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Virtual Test Environment for Fail-safe Algorithm Development of a MCU Using a HIL Simulator

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Abstract

This paper presents a design procedure of the virtual test environment for fail-safe algorithm development of a motor control unit (MCU) in the electric or hybrid-electric vehicle, using a hardware-in-the-loop (HIL) simulator. Mathematical models of the vehicle, the battery, the permanent magnet synchronous motor (PMSM), and the inverter are developed based on the physical and engineering principles and programmed to be executed in real-time. The programmed models emulate the performance of each component and run in the HIL simulator. The signal interface between the HIL simulator and a MCU is also developed by designing appropriate wire harness and signal matching. Fault diagnosis of a MCU is conducted to show the feasibility of the virtual test environment. Several different failure modes of the MCU are implemented and tested by the HIL simulator to show the possibility of fault detection and fault diagnosis algorithms of the MCU in real-time.

Keywords: ″HILS(Hardware-In-the-Loop Simulation)", "MCU(Motor Control Unit)", "RCP(Rapid Control Prototyping)", "PMSM(Permanent Magnet Synchronous Motor", "Failure Mode", "Fault Diagnosis"

1 Introduction

Fail safety including fault detection, diagnosis and management has been applied to various vehicle control systems. In the complex electric drive system in the electric or hybrid-electric vehicle, abnormal status, which can cause malfunction and critical failure and should be considered at first stage of development, are diverse and irregular, and so difficult to predict.. Therefore, the study of fail-safety technology is required prior to beginning any development process.

In many cases, failure mode test of a motor control unit (MCU) is not easy to conduct in a laboratory environment. In general, there are simple forms of failure mode in a MCU such as wire short or open as well as complex forms like abnormal signals of the current sensor or angular position sensor. Tests of complex forms are especially difficult in the laboratory since they are time-consuming, expensive, and limited numbers of test samples. Therefore, we have to consider an alternative method using a hardware-in-the loop (HIL) simulator.

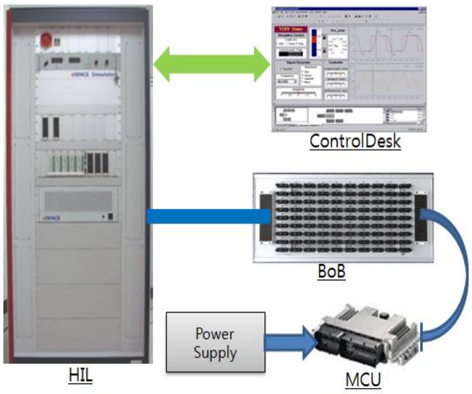

Figure1: HIL Simulation wiring and monitoring tool

The conditions and environment for the failure mode test can be emulated by fault insertion of a HIL simulator which ideally suited to make high performance for electric drive system test. The real time simulation is operated with dynamic model in the HIL simulator.

A simple mechanism of wiring and monitoring tool of the HIL simulator is given in Fig 1. There are models and I/O blocks in HIL simulator. The HIL simulator supplies many types of signals such as the position sensor output and run/command signals, which measure the PWM duty ratio and frequency of MCU output signals to operate electric drive model. The MCU is connected to the HIL simulator with BOB and other connectors. A graphical user interface (GUI) monitoring tool is used to draw graphs and to modify parameters.

A rapid control prototyping type equipment is used as the MCU in this test to mitigate the hardware limitation and to increase flexibility on the algorithms and parameters.

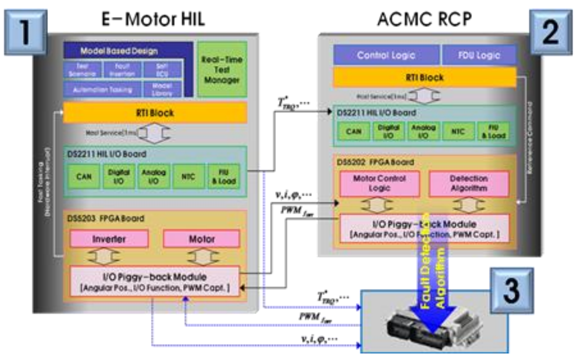

Figure2: HIL and RCP operating block diagram

The block diagram in Figure 2 shows the relationship between E-Motor HIL and ACMC RCP. Based on the HIL simulator and the RCP hardware, we can build virtual development environment to test MCU performance in the normal and failure modes.

This paper presents a design procedure of the virtual test environment for fail-safe algorithm development of a MCU in the electric or hybrid-electric vehicle, using a HIL simulator. Mathematical models of the vehicle, the battery, the permanent magnet synchronous motor (PMSM), and the inverter are developed based on the physical and engineering principles and programmed to be executed in real-time. The programmed models emulate the performance of each component and run in the HIL simulator. The signal interface between the HIL simulator and a MCU is also developed by designing appropriate wire harness and signal matching. Fault diagnosis of a MCU is conducted to show the feasibility of the virtual test environment. Several different failure modes of the MCU are implemented and tested by the HIL simulator to show the possibility of fault detection and fault diagnosis algorithms of the MCU in real-time.

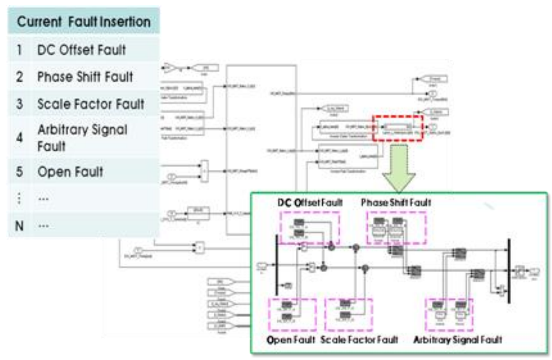

Figure3: Modelling for current fault insertion

2 PMSM Modelling

The instantaneous torque value is calculated for precision control and position control every sampling time. Acceleration rate, rpm and position of motor are decided by the instantaneous torque. It is influenced by current and magnetic flux interlinkage, and then the vector control logic is applied for instantaneous torque control. Vector control is a method to control a PMSM, where field-oriented theory is used to control space vectors of magnetic flux, current, and voltage. It is possible to set up the coordinate system to decompose the vectors into a magnetic field-generating part and a torque-generating part. The structure of the motor controller is then almost the same as for a separately-excited DC motor, which simplifies the control of a PMSM. PMSM Control Structure

2.1 PMSM Control Structure

Electric drive system with PMSM is composed of control part for RPM, motor current and transformation part for phase transformation. In control part, the command value is calculated by difference between Ref. RPM and simulated RPM value.

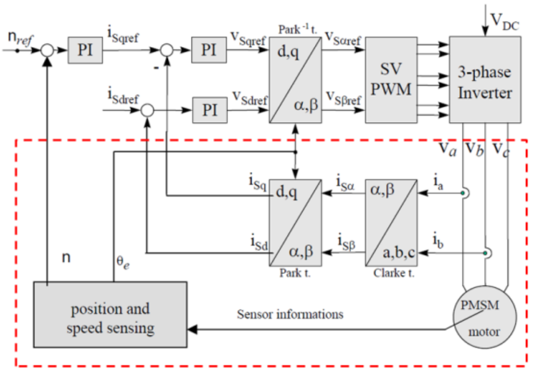

Figure4: PMSM Control Structure

In the case of the current control unit, the command value means 'q' axis current value or magnitude. 3-phase current is converted to 2-phase by Clarke-Park transformation. 2-phase current, 'q' and 'd' axis, is controlled by PI controller, respectively.
Inverter model receives PWM signal from MCU, and then put out 3-phase voltage to a motor.

PMSM modelling position is indexed in " ⬚ ". PMSM model is composed with some working groups. 3-phase voltage of inverter model is converted by Clarke Transformation and Park Transformation to 2-phase type. It figure out 2-phase current value from voltage and convert to 3-phase current applying Inverter Transformation.

2.2 PMSM Model

Clarke Transformation makes a 3-phase system be transformed into a 2-phase system. The space vector can be transformed in another reference frame with only two orthogonal axis called (α, β).

Assuming that the axis a and the axis α are in the same direction, and then the projection that modifies the three phase system into the (α, β) two dimension orthogonal system is presented below.

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (1)$$

Park Transformation is the most import in the FOC. This transformation method modifies a 2-phase orthogonal system (α, β) in the (d, q) rotating reference frame. The transformation can be expressed as below.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \qquad (2)$$

If we consider the d axis aligned with the rotor flux, the next diagram shows, for the vector, the relationship from the two reference frame.

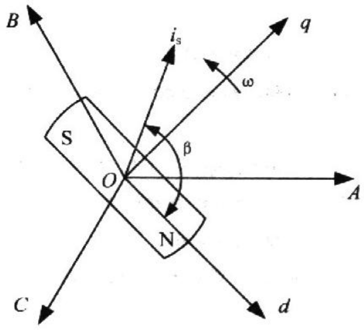

Figure5: d-q Transformation

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + \frac{d}{dt}L_d & -\omega L_q \\ -\omega L_d & R_a + \frac{d}{dt}L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \Psi_a \end{bmatrix} \qquad (3)$$

where Ψ_a : Flux induced by the magnet
L_d : Direct axis inductance
L_q : Quadrature axis inductance
ω : Mechanical angular velocity
R_a : Stator winding resistance

2.3 Numeric Solver

PMSM model consists of differential equations are applied to real-time simulation using Simulink. In order to obtain a discrete solution of the equations the numeric solver is required, and we apply Tustin method in this paper.
Assume state space equation of PMSM model is expressed as below.

$$\dot{x}(k) = A(k)x(k) + B(k)u(k) + C(k) \qquad (4)$$

It is then possible to define the PMSM voltage equation as follows:

$$x(k+1) = \left(E - \frac{T}{2}A(k+1)\right)^{-1} \left\{\left(E + \frac{T}{2}A(k)\right)x(k) + \frac{T}{2}B(u(k+1)+u(k)) + \frac{T}{2}(C(k+1)+C(k))\right\} \quad (5)$$

where $A = \begin{bmatrix} -\frac{R_a}{L_d} & p\omega\frac{L_q}{L_d} \\ -p\omega\frac{L_q}{L_d} & -\frac{R_a}{L_q} \end{bmatrix}$,

$B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}$, $C = \begin{bmatrix} 0 \\ -\frac{p\omega\Psi_a}{L_q} \end{bmatrix}$

3 HIL Simulator

The HIL device provides real-time interface that can simulate the signal level of real hardware in the MCU development process. We can make the various test scenarios for MCU evaluation and simulate failure mode by establishing the HILS development environment.

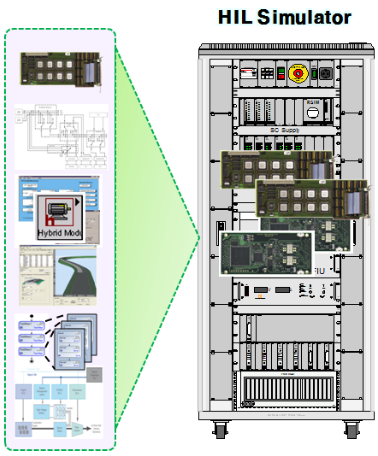

Figure6: HIL Simulator Structure

The HIL simulator for performance measurements and failure mode test of PMSM includes the component model, vehicle load model and interface block for interfacing between MCU(real hardware) and model in HIL simulator. Simulation model works in real-time.
HIL simulator for MCU evaluation is consisted as below.

① Processor board for implementation green car vehicle model

② FPGA board for real-time simulation of a inverter and PMSM

③ HIL I/O board for supplying various information to MCU

④ MCU or RCP device

⑤ Monitoring PC for controlling and monitoring the HIL simulator

3.1 Failure Mode

HIL simulator is available fault insertion test with a diversity of conditions and environments of electric driving system. Failure mode can be implemented as an operation of real-time simulator. We can make a test scenario for not only simple mode like wiring open/short, but also complex form like offset value and scaling.
There is some failure mode simulated as below.

① Current sensor signal(This failure breaks out at the current sensor between a inverter and a motor.)

- Short to GND
- Short to VCC
- Fixed output

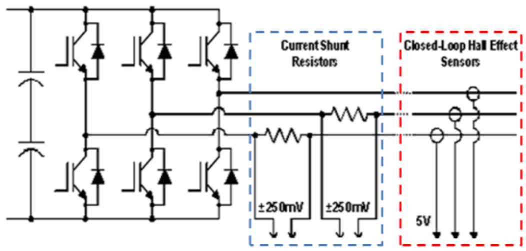

Figure7: Current Sensor Circuit

② Position sensor

- Angle offset: offset between real motor position and position sensor output
- Encoder index signal error
- Deviation of resolver signal: Amplitude and Angle deviation

4 MCU (Motor Control Unit)

Motor Control Solution provides the possibility to perform rapid control prototyping (RCP) for PMSM MCU using a model-based design and the I/O blocksets. In this paper, the RCP device substitutes MCU hardware to conduct the motor control and failsafe algorithms.

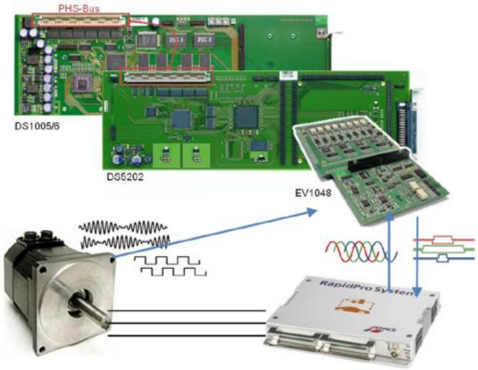

Figure8: Motor Control Solution

4.1 MCU Structure

The RCP system used as the MCU consists of processor board, FPGA-base board and piggy-back. Signal conditioning hardware is used as interface to 3 phase inverter and sensors. Sensor inputs are converted into velocity and rotor position for hall sensors, incremental encoders, resolvers. 8 analog inputs are used as current signal, AD channels, and battery voltage with integrated signal processing such as filtering. For generation of PWM, there are 6 digital outputs.

The controller model is executed on the processor board. The RTI (real-time-interface) blockset functions as an interface between the processor board and the FPGA board. Low-level signal processing is performed on the FPGA board. This contains the processing of velocity and rotor position from several types of position sensors, processing of data from analog-digital-converters on the piggy back module and the generation of PWM-signals for 3-phase-motor control.

4.2 Simulation Model

The RCP simulink model is consisted input block, includes current sensor input and position sensor, MCU system and PWM output block. Signal processing like as position sensor signal and ADC expect CAN protocol is available in the RTI block supplied by FPGA solution.

Transformation blocks are included for vector control of PMSM. 3-phase input current value is converted 'dq' axis by Park-Clarde Transformation and then passed the PI controller for each current control.

The output of current controller block is 2-phase voltage calculated by 2-phase current, rotor speed and position. Voltage is converted to 3-phase by inverse transformation, and then 3 PWM duty ratios are generated by comparing to battery voltage.

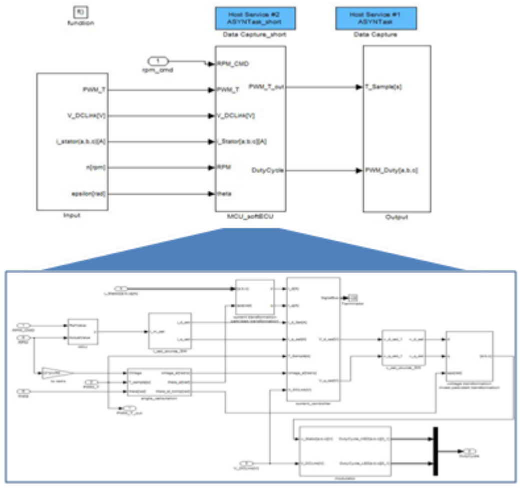

Figure9: RCP Simulation Model

5 Simulation

For the MCU test using HIL simulator, the wiring between HIL simulator and MCU (or RCP) is needed. System and component models can be operated in the HIL simulator by RTI blockset. Internal signals are controlled and monitored by monitoring tool (ControlDesk) and interface I/O is monitored by scope.

There are state setting panel for operating simulation and graph setting panel in the HIL monitor. Cycle time is set to 1,000s for checking a running pattern of a vehicle. They are observed in 3 graphs that are vehicle speed, SOC and motor torque. The vehicle speed is evaluated by comparing speed command and simulated speed. SOC means state of charge for battery.

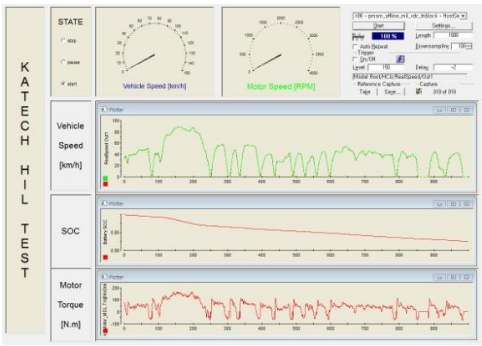

Figure10: Normal mode simulation result

RCP performance graphs include current signal, PWM duty ratio and motor angle. 0.1s cycle time is selected for RCP monitoring, because instantaneous signals need very short time interval to check the wave form. Current signal is output of current sensor and it is consisted of 3-phase U/V/W with 120 degree phase difference.

Figure11 shows the MCU performance graphs of RCP monitoring tool and it's the current sensor fault test. As we mentioned at 'Failure Mode', the current signal faults of one- phase output are simulated.

① Short to GND

- The loss of control function of MCU results in abnormal PWM duty ration output. The motor angle output remains steady until 0.08s, but it turns very fluctuating after 0.08s. Current value of U-phase is go to Min. value and others are very unstable after 0.003s.

② Short to VCC

- It shows similar pattern to GND fault.

③ Fixed output

- U-phase current is fixed after fault insertion, and others have broad amplitude. The motor speed is not significantly changed.

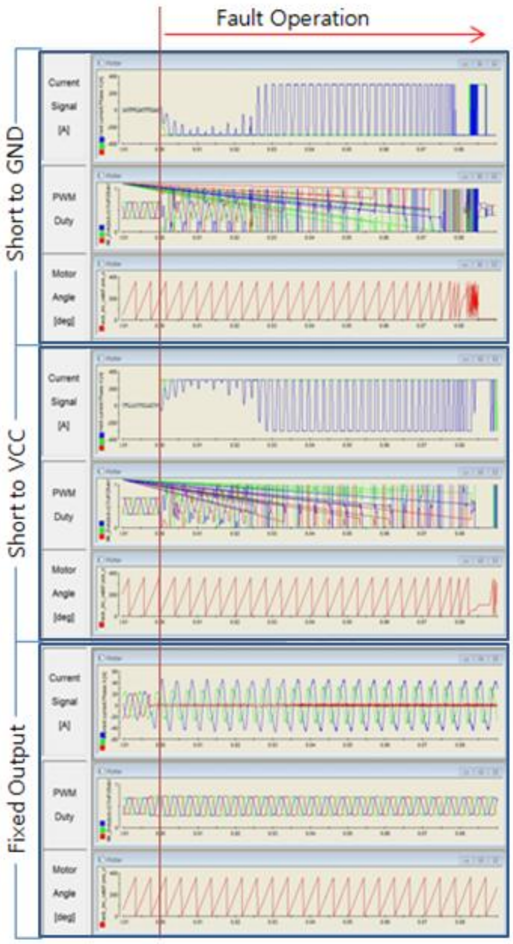

Figure11: Fault Insertion Test (RCP Monitoring)

Fault diagnosis is simulated with RCP and HIL simulator by applying that sum of 3-phase current is zero. We define the threshold value of current signal to '0.5 ~ 4.5V' and the other range is read as a fault signal. And considering the phase angle is 120 deg, a fault mode is added in case of going out of bounds.

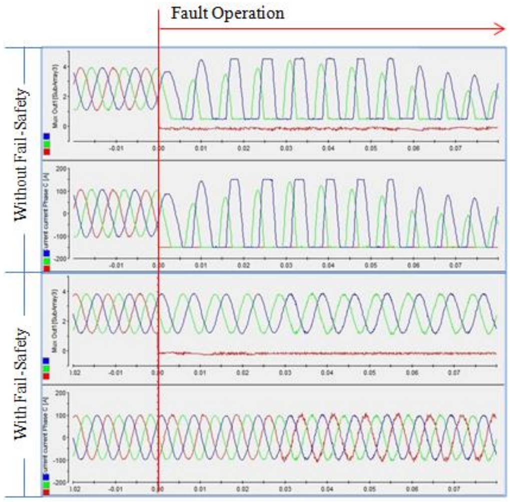

Figure12: Fail-Safety Test (Current Signal Monitoring)

Graphs (Figure12) present current sensor output signal (ADC, 0~5V) and calculated current value (-150~150A) at with/without fail-safety. In the with fail-safety mode, the simple logic for detecting and overcoming fault insertion is applied. Each failure output signal of current sensor shows similar pattern that is fixed value after fault operation at the ADC graphs. But it can be checked the difference between with and without fail-safety logic at the calculated current value during fault operation. The last graph maintains steady state, in spite of the fault insertion.

6 Conclusion

In this paper, a method for the simulation and diagnosis of faults in PMSM was proposed. Using HIL simulator and RCP, the algorithm for fault diagnosis of failure mode is simulated. The failure signal to the MCU I/O interface is made by HIL simulator and evaluated the performance of MCU. It can be preceded the fault detection and fault diagnosis of real hardware, for saving cost and development time. Further research will concern the applications of various fault insertion test for verifying MCU fail-safety logics.

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