Failure Safety Method According to Battery's State-of Charge Condition in Electric Motorcycle

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Abstract

The present study proposes a failure safety method for an electric motorcycle according to the battery's state-of-charge (SOC) condition. We have reliably modeled an electric motorcycle by Model Based Design (MBD) using the Automotive Simulation Models (ASM) program. The Li-ion battery used in this model could have a serious problem if it discharges to 10% of the SOC. Therefore, the power supply should be limited before the SOC reaches the minimum level. At this time, the logic used to control the power of the electric motorcycle affects the driving distance and time. Various types of control logic are simulated to determine the optimum control logic. Accordingly, we propose a suitable failure safety logic that achieves good driving distance and time as well as better dynamic characteristics

Keywords: *Automotive Simulation Models (ASM)**, Simulink**, Electric motorcycle, In-wheel motor, Control logic, Battery Management System (BMS), Model Based Design (MBD), State-of-Charge (SOC), Failure safety*

1. Introduction

In recent years, environmental and energy problems have emerged as important global issues. Among attempts to mitigate these problems, many studies worldwide have focused on electrically powered vehicles in the automobile industry. Some studies have focused on small electric cars for driving around in a city [1]. Unlike electric cars, electric motorcycles have not attracted much attention because of economic issues and a lack of relevant laws [2]. No studies have addressed the failure safety of motorcycles according to the battery's state-of-charge (SOC) condition; studies have only focused on electric cars. Furthermore, studies have generally analyzed individual components in electrically powered vehicles, and not complete systems [3].

Unlike conventional vehicles with an internal combustion engine, electric vehicles are greatly affected by the characteristics of electric and electronic equipment such as the motor, battery, and inverter. In addition, with the increasing control requirements for electric and electronic components, it has become necessary to develop control methods to ensure the lifespan and safety of each component. Furthermore, it is necessary to analyze the vehicle behavior in terms of the vehicle system [3]. In particular, Li-ion batteries, which are the most widely used energy source in electric vehicles, are affected more significantly by charge/discharge characteristics than other batteries. When a Li-ion battery discharges to

below the 2.7-V minimum discharge voltage, its internal structure is destroyed, and this strongly affects its lifespan and safety [4]. Therefore, when the battery voltage drops below a designated value, the power drawn from it should be restricted to prevent damage to the battery while still being enough to move the vehicle to a safe area.

Accordingly, the present study develops a method for optimal failure safety logic in the designated SOC range (10–20%) to protect the battery of an electric motorcycle; this method is based on an electric motorcycle model whose reliability has been verified in previous studies.

2. System Design

2.1. Electric motorcycle model

The electric motorcycle model was developed based on the specifications of a motorcycle with a 110-cc internal combustion engine, as listed in Table 1. To match the performance of a motorcycle with an internal combustion engine, a highly efficient Li-ion battery pack was installed along with a high-efficiency long-life battery management system to control it. In addition, to improve the durability and performance of the electric motorcycle, an in-wheel permanent magnet synchronous motor driving module with an embedded two-step transmission was used.

Table 1. Design specifications of electric motorcycle

Parameter	Value	Unit
Maximum rate speed	80	km/h
Cruising range (constant 50 km/h)	70	km
Capacity of battery pack	2	kWh
Maximum discharge rate	5	C
Power of motor	4.88	kW
Nominal voltage	73	V
Maximum weight	285	kg

Figure 1 shows the electric motorcycle model developed using the model-based design (MBD) technique. For modeling the electric power components, the Automotive Simulation Models (ASM, dSPACE GmbH, Germany) program was used, and a vehicle kinetic model was developed using BikeSim (Mechanical Simulation Corp., USA). ASM and BikeSim are Open Simulink models for real-time simulation, which are third-party programs based on MATLAB/Simulink. Therefore, they are reliable and compatible with other Simulink programs for real-time simulations such as the hardware-in-the-loop simulation [4]. Figure 2 shows the flow of each component of the electric motorcycle model. The reliability of the electric motorcycle model used in this study was verified through a comparison between the vehicle test results and the simulation results.
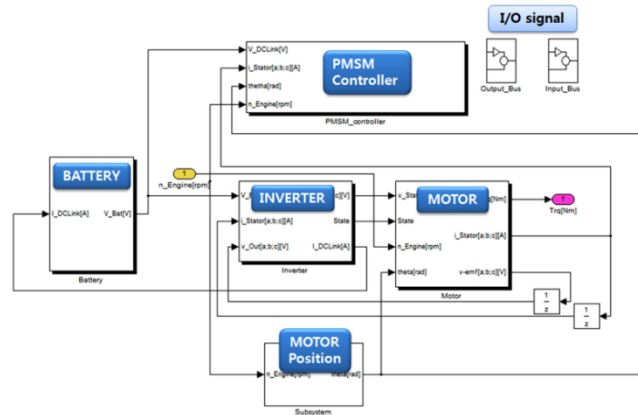
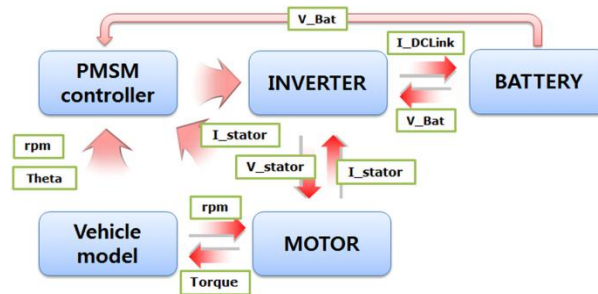**Figure 1. Component model of the electric motorcycle**

Figure 2. Control logic flowchart of the electric motorcycle

2.2. Failure safety system configuration

This chapter introduces the failure safety method according to the SOC of an electric motorcycle battery. As mentioned above, a Li-ion battery has higher efficiency than other batteries, but it is strongly affected by charge/discharge characteristics. Particularly, if it overdischarges to below the minimum discharge voltage (2.7 V), serious safety problems occur owing to the destruction of the internal structure of the battery. Therefore, for the electric motorcycle model used in this study, an integrated controller model was configured to protect the battery by restricting the power drawn from it. The integrated controller model was configured for step-by-step control using MATLAB's Simulink and Stateflow.

Figure 3 shows the discharge curve of the battery used in the electric motorcycle. A Li-ion battery has a different characteristic curve according to the discharge rate. As shown in Figure 3, the voltage of the high-efficiency discharge curve differs from the basic discharge curve by ΔV.[6] Because the maximum discharge rate of the battery used in the electric motorcycle was 5 C, the failure safety logic of the integrated controller was designed based on the discharge curve for a discharge rate of 5 C. When discharging at 5 C, the discharge voltage drops to 2.7 V when the SOC drops to 10%; therefore, restriction of the vehicle power begins when the SOC reaches 20% to secure sufficient time to warn the driver to move the vehicle to a safe place. In addition, when the SOC drops to 10%, the power is cut off entirely to protect the battery, making it impossible to drive the vehicle. Accordingly, every simulation was carried out in the 10–20% SOC range. To set the standard to restrict the power drawn from the battery, a simulation plan was made in the following order.

- Step 1: Define the most efficient range of speed.
- Step 2: Define the most efficient type of control logic.
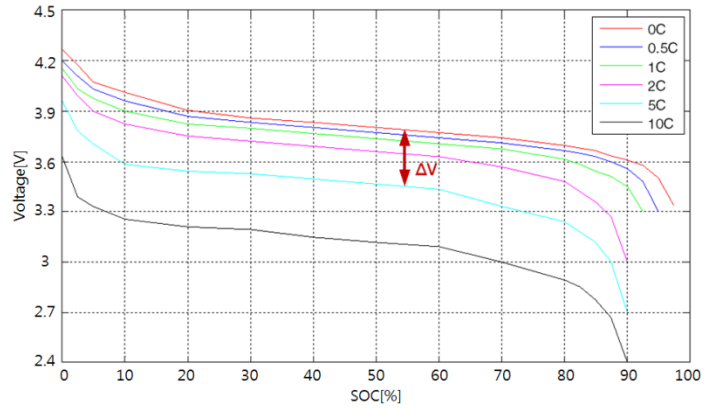- Step 3: Define the safest type of control logic.

Figure 3. Discharge curve of the battery

3. Simulation and Result

3.1. Real-time environment configuration

The ds1006 and ds1401 modules of dSPACE were used to simulate the electric motorcycle model and the integrated controller model, respectively, in the real-time environment. These two models could exchange input/output values using controller area network communication.

Figure 4 shows the panel of the graphical user interface environment that is used to send commands to the electric motorcycle model and the integrated controller model through ControlDesk and to record the resulting values from them. The electric motorcycle simulation was carried out through this interface.
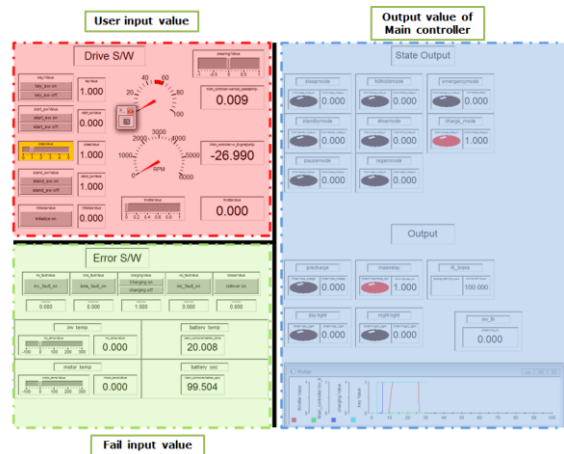

Figure 4. User interface of ControlDesk

3.2. Simulation and result

The road environment for the electric motorcycle simulation was modeled using BikeSim. The motorcycle was designed for riding around in a city; therefore, the simulation environment was made to comply with city road standards and Korean traffic laws [10]. The maximum speed of the electric motorcycle was set to 70 km/h, and accordingly, a road plane curve radius of 200 m designated for this speed was applied in the road environment. The electric motorcycle model was then ridden in a circular path with a radius of 200 m.

When the battery SOC was below 20%, the simulation reduced the speed to restrict the power consumption for an optimal drivable time and distance. For the simulation, the driving speed was set in the range of the minimum speed for stability (20 km/h) to the maximum speed of the motorcycle (70 km/h) in 10-km/h steps. Figure 5 shows the drivable time and distance at each test speed. As shown in Figure 5, the maximum difference in distance in response to the driving speed was 1000 m, and the maximum difference in time was 700 s. This result indicated that the most efficient speed range for drivable distance and time was 20–40 km/h. Therefore, when the battery SOC reached 20%, the speed was restricted to 20–40 km/h.
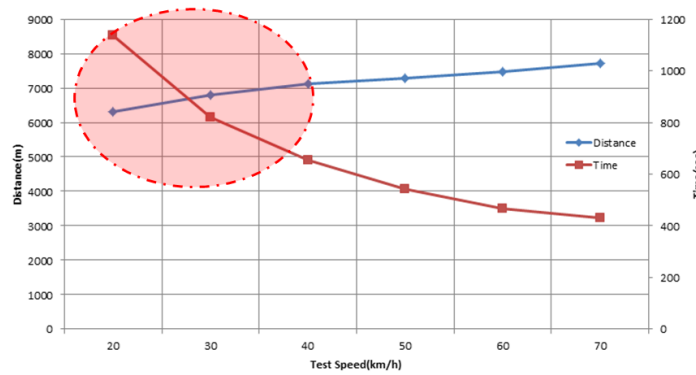

Figure 5. Graph of effective driving speed

Figure 6 shows five failure safety logics in the 10–20% range of battery SOC. Because the speed range with the highest efficiency was identified in the simulation to be 20–40 km/h, the failure safety logic to restrict the power was configured using this speed range. Logic type 1 maintained the driving speed at 30 km/h and had the best transportable distance and time efficiency. Type 2 was configured to reduce the motorcycle's speed linearly from the maximum (70 km/h) to the minimum (20 km/h) in the set speed range stated above. In type 4, at the 15–20% range of battery SOC, the speed was linearly reduced from the maximum (40 km/h) to the minimum (20 km/h) in the set speed range, and in the 10–15% range of battery SOC, a speed of 20 km/h was maintained. In type 5, the minimum speed (20 km/h) of the set speed range was maintained continuously.

Figure 7 shows the simulation result for each type of failure safety logic, showing that types 3 and 4 best satisfied the requirements for maximum transport time and distance. Thorough this, it is shown that in the 10%–20% range of battery SOC, because the range to maintain a speed of 20 km/h is longer, the transportable distance is shorter, but the operating time is longer.
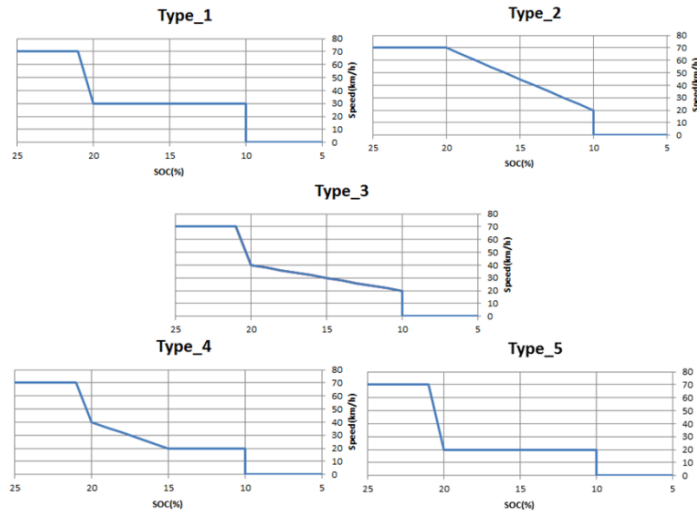
Figure 6. Types of failure safety logic
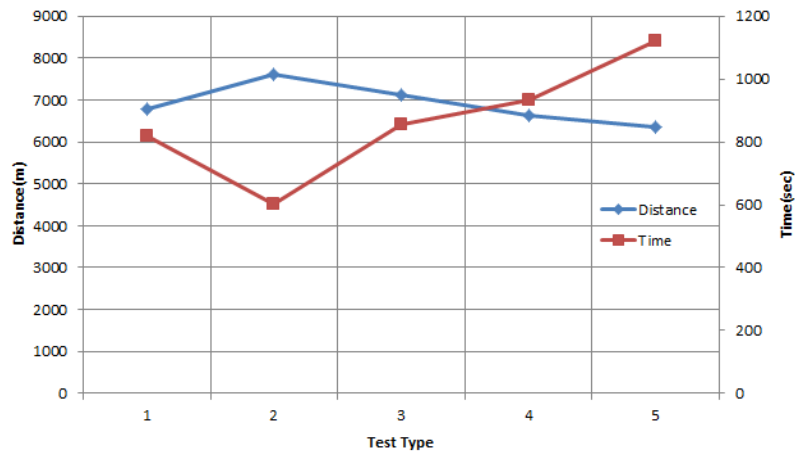
Figure 7. Distance and time result of each failure safety logic test

Figure 8 shows graphs that compare roll rates for types 3 and 4 selected based on the above result. When the battery SOC drops below the set limit, it is important for the driver to control the vehicle safely. In addition, because motorcycles have two wheels, unlike normal vehicles, the roll rate is an essential parameter for vehicle safety. Therefore, to identify the behavior of the motorcycle, two roll rates were compared. As shown in Figure 8, in both cases, the maximum roll rate was 8°/s, but the roll rate of type 3 converges to zero without a radical change. Accordingly, it was determined that type 3 is the optimal failure safety logic for the motorcycle used in this study.
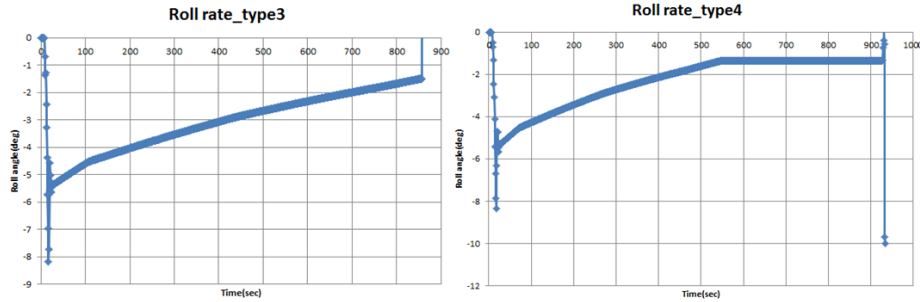
Figure 8. Graphs of roll rate results

4. Conclusion

In the present study, an optimal failure safety method was developed according to the battery SOC condition for an electric motorcycle model using MBD. To ensure the safety and lifespan of the battery, power was restricted to the 10–20% range of SOC by an integrated controller; at this time, the failure safety logic was configured to provide sufficient time and distance so that the driver can reach a safe area.

In addition, the vehicle's kinetic behaviors under five types of failure safety logics were examined using BikeSim. The result showed that the failure safety logic that reduced the vehicle speed linearly from 40 to 20 km/h in the battery SOC range described above afforded the greatest transport distance (7,000 m) and transport time (820 s). In addition, through a comparison of roll rates, a stable graph that converged without a radical change was obtained. Therefore, type 3 failure safety logic was identified to be the optimal method according to the battery SOC condition of the electric motorcycle.

The present study provides an optimal failure safety method according to the battery SOC condition of an electric motorcycle using MBD. In future studies, a failure safety method for key power components of the electric motorcycles, such as the motor and inverter, will be addressed.

Acknowledgements

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