

Development of Three-Motor Electric Vehicle “EMIRAI 2 xEV”

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ABSTRACT

Mitsubishi Electric has developed a concept car “EMIRAI 2 xEV” that features an electric vehicle (EV) powertrain for safe, comfortable, eco-friendly driving experiences in the future. The vehicle was exhibited during the 2013 Tokyo Motor Show and the 2014 Automotive Engineering Exposition. The xEV is a four-wheel-drive EV with three motors: a water-cooled front motor and two air-cooled rear motors with integrated inverters. The rear wheels can be driven independently. The degrees of freedom of the actuation can realize improved maneuverability and safety. The vehicle is also equipped with an onboard charger with a built-in step down DC/DC converter, an EV control unit, a battery management unit, and electric power steering. All of the instruments are developed by Mitsubishi Electric. Motion control systems for the xEV have been developed based on our proprietary motor control technology. In particular, this paper shows the design of three controllers: the high-precision traction control, the smooth G control, and the speed control. The effectiveness of the controllers is verified in simulations and driving experiments.

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INTRODUCTION

Concept of xEV

EMIRAI 2 xEV is a concept car that features an electric vehicle (EV) powertrain for safe, comfortable, eco-friendly driving experiences in the future. An overall view of the xEV is shown in Figure 1. In the 2011 Tokyo Motor Show, Mitsubishi Electric exhibited the EMIRAI EV concept car, which is based on the concept of “Intelligent Connect” for linking cars and diverse information for greater convenience, eco-friendliness and safety. For the 2013 Tokyo Motor Show and the 2014 Automotive Engineering Exposition, Mitsubishi Electric developed EMIRAI and exhibited EMIRAI 2 which comes in two versions [1]: EMIRAI 2 xEV and xDAS. The latter is developed to show the technology of our driving-assistance system for greater driving safety and comfort. In this paper, we focus on the former and show motion control technologies to realize the concept of the xEV.

Design and Features of xEV

The xEV contains Mitsubishi Electric's water-cooled front motor and its inverter, two air-cooled rear motors with integrated inverters, an onboard charger with a built-in step down DC/DC converter, an EV control unit, a battery management unit, and electric power steering. In particular, the propulsion system is divided into three motors for independent operation with one for the front axle, and two for each rear wheel. The front motor is connected to the front wheels through a reduction gear and an open differential gear. The motor produces maximum of 65 kW of power, while each rear motor reaches 30 kW. The three motors create 4WD experience different from gasoline vehicles.



Figure 1. Powertrain concept car “EMIRAI 2 xEV”.



Figure 2. Rear powertrain of the xEV. There are the two air-cooled rear motors with the integrated inverters. The rear motors are connected to the wheels with the clutches. By disengaging them, the xEV can switch the 2WD and the 4WD modes while driving.

A picture of the rear powertrain is shown in Figure 2. The xEV's rear motors are connected to the wheels using clutches. By disengaging them, the vehicle can run in the front wheel 2WD mode like many cars on the road. Conversely, the rear motors can be swiftly synchronized to the speed of each wheel before engaging the motor clutches for seamless transition to the 4WD mode. Switching of the modes allows the motors to operate at an optimal point of efficiency, and leads to longer driving range as shown in Figure 3.

Table 1. Specification of EMIRAI 2 xEV.

Weight, Measurements	
Total Weight [kg]	893
Total Length [mm]	3130
Total Width [mm]	1786
Wheelbase [mm]	2530
Minimum Ground Clearance [mm]	130
Overall Height [mm]	1320
Wheel Diameter [mm]	618
Occupancy	2 people
Front Motor (Interior Permanent Magnet Synchronous Motor)	
Maximum Power [kW]	65
Maximum Torque [Nm]	130
Front Inverter	
Type	Water-Cooling
Rear Right/Left Motor (Interior Permanent Magnet Synchronous Motor)	
Maximum Power [kW]	30
Maximum Torque [Nm]	50
Rear Right/Left Inverter	
Type	Air-Cooling
Battery	
Type	Lithium Ion
Rated Voltage [V]	270
Total Electric Energy [kWh]	10.5
Gear Ratio	
Front	12.35
Rear	17.87

In the market, electrified vehicles which have multiple motors to enhance energy efficiency, driving performance and ride comfort have been developed and started to be sold from car makers. There is the same trend in academia. For example, electric vehicles with four in-wheel motors [2, 3, 4] and two motors for the rear right and left wheels [5] are developed. However, determination of the optimal numbers and layouts of the motors is an open issue and some researchers deal with it [6]. Our xEV adopts the three-motor system to achieve high performance cornering with the yaw moment control using the independently driven rear wheels as well as high energy efficiency by switching the 2WD and the 4WD modes considering the motor characteristics.

To reduce the size and the weight, the xEV's rear inverter and motor units are air-cooled thus using fewer components. At the same time, the gearbox is integrated into a single unit, further reducing the size and weight. Finally, the motors and the gearbox are placed alongside each other to lower the center of gravity making cornering more stable. Specifications of the xEV are shown in Table 1.

Motion Controllers for xEV

Mitsubishi Electric has developed motion control systems to realize the concept of the xEV: powertrain of electric vehicles for safe, comfortable, eco-friendly driving experiences in the future.

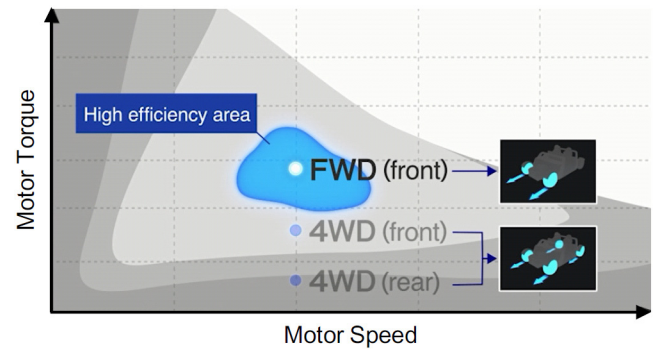


Figure 3. An image of efficient motor operation by switching the drive modes.

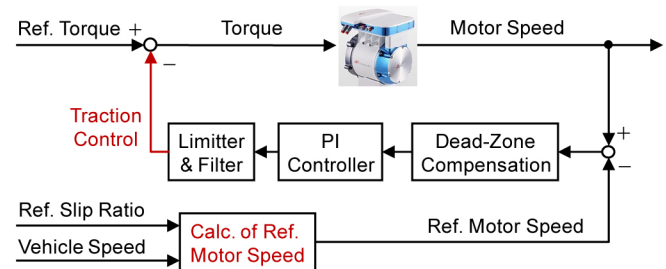


Figure 4. A block diagram of the traction control. The controller is applied to each motor.

Electrified vehicles have significant potential to realize advanced motion control [2] and this paper is focused on three control systems developed for the xEV:

- High-Precision Traction Control
- Smooth G Control
- Speed Control

In the following sections, the technologies embedded in the controllers are introduced and experimental verification in driving tests is shown.

HIGH-PRECISION TRACTION CONTROL

Traction control is important for safe driving on wet or snow-covered roads, where tires can easily lose traction. The xEV identifies tire slippage through motor revolutions per ms. If slippage is detected, the motor output is precisely lowered to the optimal level depending on the level of slippage. The vehicle maintains optimal drive power allowing safe driving.

Control Algorithm of Traction Control

A block diagram of the traction control is shown in Figure 4. The controller is applied to each motor. The slip ratio of a driven wheel in the case of acceleration is

$$\lambda = \frac{v_m - v_c}{v_m} \quad (1)$$

v_m is calculated from the speed of the driven wheel and v_c is the vehicle speed. When the xEV drives in the 2WD mode, v_c is calculated from the speed of the non-driven wheels. The input of the traction control is determined on the basis of the difference between a reference and the actual motor velocity. The reference velocity v_{mref} is derived transforming Eq. (1).

$$v_{mref} = \frac{1}{1 - \lambda_{ref}} v_c \quad (2)$$

λ_{ref} represents a desired slip ratio which is set to generate sufficient grip between the driven tires and the roads.

As shown in Figure 4, the error of the velocity is converted to the traction control input through compensation for dead-zone of wheel speed sensors, the PI (Proportional and Integral) controller, and a limiter and a filter. The compensation is necessary because the sensors cannot detect the wheel speed at a low velocity. In the xEV, the traction control is designed not to work when the rotation of the wheel is very slow. The integral part of the PI controller is equipped with an anti-windup and a reset algorithm based on the driver's operation. The limiter and the filter are introduced to avoid excessive assist of the traction control. The PI controller gains are determined on the basis of the values obtained in the speed control described later and in our related paper [7].

Experimental Verification of Traction Control

Figure 5 shows a driving test of the traction control. The road was wet and tiled, thus a vehicle slips easily because of an inappropriate accelerating work. In the experiment, the xEV was driven in the rear 2WD mode. To demonstrate the effectiveness of the traction control, a white line was attached to the wheels. Without the traction control, there are large afterimages of the white line, while it is relatively clear when the control is applied. In addition, the traction control keeps sufficient lateral force available because the friction coefficient in the lateral direction increases as the slip ratio decrease. This prevents the xEV from spinning and leads to safe driving.

The upper picture in Figure 5 represents the difference of the driving power with or without the control. The xEV started at 0 km/h with full acceleration and the travel distance is compared in the same time. The traction control prevents the xEV from slipping and keeps sufficient driving force, which leads to long travel distance and efficient propulsion.

Figure 6 shows time histories of the wheel speed, the slip ratio, and the signal of APS (Accelerator Position Sensor) in the driving test. The APS takes values from 0 to 5 V. 5 V corresponds to the command of full throttle. In the calculation of the slip ratio of Eq. (1), the denominator v_m is replaced with a small number when v_m is very small to avoid division by zero. The non-zero slip ratio in Figure 6 before the vehicle starts is caused by noise of a motor speed sensor. Without the traction control, the xEV slips immediately after starting. With the control, the wheel speed swiftly converges to the desired level regardless of the full throttle command. The performance is achieved with the rapid and precise control technology of the motors.

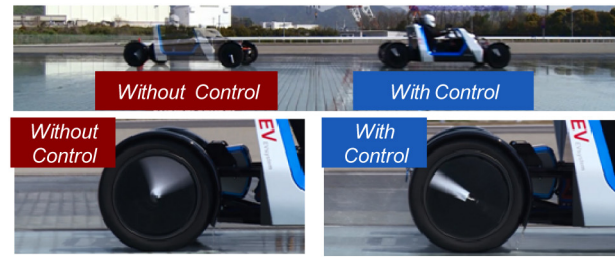


Figure 5. Driving tests of the high-precision traction control. The xEV starts at 0 km/h with full acceleration and the travel distance is compared in the same time. The control prevents the wheels from slipping and the xEV drives efficiently.

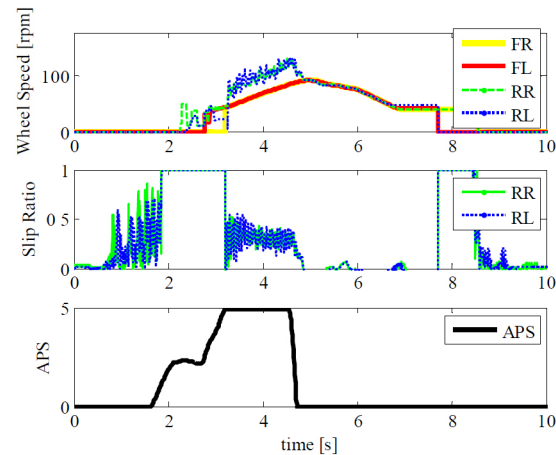


Figure 6. Time histories in the driving test of the high-precision traction control. Although the control is not available at a very low speed because of the dead-zone of the wheel sensors, the traction is recovered immediately after the control starts to work.

The traction control is designed not to work when the wheel speed is in the dead-zone of the sensor. To make the controller available for all speed range, alternative sensors to detect the very low wheel speed or a vehicle speed estimator are necessary. In particular, the latter is also effective for the traction control in the 4WD modes where the vehicle speed cannot be detected with the wheel sensors. As a future work, we are going to design the estimator based on states of the vehicle and motors.

SMOOTH G CONTROL

The smooth G control is designed to suppress vibrations of the vehicle which is generated because of elasticity of the powertrain. These vibrations are detected through the motor revolutions. The smooth G control then modifies the torque in opposite direction of the vibrations cancelling them out. This is the high grade of an acceleration smoothing control extended from Mitsubishi Electric's FA (Factory Automation) technologies.

The controller is designed on the basis of the structural characteristics of the xEV. First, frequency responses of the xEV are obtained in experiments. Then, the parameters of a dynamical model of the xEV are identified. Finally, structure of the controller is determined and its effectiveness is verified in simulations and driving tests.