Fault Injection Test for Inverter Based on Electronic-Motor Emulator

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Abstract. With rapid development of electric vehicles, there are more and more electronic devices in one vehicle. Meanwhile, with the trend of increasing technological complexity, software content, there are increasing risks from systematic failures and random hardware failures. The e-motor Drive System (e-motor and MCU), as the core powertrain system of the EV/HEVs, are safety related electronic control units (ECU) due to the severity of the accidents/incidents. Accordingly, the ISO 26262 standard has provided suggestions for the functional safety design and testing of automotive electronic devices. Therefore, the functional safety of MCU needs to be confirmed, tested and evaluated. The hardware-in-the-loop (HIL) system based on power level is an efficient and safe testing system. The objectives of this paper are to introduce fault injection test for MCU based on e-motor emulator at power level.

Introduction

In recent years, many innovations and developments in automotive industry originated from electrical and/or electronic (E/E) systems. With the trend of increasing technological complexity, software content and mechatronic implementation, there are increasing risks from systematic failures and random hardware failures. Safety is one of the key issues of future automobile development. ISO 26262 includes guidance to avoid these risks by providing appropriate requirements and processes[1].

Permanent magnet synchronous motor (PMSM) is widely used in pure electric, plug-in hybrid and other new energy vehicles due to its high economy and high power density. The inverter for e-motor, also known as the Motor Controller Unit (MCU), usually uses a voltage source inverter oriented to the magnetic field control to control the PMSM. The fault handling capability and response time are important indicators for evaluating the functional safety mechanism of the MCU[2].

According to the ISO26262 standard, the fault injection technique is a very useful verification method of testing and verification for safety-related systems. Especially, MCU is qualified for ASIL-C or ASIL-D compliance from various suppliers.

The primary purpose of MCU functional safety design is to ensure the safety of drivers, which will not be threatened by systematic failures and random hardware failures, especially in extreme driving conditions (such as high-speed driving in snow, climbing, etc). How to ensure that under extreme driving conditions, in case of emergencies, the vehicle can still smoothly enter a reliable vehicle power strategy to protect human safety is a matter to be considered in MCU fault response mechanism. The basic and important function of MCU is to control the torque output of e-motor.

Introduction of EME

Fault injection test for MCU generally refers to the fault simulation of the motor and the sensors. Considering that the three-phase short/open circuit, temperature, stall, demagnetization, sensor and mechanical fault tests, etc., which are difficult or dangerous to test by real e-motor and dyno, this paper uses an e-motor emulator (EME) to perform fault injection test. Fig 1 is the overview of the e-motor emulator.
The EME is a ‘virtual dyno’ designed by SET Power System GmbH, which is one of the subsidiaries of the AVL List GmbH. It can emulate e-motors to test drive inverters on power level without the need for mechanical setups. This power-hardware-in-the-loop (PHIL) can provide numerous advantages compared to other inverter test methods[3-5]:

1) No real e-motor and dyno required (e-motor is a software model, no dyno control influences)
2) Full four quadrant power test runs in a lab environment
3) Fault stimulation allows complex test scenarios
4) Protection for the inverter under test via active phase current limitation
5) Realistic test of all inverter controls (current, torque, speed) without mechanical setup
6) No mechanical hazards, mechanical limitations or wearing out
7) Extreme dynamical torque/speed scenarios can be tested with real life scenarios

Through EME, we can carry out the testing work of MCU efficiently and safely, which can simulate the motor and battery system in the vehicle. The EME consists of the e-motor simulator, battery simulator, inverter table, power supply, water cooling system and host computer. MCU is placed in the inverter table, U,V,W three-phase are connected with the motor simulation cabinet. E-motor temperature sensor wires and rotary signal wires are connected with the motor simulation cabinet. DC bus is connected with the battery simulator.

By importing the linear or non-linear parameters of the motor into the host computer, the real e-motor behavior can be simulated, and the e-motor parameters can be downloaded and tested. Fig 2. is a schematic diagram of the e-motor emulator.
The EME can realize load test at power level. The current test range can reach 600 Arms, the power can reach 250 kW, and the switching frequency can reach 800kHz, which can meet test needs for sic inverter.

![EME Type Diagram]

Figure 3. Magnetoelectric model of motor.

The acceptable motor parameters of the motor simulator include linear parameters, look-up table parameters, ANSYS simulation results parameters, etc. It has the functions of electromagnetic model and thermal model calculation. Fig 3. shows the magnetoelectric model of the motor.

**Basic Fault Injection Test Type**

As the e-motor is a high inductive load, it cannot be directly open circuited to bring the vehicle drive torque to a controllable value. So in case of fault scenario, the MCU will switch to safe states, such as ASC and freewheeling. The test items that can be implemented for MCU are shown in Table 1.

| Fault injection test type                                      |
|---------------------------------------------------------------|
| Resolver-error stimulation(noise and EMC peaks)              |
| AC excitation signal (max.7Vrms/10kHz) disconnection          |
| Cosine signal disconnection                                   |
| Sinusoidal signal disconnection                                |
| Adjust excitation and sine phase                               |
| Adjusting the phase of excitation and cosine                  |
| Phase adjustment of sine and cosine                            |
| Rotation variable ratio                                        |
| Sinusoidal signal gain                                         |
| Cosine signal gain                                             |
| The rotation signal is short.                                  |
| Sinusoidal cosine signal noise injection                       |
| Injection of amplitude and frequency controlled electromagnetic pulse signals on sine / cosine signals |
| The connection between rotor sensor and shaft is broken.      |
| Rotor sensor loosening (simulated rotation on axis)           |
| Motor temperature sensor related fault: terminal temperature sensor (NTC/PT100/PT1000) |
| Signal breakage of motor temperature sensor                   |
| Short circuit of motor temperature sensor                     |
| Motor temperature value exceeding threshold abnormal |
|-----------------------------------------------------|
| Overtemperature of motor                            |
| Motor temperature sensor type matching abnormal     |
| Temperature step anomaly of motor                   |
| **Stator winding related faults**                   |
| Stator winding slowly increases                     |
| Winding inductance error                            |
| Short circuit between windings                      |
| U,V,W phase voltage signal detection line disconnection |
| U phase is short circuited with V (power level).     |
| V phase is short circuited with W (power level).     |
| W phase is short circuited with U (power level).     |
| U,V,W simultaneous short circuit (power level)       |
| U,V,W is short circuit (power level) for battery.    |
| U,V,W has negative short circuit (power level) for battery. |
| U,V,W shell short circuit (power level)              |
| Simulated phase beam aging                          |
| U,V,W external signal short circuit                  |
| **Rotor related faults (permanent magnet synchronous motor)** |
| Rotor flux linkage error is too large.               |
| Rotor degaussing                                    |
| The rotor inertia error is too large.                |
| Air gap anomaly: excessive error                     |
| Air gap abnormality: changes with rotor angle        |
| Bearing abnormal: friction increases                 |
| Bearing abnormal: friction varies with rotor angle.  |
| **Axis anomaly**                                    |
| Broken shaft (instantaneous loss of resistance moment) |
| Bearing blocking (DC test)                          |
| Abnormal load, brake exception                      |
| Wave torque injection                               |
| Torque transient anomaly                            |
| Rapid change in friction                            |
| Shaft is dragged for speeding.                       |
| **Controller failure mechanism**                    |
| Overvoltage/undervoltages fault                     |
| CAN bus disconnection fault                         |
| CAN bus short circuit (to ground /power supply/ short connection to each other) |
| CAN load rate fault injection                       |
| Failure response time                                |

### Integrated testing with dSPACE HIL

Aiming at the fault injection test of e-motor controller, this paper chooses a domestic permanent magnet motor inverter in China, focusing on MCU temperature protection, rotation fault injection and phase short circuit test.

1) Phase-to-phase short-circuit fault injection test:

When the motor operates at 3000rpm/120N.m, the action of U, V and W phase short-circuit is applied, the motor suddenly enters the active short-circuit protection state and sends out the shutdown
signal. Fig 4. shows the operation interface of high voltage switch matrix - power contactors use for ASC test.

Figure 4. High voltage switch matrix - power contactors.

2) Resolver fault injection test:
Analog sinusoidal output sinusoidal (SIN+) disconnection, i.e. the observation controller state response (IGBT shutdown behavior occurs in the corresponding time of failure) at the fault occurrence time in Fig 5.

3) Load transient fault injection test:
After the instantaneous change of the motor torque is relatively fast, the controller has an overcurrent fault and reports an error after operation. The test results are shown in Fig 6.

Figure 5. Waveform of fault response for rotary fault.

Figure 6. Load transient.
Conclusion

Based on EME, the power level hardware-in-the-loop simulation method is adopted, which can efficiently and safely test the fault injection of analog motors, sensors and machinery. It is very useful to carry out MCU's functional safety and fault diagnosis test. With the development and renewal of automotive e-motor functional safety, the trend of formulating new national standards in China related to electric drive control system has become increasingly urgent. Fault injection test for e-motor controller is an important part of functional safety system test. Therefore, the establishment of fault injection test capability and evaluation system of MCU will be of great significance to the development of domestic electric vehicles.

Reference

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