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An assist-mode hybrid electric motorcycle

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Abstract

This paper proposes a design and implementation of an assist-mode, hybrid electric motorcycle (H.E.M.). The proposed hybrid electric motorcycle is a revised vehicle from a 50 cc motorcycle and designed to match up with a 100 cc motorcycle. In order to expedite the developing phase and lower down the cost, a master–slave tracking control method is utilized. A dc servo-motor is deployed to track the speed of the rear wheel of the motorcycle and to provide more torque through power composite into the rear wheel so that the performance of hybrid electric motorcycle can be promoted. The advance of performance as well as the energy saving can both be expected. In road trip experiment, the H.E.M. prototype achieves an average gasoline mileage of 46 km l^{-1} compared to the original 34 km l^{-1}. The overall efficiency is about 35% lift. Experimental results confirm the feasibility and prosperities of the proposed hybrid electric motorcycle.

Keywords: Hybrid electric vehicle; Hybrid electric motorcycle (H.E.M.); Master–slave mode tracking control; Power composite

1. Introduction

Due to the oil crisis and continuous war in the oil producing countries during recent years, the oil price is sky-rocketing. In addition, the awareness of the environment protection and the green house effect due to global warming, has resulted in the search for environmentally friendly resources. As a result, electric vehicles and fuel-cell electric vehicles have been developed [1–3]. These electric and fuel-cell powered cars feature zero pollution, high efficiency and high torque in low speed. However, they have not been well accepted by consumers due to several bottlenecks remaining unresolved such as short cruise distance, long charging time, lack of places to recharge battery for the electrical vehicle and high initial cost, lack of places to refuel hydrogen for the fuel-cell vehicle. These are the main reasons why electric and fuel-cell vehicles do not replace gasoline cars yet. In Asia, even though Taiwan government has promoted and subsidized the electric vehicle industries, both cars and electric mopeds, the public has not yet accepted it. Hybrid vehicles offer a best possible solution because electrical driving system is always high in efficiency and reduces the overall exhaust emission. In Asia and south Asia, motorcycles are the major way of transportation. For example, there are 13 million registered motorcycles in Taiwan in the year 2006, in other words, half of the population in this small island owns a motorcycle. The number of motorcycle is increasing by 0.35 millions per year for domestic sales and 1 million for export into south Asia markets. However, there is no compact hybrid electric vehicle in any form existing in the consumer market. The development of a hybrid electric motorcycle is both good for a healthier environment and for economy reasons. This inspires us to initiate the hybrid electric motorcycle (H.E.M.) project since July 2003. In near future, motorcycle will be the most affordable and prevailing way of transportation in developing countries like China, Thailand, Indonesia, etc. The developing countries are responsible for main portion of air pollution for the world. There is a strong call for a cleaner motorcycle for these counties to save fossil fuel preservation and meet the demands for prosperity.

The main purpose of this article is to design a hybrid electric motorcycle, which meets the Taiwan national exhaust emission standards, as well as promote motorcycle's performance and gasoline efficiency. Design and implement procedure and circuits are discussed in details in the following paragraphs. Research objective of this paper relies heavily on the feasible

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way to coordinate the engine's and electric motor's power accordingly, which will produce more thrust and improve overall system efficiency, hopefully lead to a development of a consumer-friendly hybrid electric motorcycle.

2. Design principle

In general, the composite electric-engine vehicle is categorized into two types, serial or parallel, depending on the layout of its engine, motor, battery and transmission [1,2]. In a parallel type composite electric-engine vehicle, shown in Fig. 1, engine provides both the power to drive the vehicle and to generate the electricity for recharging the battery at the same time. If the battery terminal voltage is high enough for operation, engine and electric motor are both activated, thus producing a combined torque to turn the drive shaft and move the vehicle forward. Bose et al. [4] proposed Eqs. (1) and (2) that determine the power contribution from engine and electric motor:

$$P_{\mathrm{mc}} = P_{\mathrm{C}} \left(\frac{P_{\mathrm{M}}}{P_{\mathrm{M}} + P_{\mathrm{E}}} \right) \tag{1}$$

$$P_{\mathrm{ec}} = P_{\mathrm{C}} - P_{\mathrm{mc}} \tag{2}$$

where P_{C} is the total power demand; P_{mc} the power provided by motor; P_{ec} the power provided by engine; P_{M} the motor maximum power and P_{E} is the engine maximum power.

The equations mentioned above are applicable for designing a hybrid electric motorcycle. The composite electric motorcycle mentioned in this paper is based on a modified 50 cc motorcycle available in the market. Possible designs for modification are diverse. The main challenge is that the usable space in a motorcycle is much less than that of a car. The second challenge is to design a hybrid electric motorcycle in a shortest time possible using the most economical method. After reviewing several reference papers [1–11] and the existing design of Toyota's hybrid car, Prius, a single-shaft, bi-axle parallel transmission structure is adopted (as shown in Fig. 1) as the blueprint for this concept prototype H.E.M.

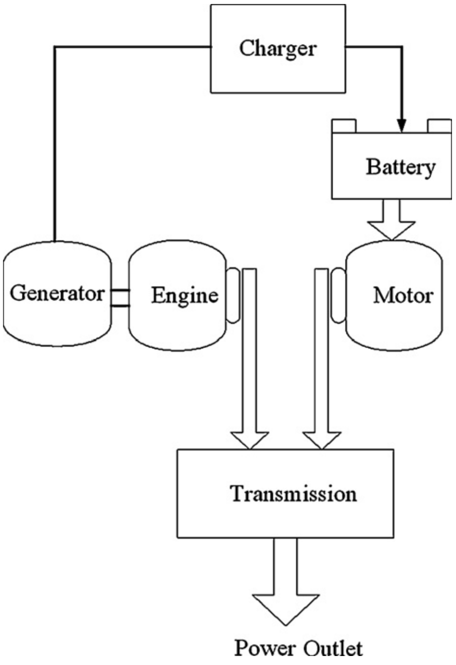

Fig. 1. Single-shaft, bi-axle parallel transmission structure.

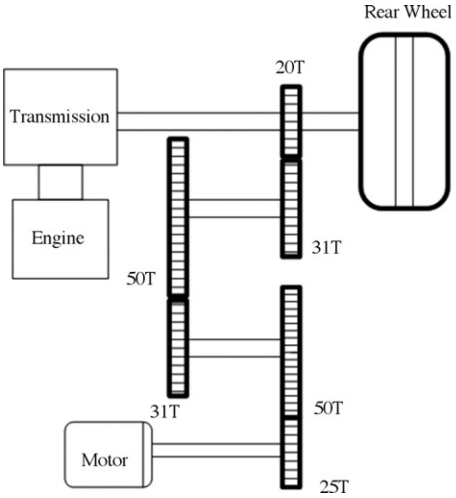

Fig. 2. Coupling power between engine and motor via gearbox.

We went through used motorcycle dealers for some suitable types. Finally, we picked up a 50 cc motorcycle called Tact from Sang-Yang Motorcycle Company, Taiwan. The main reason we chose a 50 cc Tact is because there is a 100 cc Tact in the same series. We can take the 100 cc type as a reference model for improvement and the technical manual [12] for Tact Series is available. Another significant reason for picking up 50 cc motorcycle is because this type of scooter is the major form of transportation in urban areas. After we disassembled the motorcycle for investigation, we found that the space of transmission box is so compact, it is impossible to add any additional mechanical structures in; therefore, we modified the conventional single-shaft, bi-axle transmission structure slightly by attaching the motor's gearbox to the rear wheel. The gear ratio is 4:5 to match the servo-motor's and the rear wheel's speed, shown in Fig. 2. In order to determine the electric motor's specifications, a Tamagawa-Seiki 500 W (3600 rpm/75 V) servo-motor is chosen to provide the torque difference of 0.43 kg m between the 100 cc Tact's maximum torque (0.98 kg m) and the 50 cc Tact's (0.55 kg m). By calculation, motor can provide a maximum torque of 0.42 kg m under 20 V operating voltage and 20 A operating current with maximum speed of 960 rpm. Theoretically speaking, the modified 50 cc Tact should have the performance of a 100 cc Tact in terms of torque and maximum speed at about 90–100 km h^{-1}.

3. Design and analysis of a master–slave mode H.E.M. control module

Since there are two individual powers from the engine and electric motor driving the electric motorcycle's rear wheel at the same time, the control module plays a very important role. The pre-requisite condition for these two different types of power to work together is that the rotation speed of the rear wheel and that of the electric motor needs to match each other (refer to Fig. 2). Therefore, we designed a real-time speed monitoring controller and a set of gearboxes that matches up two power types. The master–slave type composite power control module includes a gearbox, frequency–voltage converters (FVC) and a set of proportional, integrative and derivative (PID) speed tracking controller. Each and every component of the control module is described separately below.

3.1. Gearbox design

Since the maximum rotation speed of the rear wheel and motor are different, we needed to design a gearbox that can resolve the difference and result in additive thrust for the hybrid electric motorcycle. The detailed structure of the gearbox is shown in Fig. 2. The gear ratio between the electric motor and the rear wheel is set to 4:5. In addition, the gearbox is designed to avoid reversing power transmission, thus prevent the electric motor from being an unexpected load when the motor's speed is lower than the wheel's.

3.2. Frequency–voltage converter (FVC)

The purpose of this device is to convert the frequency signals of the rear wheel and electric motor rotational speeds into voltage signals accordingly. A Hall device is used as the sensor to pick up four permanent magnets placed evenly along the rear wheel. Then a Schmitt trigger gate detects 4 pulses/revolution signal from the rear wheel and transforms into standard transistor–transistor logic (TTL) pulses. In contrast, the encoder on the electric motor can detect 600 pulses/revolution signal. The tracking device is 150 times faster than the traced signal. The FVC design is based upon the rotation speed of the rear wheel and motor. The motorcycle maximum speed is about 90 km h^{-1}. According to the LM2907 design manual [13,14], we set the voltage 9.6 V at 90 km h^{-1}. According to Fig. 3, we set two sets of frequency–voltage converters values separately. FVC test results are listed in Table 1, actual experimental values and comparison with theoretical calculations. Accuracy of FVC at low speed is fine, but when the speed is above 40 km h^{-1}, the error is lowered to less than 1.5%.

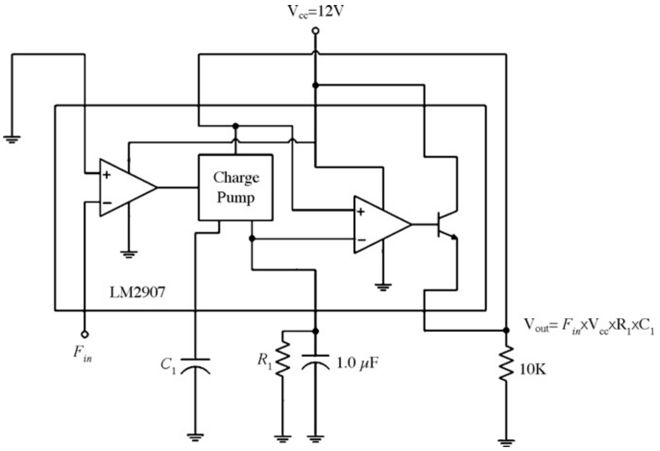

Fig. 3. Frequency–voltage converter.

3.3. Proportional, integrative and derivative (PID) speed tracking controller design and testing

The main purpose of the PID speed tracking controller is to manipulate motor speed and to match automatically up the rear wheel's rotation speed in a preset ratio, thus resulting in the effective integration of two individual powers. The PID control system features quick response time, low overshoot, and low steady-state error. It is a simple, mature, reliable circuit technology with stable closed-loop architecture. Therefore, we adopt the PID speed tracking controller using analog circuits [13,14]. The detailed circuit design of PID speed tracking controller is shown in Fig. 4 and system block diagram is shown in Fig. 5.

4. Electric motor driving and recharging system

The main goal of the hybrid electric motorcycle is to operate the electric motor safely and stably. The actuation system includes motor driving circuit, current-limiting protection circuit and the low battery voltage protection circuit. The details of the driving circuit and safety protection circuits are shown in Fig. 6. Sub-systems are described in details below.

Table 1
Speed of the vehicle, rear wheel, motor and FVC

Speed (km h^{-1})	Rear wheel				Servo-motor			
	Speed (rpm)	Frequency (Hz)	FVC output voltage		Speed (rpm)	Frequency (Hz)	FVC output voltage	
			Theoretical	Test			Theoretical	Test
0	0	0	0	0	0	0	0	0
7.5	100	6.67	0.80	0.96	80	800	0.80	0.90
15	200	13.34	1.60	1.76	160	1600	1.60	1.70
30	400	26.67	3.20	3.22	320	3200	3.20	3.28
45	600	40.00	4.80	4.81	480	4800	4.80	4.87
60	800	53.34	6.40	6.40	640	6400	6.40	6.46
75	1000	66.67	8.00	8.00	800	8000	8.00	8.03
90	1200	80.00	9.60	9.60	960	9600	9.60	9.60

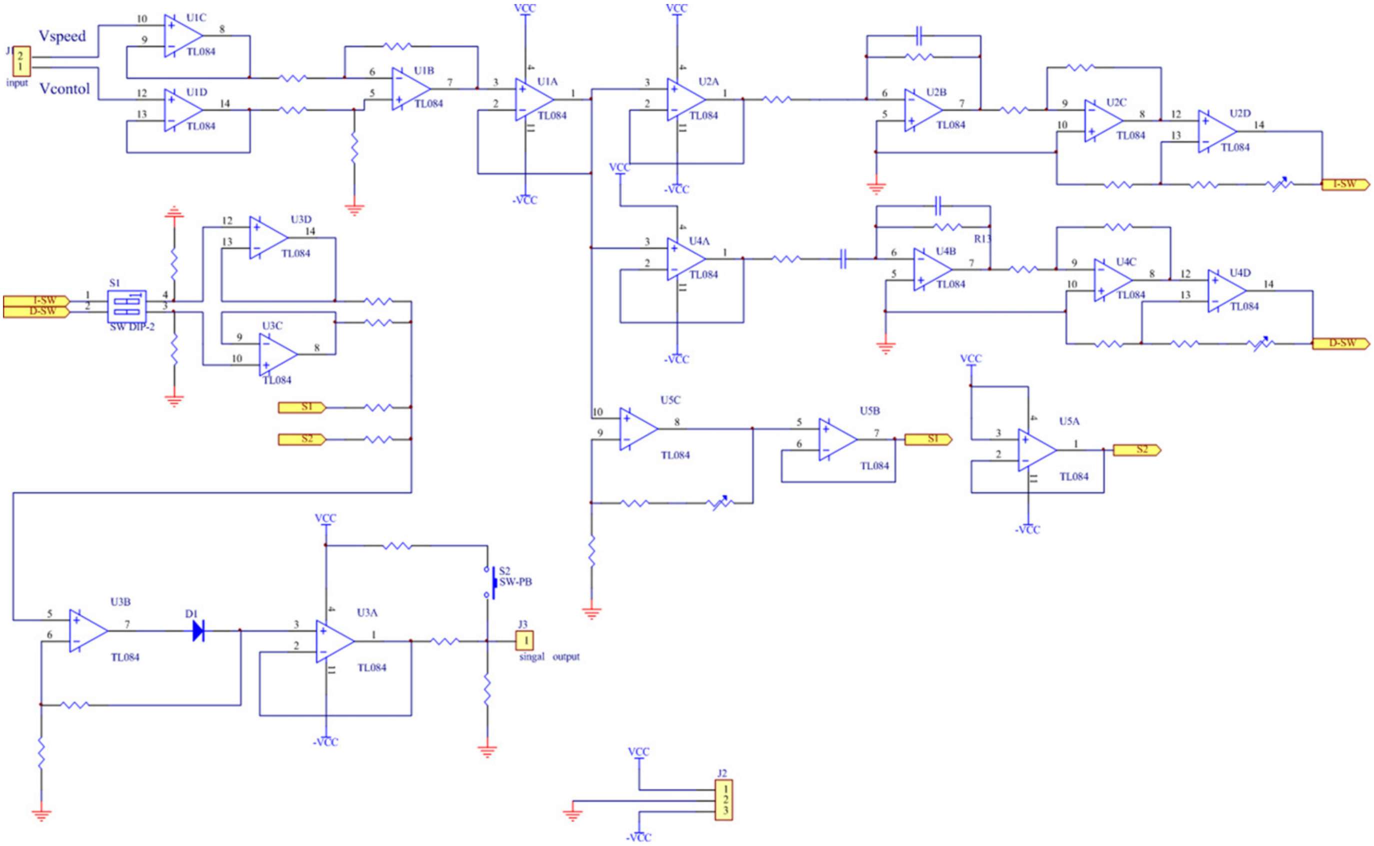

Fig. 4. PID speed tracking controller circuit.

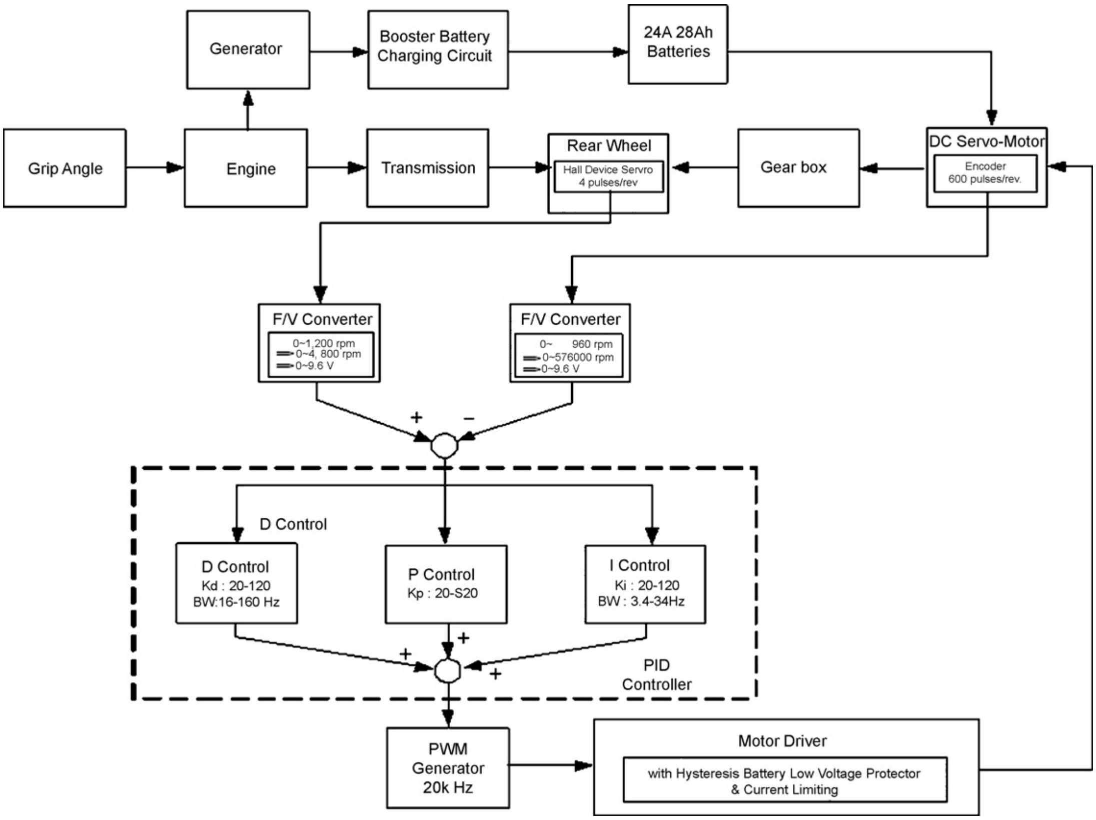

Fig. 5. System block diagram of hybrid electrical motorcycle and PID speed tracking controller.

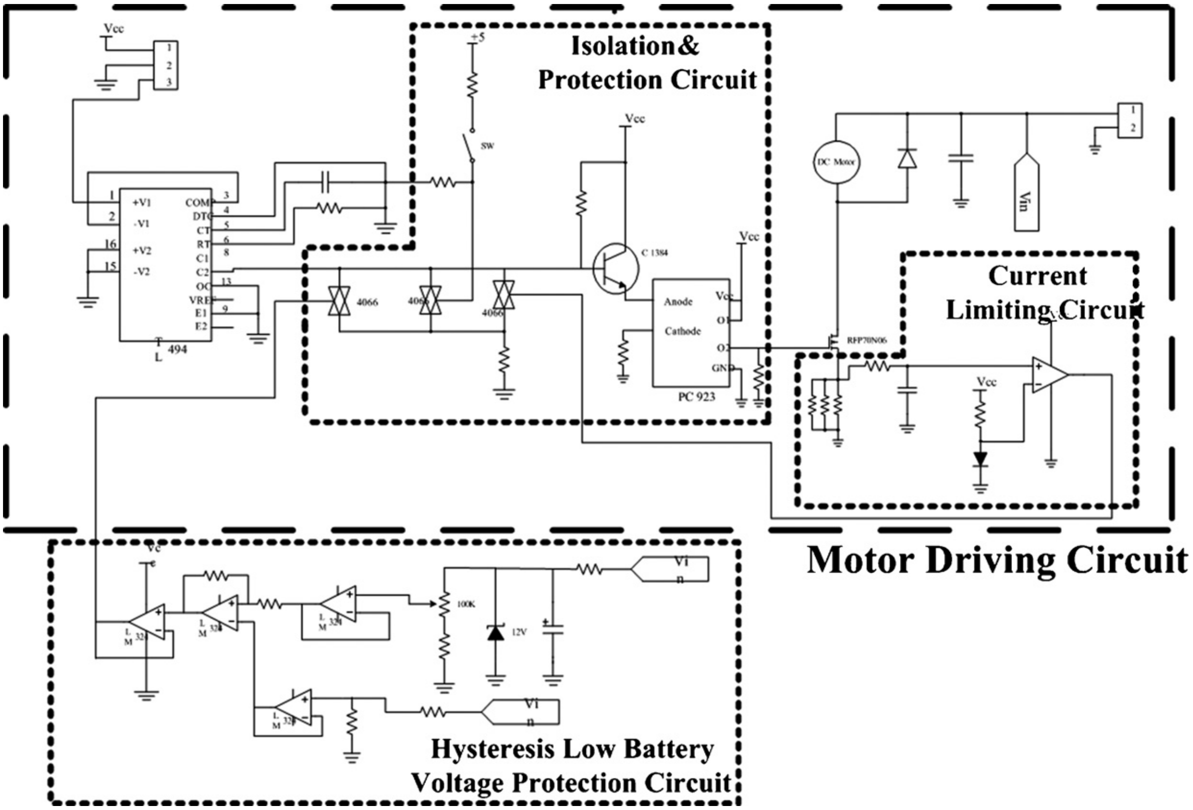

Fig. 6. Motor driving circuit and protection circuits.

4.1. *Electric motor driving circuit*

The electric motor driving circuit of this prototype adopts the TL494 PWM Control IC chip. The chip induces a 20 kHz pulse width modulation (PWM) signal. Through the PID, closed-loop feedback methodology, TL494 adjusts the PWM signal's duty cycle to control the motors rotation speed to match up that of the rear wheel's. Since the electric motor requires a strong current, one power metal oxide semiconductor field effect transistor (MOSFET), which has a maximum voltage of 60 V and a maximum current of 70 A, is utilized as the driving component [9,15]. The detailed circuit design of driving circuit is shown in Fig. 6.

4.2. *Isolation and current-limiting protection circuit*

Not only does the current-limiting protection circuit need to protect the engine and transmission from a power surge by the dc motor, but also needs to protect the electric motor by limiting the driving current. Elements of motorcycle could be prevented from malfunctioning or damage for unknown reasons by doing so. In addition, limiting the driving current can prevent the electric motor from providing too much torque instantly, thus causing bursting and discomfort to the rider and passenger during the low speed region or start-up. The instantaneous driving current is limited to 20 A. Furthermore, limiting the current will slow down battery dissipation.

Optical Coupler PC923 is used to separate large motor driving current circuits from control signal circuits. Therefore, optical coupler is utilized to block the PWM control signal from current overloading, low battery voltage and inhibiting the electric motor. The detailed design of both current-limiting protection and isolation circuits are shown in Fig. 6.

4.3. *Battery low voltage protection circuit*

Since we are using a rechargeable acid-lead battery, the electricity from the motorcycle's engine recharges the battery during the cruising. Thus, it results in energy recycling and eliminates the need for stationary recharging like traditional electric vehicles. This is a very important feature of this H.E.M. design. If the battery voltage is too low (18 V) for operation, the H.E.M. will automatically switch back to engine only and recharge the battery until the battery is charged to an operative condition (22 V). During the switching process, motorcycle rider does nothing and fells no jumpy-bumpy. The energy recycle is shown in the upper part of the system block diagram in Fig. 5.

The life expectancy of acid-lead battery will be shortened if battery is over-discharged. Preventing battery from over-discharging is accomplished by utilizing a hysteresis low battery voltage protection circuit (HLBVP) [13,14]. Fig. 7a illustrates the characteristic of this HLBVP circuit. As the battery voltage becomes lower than a preset low threshold, $V_{LT} = 18$ V, causing COMS switch IC 4066 to activate and stop the PC923 Optical Coupler. Battery stops supplying electricity to the motor until the battery is sufficiently recharged with electricity from boost converter recharging circuit. When battery terminal voltage rises up above a preset high threshold, $V_{UT} = 22$ V, battery is back to line to activate the electric motor. Fig. 7b is an oscilloscope hardcopy

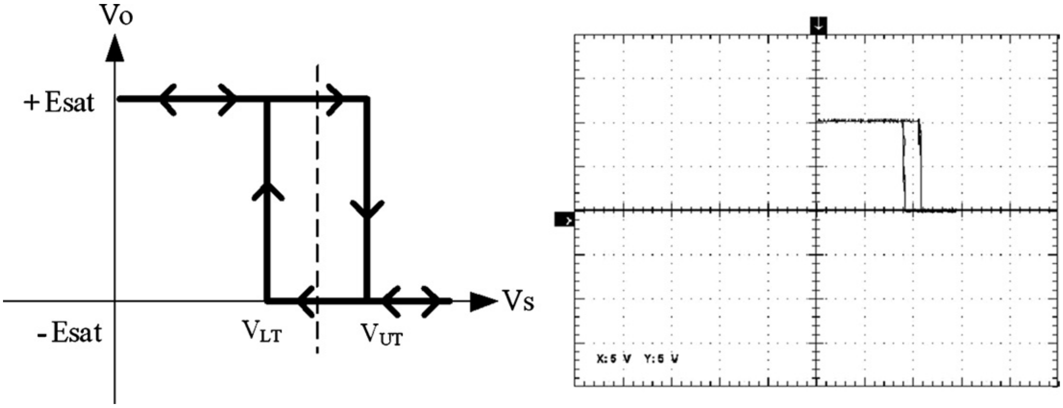

Fig. 7. (a) Characteristic of HLBVP. (b) Oscilloscope hardcopy.

that illustrates the nature of the HLBVP circuit. Fig. 6 shows the detailed circuit design of the HLBVP circuit.

4.4. Boost converter battery charging circuit

Since the hybrid electric motorbike uses two 12 V maintain-free, acid-lead, batteries in serial as the source of electricity and the generator of the motorcycle can only provide 12 V, there is a need to design a converter to boost the voltage in order to recharge the 24 V batteries.

The battery charging circuit adopts a closed-loop voltage booster converter to boost the dc 12 V from the generator into 30 V [15]. The boosted voltage is then sent to the battery for recharging. The battery charging current is limited to 4 A. Fig. 8 shows the circuit diagram of the battery charging circuit.

5. Test results

All of the circuits are tested before assembling the system. Test results such as limiting current values, FVC, HLBVP, etc. are given in related paragraphs. After we put all parts together, we run the most important test of this project: speed tracking control test. This is the keynote technology of this hybrid vehicle. Closed-loop test without load, the tracking control performs well without any significant delay and steady-state error for both 0–10 V (0–90 km), 0.154 Hz ($T = 6.5$ s), swing triangle signal. We consider this as the limit of this tracking system. It is equivalent to accelerate a motorcycle from 0 to 90 km in 3.3 s. This is quite impossible to happen for a 50 or 100 cc motorcycle. Closed-loop test with rider (65–70 kg) as load, the tracking control performs well without any significant delay and steady-state error for both 0–4 V (0–40 km), 0.1 Hz ($T = 10$ s), swing triangle signal. Fig. 9 shows the hardcopy of the tracking control test. Left upper part of Fig. 9 is the given triangle signal and left lower part of Fig. 9 is the tracking response from motor encoder. Right half part of Fig. 9 shows that if we align given signal and the response, they match up perfectly with each other. This confirms that the speed tracking controller system is working effectively.

In road trip experiments, three riders took turns to run road trip tests for about 3 h in the afternoon, three times. The H.E.M.

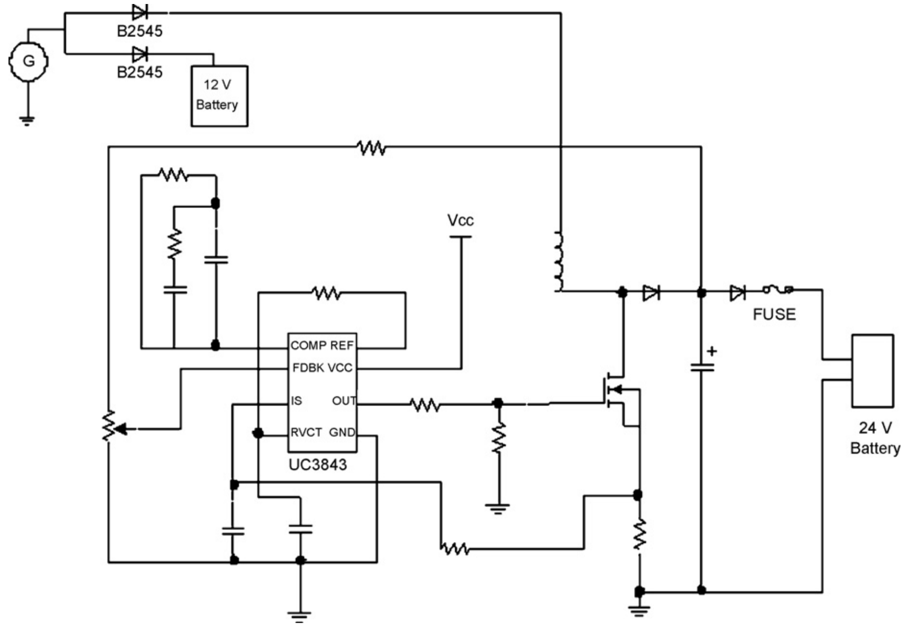

Fig. 8. Booster and battery charging circuit.

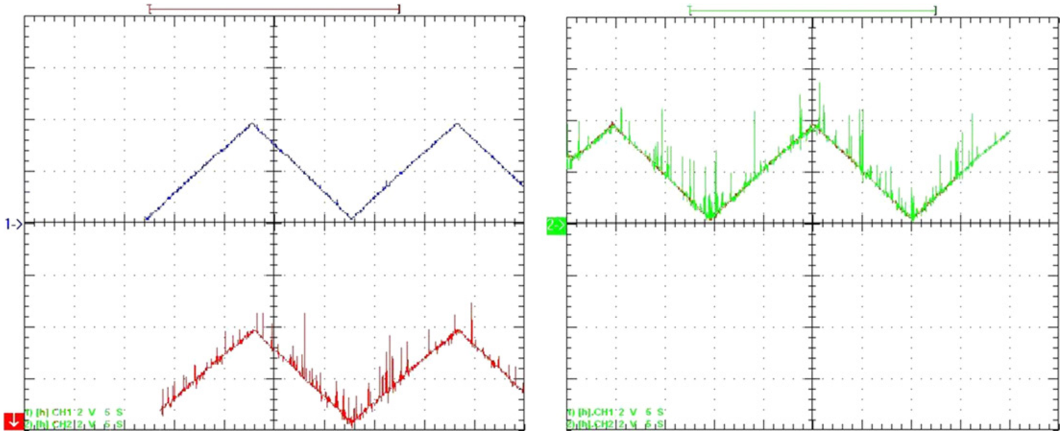

Fig. 9. Speed tracking controller test hardcopies.

Fig. 10. Pictures of H.E.M. prototype.

was fueled in 1 l gasoline and run until the gasoline dried out. The average gasoline-mileage for engine only operation is 34 km l^{-1} and the average mileage for engine–motor composite is 48 km l^{-1}. If the speed of H.E.M. is in the range of 40–50 km h^{-1}, the gasoline mileage can go up to 54 km l^{-1}. We think in this speed range the H.E.M. can achieve the best performance. The overall efficiency is about 35% lift.

6. Conclusions

This paper reports a concept and an implement of a hybrid electrical motorcycle as shown in Fig. 10. We have accomplished following objectives: (A) This prototype features a single-shaft, bi-axle parallel transmission structure by attaching a servo-motor and gearbox to the rear wheel. A closed-loop, speed control tracking controller is utilized to composite engine and motor. Tests and Fig. 9 confirm that this structure is working well. (B) This prototype H.E.M. runs smoothly and safely. If the battery voltage is too low (18 V) for operation, the H.E.M. will automatically switch back to engine only and recharge the battery until the battery is charged to an operative condition (22 V). This is energy recycling and eliminates the need for stationary recharging like traditional electric vehicles. During the switching process, motorcycle rider does nothing and fells no jumpy-bumpy. (C) On road tests, the H.E.M. prototype achieves an average gasoline mileage rate of 46 km l^{-1} compared to the original 34 km l^{-1}. The overall efficiency is about 35% lift. Engine system of this H.E.M. is not modified at all, the emission is the same as the 50 cc Tact designed. However, for the same range of trip, less fuel consumption means less air pollution. (D) The noise of this revised H.E.M. mainly comes from the 50 cc engine. Noise from motor can hardly be heard. (E) The overall cost for adding servo-motor, batteries, and control unit sums up US$ 300. For average, 50 cc motorcycle costs US$ 1100 and 100 cc motorcycle costs US$ 1500. There is still a price difference, plus hybrid motorcycle can save gasoline and reduce air pollution for long-term interest. The same design principle can also be applied to modify a 125 cc scooter into the performance of 250 cc range which is the maximum engine allowed for non-sporting group in Taiwan.

For further research, we expect to build a high performance hybrid electrical motorcycle by redesigning a driven-by-wire structure and revising the controller circuits into artificial-intelligent features to further improve overall fuel efficiency [8,10,11].

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