Novel System Designs and Controller Development for a New-type Dual-Hybrid Electric Vehicle

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Abstract

Based on continuous efforts devoted to the clean vehicular technology, ITRI successfully developed the first new-type Dual-Hybrid Electric Vehicle (Dual-HEV) in Taiwan. An innovative system design and advanced control technologies make this dual-HEV as a promising product in the near future. Domestic automakers even international manufacturers show strong intentions to ITRI core technologies. This paper firstly describes the proper system designs of the target vehicle. An electric-clutch is applied to properly switch the serial/parallel modes for improving the drivability and fuel economy. Next, the controller schemes, operation modes, and the energy management are also introduced. The control strategies of mode switching, gear shifting, also energy distribution are derived via ECMS (Equivalent Consumption Minimization Strategy) analysis which leads to the minimized energy consumption. Designed system and the advanced vehicle control unit are ultimately integrated. The strategy verification, parameter calibration, and the system modification then can be conducted on the dynamometers and eventually on the road. Based on the test results, a dramatic improvement of fuel economy exceeds 50% compared with the traditional ICE vehicle.

Keywords: hybrid powertrain, system integration, control strategy

1 Introduction

With stringent laws legislated and rising environmental concerns globally, governments and automakers are searching for the solution to reduce CO, CO2, NOx, and other toxic gases produced by the transportation. Various types of advanced vehicles using alternative energy sources, electric power sources, innovative mechanical and control system designs, are able to reduce the well-to-wheel energy consumption.

From the evaluation of California EPA in the US, Hybrid Electric Vehicles (HEVs) have become a promising product with mass commercialization nowadays [1]. Global automakers such as Toyota, Honda, Ford sale their hybrid vehicles with different patented designs worldwide [2]. A HEV, with dual power sources mounted, is characterized by the high output torque assisted from the motor, fuel saved by the power distribution control, energy recovered by the engine/ generator or the brake regeneration, etc.. With these advantages, HEVs are expected to occupy 18% market sales in 2020.

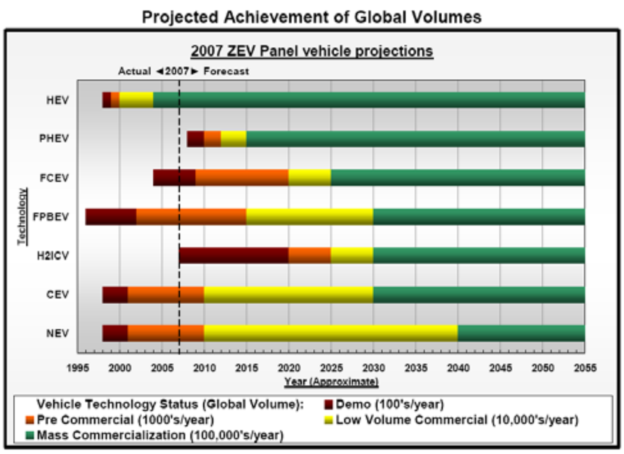

Figure 1 US California EPA Evaluation for commercialization of Advanced Vehicles

Industrial Technology Research institute (ITRI), being the best research organization in Taiwan, has put a lot of efforts on advanced /green vehicles development. Innovations and pioneering technologies of ITRI drive Taiwan's automotive industry competitive in the global market. For the past decades, advanced vehicles such as HEVs, EVs, fuel cell vehicles, Light EVs (LEVs), etc. are chosen as platforms for technology development. Therefore, in this paper, an innovative dual-HEV is introduced. Following the process of system designs, controller development, vehicle integration, and laboratory tests, a dramatic 50% growth of fuel economy is achieved.

2 Novel hybrid system designs

In this Section, vehicle subsystems, vehicle specification, and operation principle will be firstly described. Next, key components such as the electric-clutch, the traction motor, the high power lithium battery package will be detailed.

2.1 Dual hybrid system and its operation

Figure 2 shows the vehicle structure of the dual hybrid system. It consists of a 375 c.c. SI engine, a 7kW Integrated Starter Generator (ISG), a 15kW Permanent Magnetic Synchronous Motor (PMSM), a 144V lithium battery package, a 6-speed AMT, and an electric clutch. Detailed specification is listed in Table 1 [3].

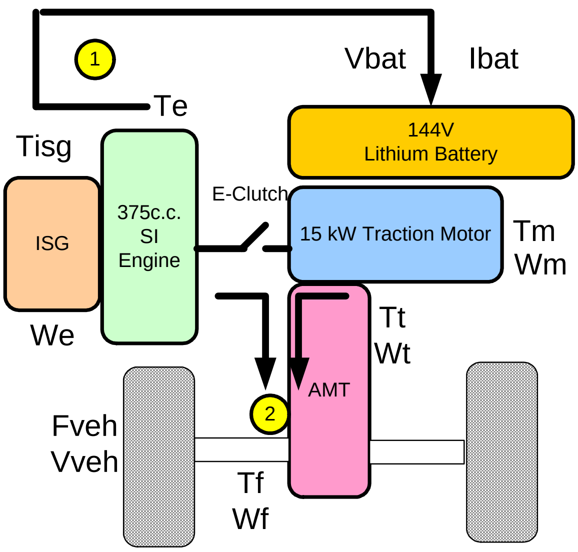

Figure2: Vehicle structure and operation mode

The e-clutch plays the key role of switching the series hybrid mode and the parallel hybrid mode. When the e-clutch is disengaged, it is in the series mode. The engine is only able to drive the ISG to produce electricity for the purpose of remaining the SOC of the battery. The traction motor which is powered by the battery set, propels the vehicle via the AMT system. Investigating the energy transferring path (marked as path 1), it is the serial hybrid mode. Once the e-clutch is engaged, the traction motor and the engine can drive the vehicle simultaneously, the vehicle is thereby in the parallel mode (marked as path 2). By properly operating the clutch, the fuel economy and the vehicle performance are improved.

Table 1 Specification of the dual hybrid vehicle

Prototype Vehicle	• Gross Weight: 950 kg • Max. Tq. 70N-m @2500rpm • Max. Pwr 24kW @3500±500rpm • Max. Speed: 90 kph • Pure Electric Drive >40kph • Acceleration 0-60kph≦10 sec
ISG	• Max. Gen. Pwr 7kW @4000rpm • Eng. Cranking＜0.5sec
Engine	• 375 c.c./Lean Burn/V2/4-Stroke • Water Cooling System • Max. Tq. 33 N-m @4000 rpm • Max. Power 16.0 kW @5500 rpm • BSFC：260 g/kW-hr • Electric Throttle Control • CAN Bus 2.0b-500MHz
Traction Motor	• PMSM/Hall Sensor • Max. Drv. Tq. 60N-m @<2000rpm • Max. Drv. Pwr. 15kW @3000rpm • Max. Gen. Pwr. 15kW @3000rpm • Max. Drv/Gen Eff.: 92% • CAN Bus 2.0b-500MHz
Trans. System	• 6-Speed AMT • Final Trans: Gear Pair
Battery	• Lithium/144V/40Ah • Max. CHG/DCHG Pwr：20kW @ 50% SOC-10sec. • Power Density>1500W/kg • CAN Bus 2.0b-500MHz

Noted that the determination of subsystem specification, also the evaluation of vehicle performance are completed by using an ITRI-made vehicle simulator: Dual HEV-SIM as depicted in Figure 3. Each block represents a subsystem, while the driver model, the vehicle control strategies, and the driving scenario are also integrated to fulfil the R & D needs. Vehicle performance, the engine and motor torques and speed, the battery SOC, the gear shifting, and the fuel economy are capable of being observed in this software.

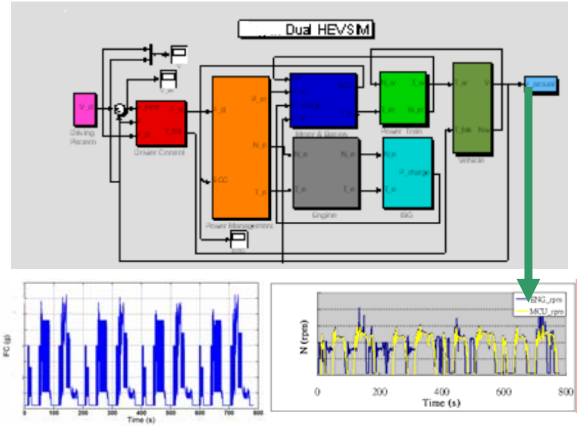

Figure 3 ITRI vehicle simulator-Dual HEV-SIM

The dynamic equations are listed as follows:

(1)Series Mode (e-clutch off):

Key Components:

$$P_{bat} = V_{bat} \times I_{bat} = T_{isg} \times \omega_e \times \eta_{isg} \times \eta_{chg}$$
$$\omega_e = \omega_{isg}, T_{isg} = T_e \times \eta_e(T_e, \omega_e)$$
$$FE_e = BSFC(T_e, \omega_e) \times T_{isg} \times \omega_e / 1000 \quad (g/s) \quad (1)$$
$$T_t = T_m = \frac{P_{bat} \times \eta_{dchg}}{\omega_m} \times \eta_m(T_m, \omega_m)$$
$$\omega_m = \omega_t / GR(\alpha_{th}, \omega_m) = \frac{V_{veh}}{3.6 \times (R_{whl}) \times GR}$$

Vehicle Dynamics:

$$\dot{V}_{veh} = \frac{F_{veh} - 0.5 C_d \rho A V_{veh}^2 - \mu m_{veh} g \cos(\theta) - m_{veh} g \sin(\theta)}{m_{veh}}$$
$$F_{veh} = T_t \times GR(\alpha_{th}, \omega_m) / R_{whl}$$

(2)

where variables: P, V, I, T, ω represent power, voltage or speed, current, torque, rotational speed, separately. Variables: $BSFC$, η, GR, α, m mean engine efficiency, gear ratio, throttle position, and mass. Other road load-related parameters: ρ, A, g, R, θ indicate air density, front area of the vehicle, gravity, radius and the road slope. For the suffixes: bat, isg, chg, $dchg$, m, t, veh, whl mean battery, generator, charge, discharge, motor, transmission, vehicle, wheel.

Equation (1) shows the relationships of variables of key components. The engine and the ISG generate electricity with the same rotational speed, while the fuel economy can be determined by the engine speed and its output torque. The transmission torque equals to the motor torque. Equations (2) shows that the vehicle speed is influenced by the net force of the traction force and the road load.

(2)Parallel Mode:

Key Components:

$$T_e = T_{e\_drv} + T_{e\_gen}$$
$$I_m = I_{isg} + I_{bat}$$
$$T_t = T_m + T_e + T_{isg}$$
$$I_{bat} = P_{bat} / V_{bat} \times \eta_{chg} \quad if \quad P_{bat} > 0$$
$$I_{bat} = P_{bat} / V_{bat} / \eta_{dchg} \quad if \quad P_{bat} < 0$$
$$I_{isg} = T_{isg} \times \omega_{isg} \times \eta_{isg} / V_{bat} \quad if \quad I_{isg} > 0$$
$$I_{isg} = T_{isg} \times \omega_{isg} / \eta_{isg} / V_{bat} \quad if \quad I_{isg} < 0$$
$$\omega_e = \omega_{isg} = \omega_m = \omega_t / GR(\alpha_{th}, \omega_m) = \frac{V_{veh}}{3.6 \times (R_{whl}) \times GR}$$
$$FE_e = BSFC(T_e, \omega_e) \times T_e \times \omega_e / 1000 \quad (g/s)$$

(3)

Vehicle Dynamics:

$$\dot{V}_{veh} = \frac{F_{veh} - 0.5 C_d \rho A V_{veh}^2 - \mu m_{veh} g \cos(\theta) - m_{veh} g \sin(\theta)}{m_{veh}}$$
$$F_{veh} = T_t \times GR(\alpha_{th}, \omega_m) / R_{whl}$$

(4)

The engine torque in Equation (3) includes the traction part (T_{e_drv}) and the generation part (T_{e_gen}). The generation torque T_{e_gen} is equivalent to T_{isg} if the ISG is in generation mode. Because of the parallel electric circuit of the motor, the ISG, and the battery, the currents of these devices obey the Kirchhoff's current law. In the parallel mode where the e-clutch engaged, the engine, the motor, the generator are interconnected directly so that the rotational speeds are the same, and the traction torque of the transmission equals to the summation of those of the three power sources.

2.2 E-clutch system

As mentioned earlier, the e-clutch is the key component to switch the serial and parallel modes.

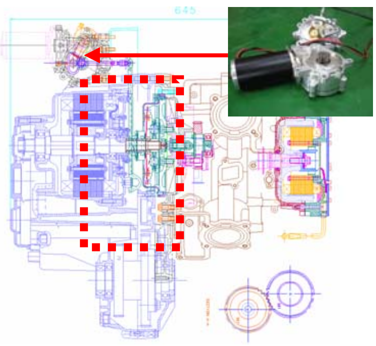

Figure 4 Electric-clutch with the hybrid system

ITRI developed the e-clutch using a self-designed 12V/500W Permanent Magnetic Synchronous Motor (PMSM) as the actuator. The motor controller precisely governs the motor rotational angle by an inner-outer close loop structure: motor angle and motor speed control. The commended PWM signal would be sent to the MOSFET module and transferred to the motor. Meanwhile, the motor also return position signal back to the control unit.

With a pair of worm and worm gear, the variation of the motor angle will be transferred to the 1-D motion of a rod via the worm gear set. Such rod is responsible for the engagement/disengagement of the clutch by pushing the clutch plate or not. The period of engagement/disengagement can be shortened to 0.3-0.4 sec. with proper parameter tuning. The clutch module is integrated into the hybrid powertrain between the engine output shaft and the AMT system as shown in Figure 4.

2.3 Lithium battery system

ITRI established the high voltage, high power battery package in the New-Generation Energy & Power Lab., which contains the best vehicle-used battery test instruments in Taiwan. It is able to measure the charge/discharge performance of a unit cell, a module, or a package under varying loadings. Unit cells purchased from domestic manufacturers or abroad will be integrated into battery modules, and a Module Management Unit (MMU) is responsible for supervising the voltage and temperature of each cell. Next, considering the requirements of the vehicle, modules will be integrated to be a battery package. The heat transferring tunnels, electric circuits, safety relays, package size are designed for this system. An ITRI Battery Management System (BMS) is applied to receive the data from MMUs via CAN bus, to calculate SOC, to control the relays and charge/discharge current for safety issue, and to send data to Vehicle Control Unit (VCU). The whole system combined with the BMS is then equipped into the vehicle.

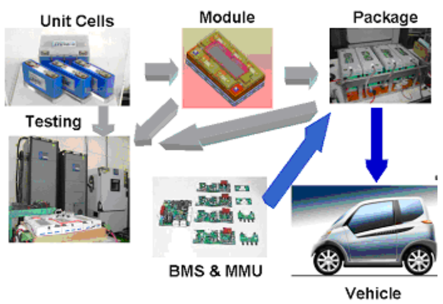

Figure 5 Battery package designs and tests

2.4 Power Sources

A 375 c.c. V2 SI engine and a 15kW PMSM traction motor are applied for the hybrid power sources.

The engine is produced by ITRI, Taiwan. It is with lean burn mode to save fuel at partial load. The designed water-cooling system extends the period of high power/torque output. The inherent maximum torque (33 N-m) and power (16kW) have been simulated via Dual HEV-SIM in advance to guarantee that the target acceleration and maximum speed can be reached. The Electric Throttle Control (ETC) and CAN Bus data transmission make this engine receive torque/speed command and produce the required performance instantly. The fuel efficient (BSFC) zone is at the middle-speed high-torque zone. It is verified at the lab., and with the optimal BSFC - 260 g/kW-hr.

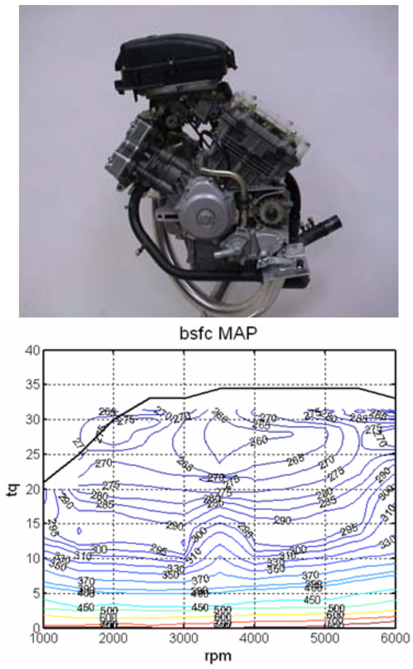

Figure 6 ITRI-made Engine and BSFC map

The other power source, a 15kW PMSM with the self-designed controller and the driver, is also integrated into the hybrid system. With proper magnetic and mechanical structure analysis, the basic performance tests can be conducted in advance. Next, a three-phase Motor Control Unit (MCU) with a 6-IGBT driver, are combined into the traction motor system.

The efficiency map with respect to the torque and rotational speed is plotted in Figure 7. The middle-speed (3000-4000 rpm), middle-torque (20-30N-m) area has the better efficiency performance. Though the CAN bus device, the

MCU receives the torque/speed command from the VCU to accurately provide the required values.

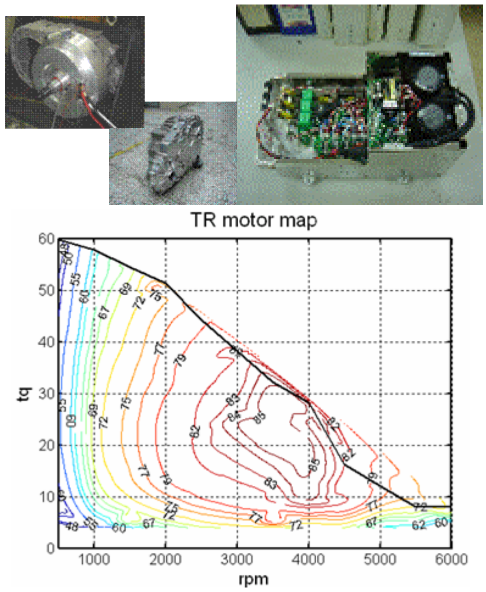

Figure 7 ITRI traction motor and efficiency map

3 Vehicle Controller Designs

Besides the novel system integration, the innovative energy management and system control strategy for the hybrid powertrain also significantly improve the fuel economy. This section firstly describes the hardware of the VCU, then the software of the operation modes. The theoretical-based energy management will then be proposed. The final part describes how to verify the hardware/software before integrating into the vehicle.

3.1 VCU Hardware

The VCU hardware is shown in Figure 8. The 12V main power keeps the VCU working. The analog input signals of the VCU include: key on, pedal position, and brake position. The digital input signals are gear position, e-clutch position, status of control units. With the DSP calculation and designed circuits of the VCU, the commands are sent out to other control units. The analog outputs are the on/off commands of the relays for control units. The digital outputs are CAN bus data transmission and also the RS-232 signals. Torque and speed commands for the power sources, commands for the auxiliary system, gear shifting commands, protection signals, etc. are included. With the ITRI–designed VCU, all required functions are able to be developed.

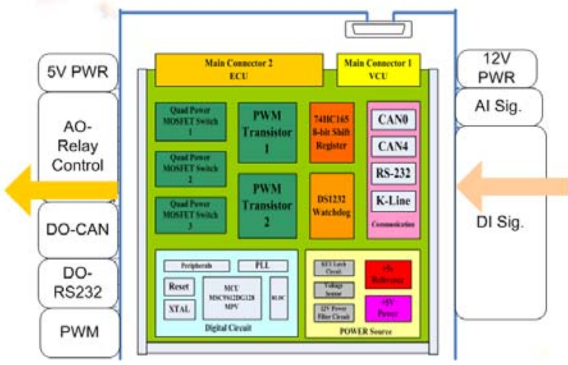

Figure 8 ITRI-designed VCU hardware

3.2 VCU software

The VCU software can be separated into three segments: signal inputs, operation modes, and signal outputs. It is built in the Matlab/Simulink platform as Figure 9 shown. The input and output blocks receives and sends out CAN data to/from the VCU, while control strategy block includes the following functions:

(1)System Ready: waking up control units and power/energy system while key on activated.

(2)Signal process: transferring the signal types for utilized in the control model

(3)Operation modes: the core technology of the VCU. It directly influences the energy consumption of the dual hybrid system. The operation modes include- EV, HEV, Engine Only, Idle Generation, Brake Regeneration, etc.. All modes are in the form of flow chart so that it is easier to debug and to prevent “mode lock”. The entrance rules and exit rules are set for each mode. Each block is able to send torque /speed commands to power and energy sources, and the shifting command to the gearbox.

(4)System calibration: a series of multi-dimension tables and gain-tuning blocks are in this section for online/offline calibration..

(5)Key off: turn off the control units and shut down energy devices by a standard process.

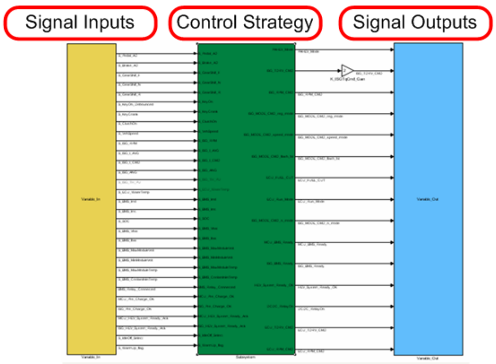

Figure 9 ITRI-designed VCU software

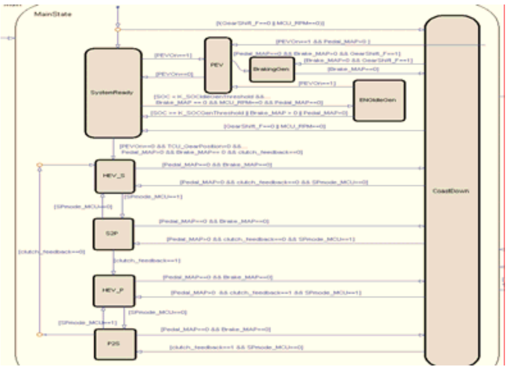

Figure 10 Structure of operation modes

The dual hybrid powertrain can operates efficiently if the structure and control strategies of the VCU software are properly designed.

3.3 Energy Management Strategy

As mentioned above, the energy management strategy directly determines the fuel economy under the SOC balance condition. An Equivalent Consumption Management Strategy (ECMS) method was applied to analysis the optimal power distribution between the engine, motor, and ISG [4][5]. The equivalent fuel consumption $\dot{m}_{f\_equi}$ is the summation of engine fuel consumption $\dot{m}_{f\_eng}$ and the equivalent battery fuel consumption $\dot{m}_{f\_batt}$, where it is defined as the input/output battery power multiplied by the average engine BSFC as shown in Equation (6). Next, vehicle variables (states) including SOC, speed of power sources, demanded torque are discretized for the global optimization searching. With $\dot{m}_{f\_equi}$ set as the cost function and to be minimized, operation modes under various situations can be determined.

$$\dot{m}_{f\_equi}(t) = \dot{m}_{f\_eng} + f(soc)\cdot \dot{m}_{f\_batt} \qquad (5)$$

$$\dot{m}_{f\_batt} = \frac{\overline{BSFC}\cdot P_m}{\eta_m \cdot \eta_{bat}} \qquad (6)$$

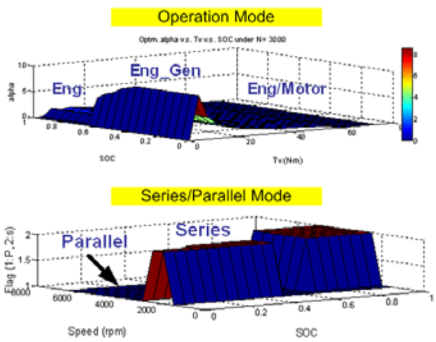

Figure 11 Optimal energy management strategies using ECMS

3.4 VCU HW/SW Verification

After the rapid prototyping of the VCU hardware and software, there are two phases for the VCU performance verification. The first stage is to test the signal transformation and data accuracy. A signal generator representing the driver's commands delivers pedal/brake/gear shift signals to the VCU. The VCU calculates the commands to other CUs and send them out to the supervisory computer to check the correctness.

The second phase is to apply a real-time simulator with the vehicle model downloaded to it as a virtual car. The VCU is linked with the simulator via AI/AI, DI/DO, CAN bus, RS-232 to form a Hardware-In-the-Loop (HIL) system. The modification of operation modes, control strategies, associated parameters can be completed in this HIL.

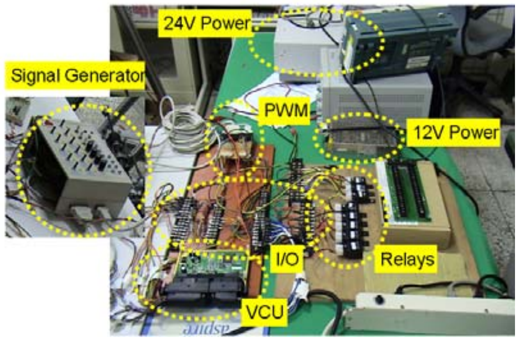

Figure 12 VCU HW simulation platform

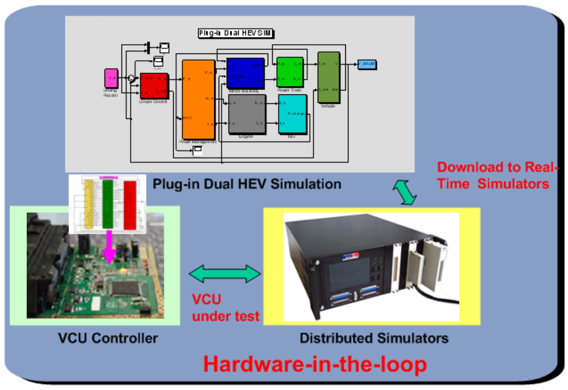

Figure 13 VCU real-time simulation platform

The R&D process of VCU includes hardware designs, software designs, and platform verification. Instead of testing on the road, the offline environment provides sufficient capacity for the VCU development.

4 Dual Hybrid Powertrain Development and Tests

With proper powertrain development in Section 2 and VCU designs in Section 3, the integration of them into the vehicle is then needed. The fuel economy measurement and on-road tests are required to complete the whole process of this novel dual hybrid powertrains.

4.1 Lab. tests and system integration

The developed VCU and dual powertrains are integrated as a complete system. The laboratory tests are needed before the vehicle integration. Figure 14 depicts the testing system in the lab.. The control unit set include: VCU, MCU, ISG control unit (ISGVU), BMS, Engine Control Unit (ECU), 144V/12V DC/DC converter, etc..

The dual hybrid powertrain is interconnected to a 75-N-m active dynamometer regarded as the road loads. This laboratory provides sufficient testing supply system including: fuel supply system, water cooling system, harness and CAN system, power supply modules, and power and signal relays. The tests include: switching control of serial/parallel, e-clutch engagement/ disengagement calibration, peak performance of power sources, optimal engine-generation searching, etc. The whole system becomes reliable and the performance is improved via such lab. tests.

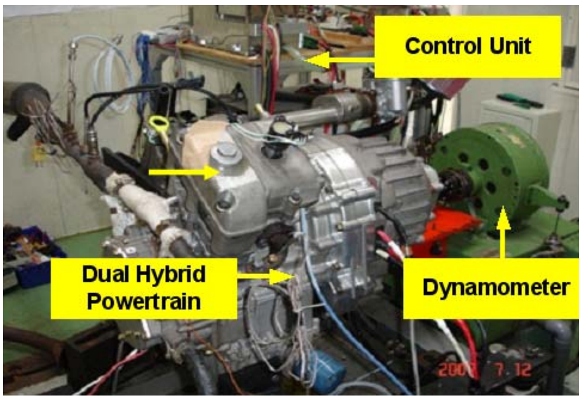

Figure 14 Laboratory tests of the hybrid system

With mature technologies developed in the lab., the 18kW dual hybrid powertrain is then equipped into the vehicle. As Figure 15 illustrated, the vehicle front part contains the powertrain and the e-clutch system. The ECU and VCU are also combined.

The trunk space integrates the 144V lithium battery package, the MCU/ISGCU, the 144V/12V DC/DC converter, the power relays, etc.. The CAN bus system and high power lines circulates the vehicle body. This novel vehicle is then able to be tested on the chassis dynamometer.

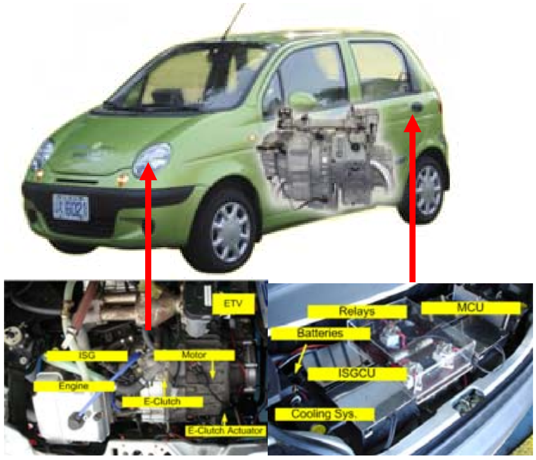

Figure 15 Vehicle integration with an advanced powertrain

4.2 Fuel economy development on chassis dynamometer

A front wheel-drive chassis dynamometer is applied for the vehicle performance tests. During the operation, a fuel economy analyzer is utilized for measuring the actual fuel consumption via the connection to the tailpipe. The lower part of Figure 16 illustrates the improvement of FE. The functions such as idle stop, idle generation, torque distribution, serial/parallel mode switching, gear shifting timing, are all studied and the contribution to the FE can be analyzed. The FE was increased from 18 km/l to 27.3 km/l, which saved a 50+% fuel economy.

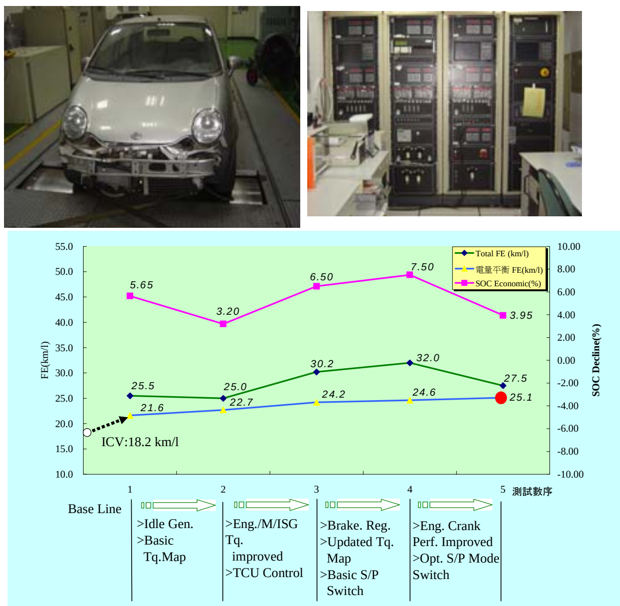

Figure 16 A fuel economy development on the chassis dynamometer

To ensure the robustness and reliability of the dual powertrain and subsystems, an on-road test was planned. The scenario includes the country side, the urban area, the highway, and the city area. The total mileage is 200+km

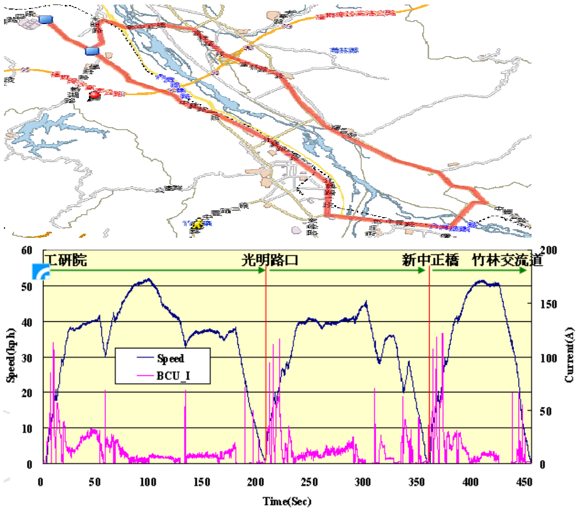

Figure 17 The route and recorded data for the on-road test

Through the tests, the vehicle and all subsystems with controllers operate well, and it proofs that ITRI, Taiwan, has the research capability to produce a novel hybrid vehicle, which improves a 50+% fuel economy by advanced control strategies and innovative system structure.

5 Conclusion

In this paper, we discuss the new-type hybrid system development and the controller designs by ITRI, Taiwan. The dual hybrid powertrain includes the 375 c.c. engine, 15kW traction motor, 7kW ISG, 144V lithium battery package, and a 144V/12V DC/DC converter. Each subsystem is governed by its control unit, and all subsystems with control units are produced by ITRI. The serial/parallel hybrid system, which is switched by the e-clutch, operates well under the lab. tests. For the VCU part, it influences the fuel economy significantly. Several stages for VCU development are proceeded such as: HW/SW designs, theoretical energy management, VCU simulator test, and the real-time simulation. The hybrid system and the VCU are ultimately integrated for the lab. tests and 200 km on-road tests. It shows that 50+% FE improved can be achieved by the outstanding research energy and testing instruments in ITRI, Taiwan.

Acknowledgments

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