopted. Using the proposed fault-tolerant logic, we can detect which sensor has a fault during driving or braking. Then, we use a bumpless transfer technique so that the control performance does not deteriorate when the estimated values are substituted for the measured values. The validity and the effectiveness of the proposed fault-tolerant control for an EMB are shown by using EMB hardware-in-the-loop simulations (HILS), so that fault tolerance is guaranteed for a scenario of sensor failures. The HILS consists of an EMB set, a TriCore-based actuator Electronic Control Unit (ECU), a host PC, and a CAN monitoring tool.

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INTRODUCTION

X-by-wire systems offer advantages such as flexibility in vehicle design and improved fuel economy, and these advantages result from the replacement of conventional complicated mechanical systems by lighter electric and electronic systems with in-vehicle networks. A brake-by-wire (BBW) system offers the same advantages because it replaces traditional components such as pumps, hoses, fluids, vacuum servos, and master cylinders with electronic sensors and actuators. A BBW system also uses a wiring harness instead of a conventional hydraulic and mechanical link, as well as uses electro-mechanical brakes (EMBs) or electric wedge brakes (EWBs) as brake actuators. EMBs or EWBs receive braking command signals from the actuator ECU and generate braking force using electric motors with a gear, screw, or wedge assembly [1-2].

A BBW system, by nature, is a safety-critical system, and, therefore, fault tolerance is extremely important for this system. A conventional brake system can generate braking torque with degraded performance during a failure; however, an EMB system cannot generate any braking torque when faults exist in the electrical parts. Consequently, vehicles with EMB systems cannot control braking torque, which can cause

extremely dangerous accidents. Therefore, research on fault-tolerant control of EMBs is necessary.

The process architecture of fault-tolerant control has two steps, namely, diagnosis and controller re-design. The diagnosis step uses the measured inputs and outputs to test their consistency with the plant model. The result is a characterization of the fault with sufficient accuracy for the controller re-design and the re-design step uses the fault information to adjust the controller to the faulty situation [3].

The core of this scheme involves the reconstruction of the process components using the identical redundant hardware components. A fault in the process component can be detected if the output of the process component is different from the output of an identical redundant component. The main advantage of this scheme is its high reliability and direct fault isolation. However, the use of redundant hardware results in high cost, and thus, the application of this scheme is restricted only to a number of key components. The intuitive concept of the model-based fault diagnosis technique is to replace the hardware redundancy by a process model that is implemented in the software on a computer. A process model is a quantitative or qualitative description of the process dynamic, and steady behavior can be obtained using a well-established process modeling technique. In this way, we are

able to reconstruct the process behavior on-line, which, associated with the concept of hardware redundancy, is called software redundancy. Software redundancies are also called analytical redundancies [4]. Faults are often classified as plant faults, sensor faults, and actuator faults. On the controller side, a sensor fault is one of the most common problems. This type of a by-wire system is designed in such a way that much of its essential information is derived from a variety of sensors, and thus, several types of redundancy usually exist in safety-critical components. For the feedback control clamping force in an EMB, a type of a force sensor is equipped, and the field orientation control (FOC) of the permanent magnet synchronous motor (PMSM), which is used for drive efficiency enhancement, requires information on the three-phase currents and the motor position. We assume that faults may occur in a clamping force sensor, a motor position sensor, or phase current sensors in an EMB set.

Previous studies on sensor fault detection and isolation (FDI) or fault-tolerant control (FTC) can be found in the literature on PMSM drives. For fault-tolerant control of PMSM current sensors, the most common approach in the detection of a current sensor fault is based on Kirchhoff's current law. If the sum of three measured phase currents is a nonzero value, a current sensor fault is detected [5]. In [6], the authors considered small magnitude faults and showed that they cause torque ripples at the electrical frequency and/or twice the electrical frequency. Modifying the q-axis current reference is proposed as a way to cancel the fault effects. This requires knowledge of the system's mechanical and electrical parameters. Moreover, some "normal" asymmetries such as eccentricity or slight unbalance can affect the proposed method of compensation. In [7], faults are detected when the machine is not running, while a closed-loop or open-loop observer compensates for a sensor outage of one or two sensors (out of two), respectively. The problem of parameter uncertainties or variations is mentioned and can cause an estimation error. To overcome parameter variation issues, the authors of [8] proposed a signal-based approach with three current sensors and a multi-observer approach based on a generalized observer scheme. The isolation of a small magnitude fault is handled well with an open-loop controller, however, when a closed-loop controller is used, the fault is propagated on all the phases, making this method no longer effective.

Motor position estimation is required for position sensor fault-tolerant control. Regarding the motor position estimation method for a PMSM, the literature is concentrated in two main areas. The first main area includes methods of using a motor model and includes three different methods. The first set of methods use estimation based on the back electromotive force (BEMF) voltage. In voltage model methods, the measured voltage and currents are used to estimate the position of the rotor flux linkage on the basis of the voltage equations of the PM motor. However, the problem with using the BEMF technique to estimate position

is that at zero speed, the BEMF approaches zero [9, 10]. The second set of methods uses adaptive sliding mode control techniques. The sliding mode controller for improving the robustness of the controllers has been proposed for some time. These controllers are insensitive to parameter variations and disturbances. Therefore, sliding mode control has been presented as a robust estimation method. A negative aspect of the sliding mode control technique is the discontinuous nature of its control action [11, 12]. The third set of methods consists of techniques based on Kalman filter observers. These techniques are ideally suited to estimate motor speed and position to reject measurement noise. However, the tuning of the matrices of the model and the measurement errors is rough and requires highly skilled operators. Moreover, the Kalman-filter-based algorithms are computationally intensive and time consuming [13, 14]. The second main area includes sensorless techniques using the non-ideal characteristics of the motor. In low-speed regions, where the magnitude of the BEMF voltage is very small, the performance is significantly degraded. A fluctuating high-frequency current signal injection is used to solve this problem. The basic concept of this method is to detect small fluctuations of the back-EMF voltage by injecting a high-frequency test current to the machine at standstill. Using this method, the maximum torque-starting capability can be obtained in the sensorless drive of the PM motor. Therefore, the fluctuating high-frequency voltage signal injection method shows good performance in the low-speed region, including zero speed [15, 16].

For force sensor fault-tolerant control, a force estimation method is also required. There has been some research on the estimation methodologies of clamping forces in EMBs, however, some intrinsic characteristics of the brake units have not been fully studied. Schwarz et al. proposed a clamping force estimation method using the relationship between the angular displacement of the motor and the clamping force. Moreover, a compensation method was considered to counteract changes in pad thickness due to abrasion. This method has an advantage in that it does not need to consider friction because of its use of the average torque during clamping and releasing, however, the method can experience errors because the backlash of the gears is not considered [17]. Hoseinnezhad et al. proposed another method using the relationship between the angular displacement of the motor and the clamping force in the frequency domain. This method can be adopted by a system that is required to have fast response characteristics, such as anti-lock brake system (ABS), however, this method also did not consider the backlash of the gears [18].

In this paper, a fault-tolerant control method is considered for EMB systems that use a PMSM as the actuator, and the control performance in a fault condition is shown by using computer simulations as well as EMB HILS. To ensure the fault tolerance of an EMB, we continuously estimate several system variables that are used in a feedback control algorithm. The clamping force is estimated by using the

motor position and hysteresis phenomenon during clamping and releasing. Current sensor faults can be easily derived from the characteristics of a three-phase balanced circuit. The motor position is estimated by applying different methods in low-speed and high-speed regions where a model-based approach is adopted. Using the proposed fault-tolerant logic, we can detect which sensor has a fault during driving or braking and then use a bumpless transfer technique so that the control performance does not deteriorate when the estimated values are substituted for the measured values. The validity and the effectiveness of the proposed fault-tolerant control method for an EMB are shown by using an EMB HILS, so that fault tolerance is guaranteed for a scenario of sensor failures.

EMB MODELING AND CONTROL SYSTEM DESIGN

The electric motor applied to an EMB system is a PMSM. In the dr - qr axis that rotates in phase with the motor position, the voltage equations, flux linkage, and electromagnetic torque T_m of a PMSM are obtained as shown in equations (1), (2), (3):

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R + \frac{d}{dt} \lambda_{dr} & -\omega_m \lambda_{qr} \\ \omega_m \lambda_{dr} & R + \frac{d}{dt} \lambda_{qr} \end{bmatrix} \cdot \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_m K_e \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \cdot \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} K_e \\ 0 \end{bmatrix} \quad (2)$$

$$T_m = \frac{3}{2} \frac{P}{2} \{ (L_d - L_q) i_{dr} i_{qr} + K_e i_{qr} \} \quad (3)$$

where v and i represent the voltages and currents, respectively; λ is the flux linkage; P is the number of poles; ω_m is the motor angular velocity; R and L represent the armature resistance and self-inductance, respectively; and K_e is the back EMF constant. All quantities with three phases are transformed to quantities on the dr - qr axis [19].

The direct torque of a motor used in an EMB system is not enough to generate the required braking torque because of limitations such as the installation space and the 12 V DC system. Thus, planetary reduction gear was usually used to obtain a larger torque. The ring gear is fixed, and the motor and torque are transmitted through the sun gear to the carrier [20]. The speed and torque ratio of the planetary reduction gear are represented in equations (4) and (5) as follows:

$$\frac{N_s}{N_s + N_r} \omega_{sun} = \omega_{carrier} \quad (4)$$

$$\frac{N_s + N_r}{N_s} T_{sun} = T_{carrier} \quad (5)$$

where N_s is the sun gear teeth number, N_r is the ring gear teeth number, ω_{sun} is the sun gear speed, T_{sun} is the sun gear torque, and $T_{carrier}$ is the carrier torque.

The screw gear transforms the rotational motion of the motor into the linear motion of the screw, which is called the head, thus pressing the pad into the disc. The rotational speed of the screw is calculated with equation (6) as follows:

$$\dot{\theta}_{screw} = \frac{1}{N} \omega_m - \frac{\cos \alpha}{r_{screw}} \dot{x}_{head} \quad (6)$$

where θ_{screw} is the rotational displacement of the screw, r_{screw} is the radius of the screw, N is the gear ratio, α is the angle of inclination, and x_{head} is the linear displacement of the head.

F_{head} , the force that acts on the head, is calculated from the rotational displacement of the screw, θ_{screw} , as shown in equation (7) as follows:

$$F_{head} = \frac{k_{screw} \theta_{screw} + b_{screw} \dot{\theta}_{screw}}{r_{screw}} \quad (7)$$

where k_{screw} is the stiffness of the screw, and b_{screw} is the damping coefficient of the screw.

The pads are positioned on both sides of the disc. During the braking operation, the inner pad is shifted by the head of the screw in the axial direction of the disc. Pressing the inner and outer pads of the caliper on the disc generates a clamping force. The force applied to both pads, F_{pad} , which is equal to the clamping force, F_{cl} , is calculated using equation (8) as follows:

$$F_{pad} = 2(k_{pad} x_{pad} + b_{pad} \dot{x}_{pad}) = F_{cl} \quad (8)$$

where F_{pad} is the force of both pads, k_{pad} is the stiffness of the pad, x_{pad} is the displacement of the pad, b_{pad} is the damping coefficient of the pad, and F_{cl} is the clamping force, which is equal to F_{pad} . The configuration of EMB assembly is as shown in Figure 1.

The overall control system has a cascaded architecture, as shown in Figure 2. Proportional-integral (PI) feedback control is applied in the current and speed controllers. The force and position controllers use a proportional-integral-derivative (PID) controller that determines the motor velocity command. The current, speed, and force controllers are designed to satisfy the required time domain specifications for the response performance.

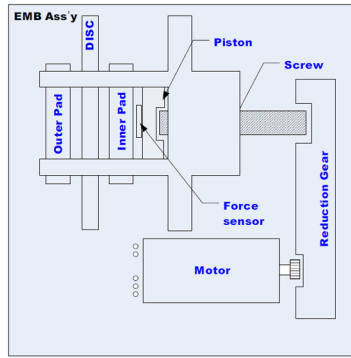


Figure 1. Configuration of EMB assembly.

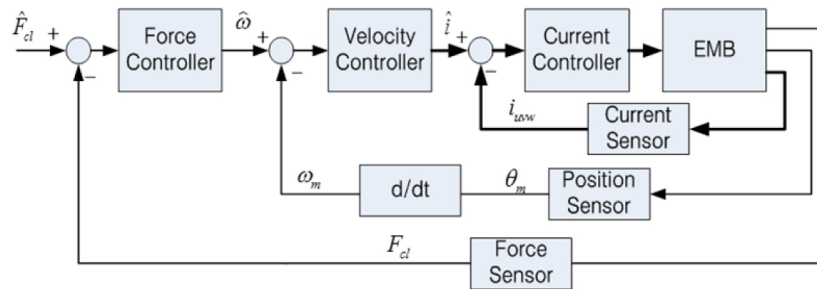


Figure 2. Block diagram of EMB control system.

FAULT-TOLERANT CONTROL METHOD

Motor Position Sensor

The estimation method for motor position using back EMF is adopted for fault-tolerant control of the position sensor, and the voltage/frequency (V/F) control method is adopted in the zero-speed and low-speed range in this study. A position estimation method using back EMF estimates the flux from the current and voltage in the α - β axis while the motor is stationary and is able to obtain the motor position from the flux linkages as shown in [equation \(11\)](#) [21, 22]:

$$\phi_{\alpha} = \int (V_{\alpha} - Ri_{\alpha})dt - L_s i_{\alpha} \quad (9)$$

$$\phi_{\beta} = \int (V_{\beta} - Ri_{\beta})dt - L_s i_{\beta} \quad (10)$$

$$\theta_m^* = \tan^{-1} \left(\frac{\phi_{\beta}}{\phi_{\alpha}} \right) \quad (11)$$

where Φ_{α} and Φ_{β} are the rotor fluxes in the α - β axis under stationary conditions, and θ_m^* is the estimated motor position.

The V/F control method, which applies a rotational magnetic field, is adopted to solve the problem in which the

flux linkage cannot be estimated in the zero-speed and low-speed range. A mode transfer technique is applied in the dead zone between the V/F control method and the position estimation method, as shown in [Figure 3](#). The values of ω_{TO1} and ω_{TO2} were experimentally determined to be 100 [rps] and 300 [rps], respectively. [Figure 4](#) shows a block diagram of the position estimation and fault detection systems for the position sensor [23].

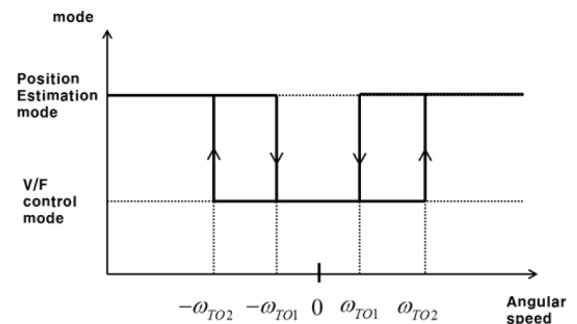


Figure 3. Position senseless operation mode by motor angular speed.