A Power Flow Control Strategy for Optimal Fuel Efficiency of a Variable Speed Engine-Generator based Series Hybrid Electric Vehicle

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***Abstract*- This paper presents a new power flow control strategy for a variable speed engine-generator based series hybrid electric vehicle. The specific fuel consumption map of the internal combustion engine (ICE) has been obtained by off-line experiments to achieve optimal fuel efficiency. The proposed power flow controller makes it possible that the ICE operates at its optimal fuel efficiency points without degrading desired dynamic performance. Experimental results of the actual vehicle test as well as the laboratory based load test are shown to verify the proposed power flow control strategy.**

Key words: variable speed engine-generator, specific fuel consumption map, series hybrid vehicle

I. INTRODUCTION

Hybrid electric vehicles (HEVs) have been received increased attention because of their inherent advantages such as improving fuel efficiency, reducing unwanted emission and having potential to enhance dynamic performance [1-2]. In terms of control issues however, it is not easy to get optimal fuel efficiency with maintaining the desired dynamic performance, because optimal fuel efficiency of an ICE varies according to both the load power and the engine speed [3-6]. In addition, it is not easy to get an accurate specific fuel consumption (SFC) map of the target engine either.

In this paper, a series HEV utilizing a gasoline engine as a main energy source and a battery module as an energy storage element is discussed. Various researches for series HEVs have tried to get optimal fuel efficiency without degrading the dynamic performance. The generator is turned ON and OFF according to the battery's state of charge (SOC) [3]. This method can improve fuel efficiency, but the large charging/discharging frequency of a battery can significantly degrade its lifetime. A fuzzy logic control strategy is developed in [7]. The engine can be steadily working in its high efficiency area in [7], but the implementation of the fuzzy logic is not easy and case sensitive. A dynamic programming for optimal fuel efficiency is introduced in [8], but it needs accurate parameters of the whole system and results in heavy computational burden.

This paper proposes a new power flow control method to get not only optimal fuel efficiency but also desired dynamic performance. Moreover, the proposed power flow control method can increase the lifetime of the battery through minimizing its charge and discharge cycles. The engine's SFC map obtained by off-line experiments has been applied to the proposed power flow control method. Speed of the engine is directly controlled according to the load power via controlling its angle of the throttle valve, and the speed reference is given from the SFC map. Also, the proposed power flow control method presents an appropriate power reference generation strategy for the battery module to achieve optimal fuel efficiency and to get desired dynamic performance at the same time. A prototype series HEV has been constructed and several tests have been made to verify the validity of proposed power flow control method.

II. LOAD REQUIREMENT OF THE TARGET VEHICLE

A vehicle typically demands broad dynamic power ranges. Thus, a power system of a vehicle should be designed considering the worst case load requirement. Here, the worst case for the target prototype vehicle is that the vehicle is accelerated from standstill to the maximum speed within the given acceleration time according to the whole operating conditions of the target vehicle. This worst case load power requirement can be estimated by referring to both the core mechanical parameters of the prototype vehicle and the

TABLE I. MECHANICAL PARAMETERS OF THE VEHICLE

Parameters	Symbol	Value	Unit
Mass of Vehicle	m	1500	kg
Radius of Wheel	r	260	mm
Mass Factor	δ	1.05	None
Rolling Resistance	μ_r	0.02	None
Density of air	ρ	1.145	Kg/m^3
Drag Coefficient	C_d	1.0	Ns^2/m^4
Cross Section	A	0.75	m^2
Max Vehicle Speed	v	50	km/h
Acceleration time	t	15	s

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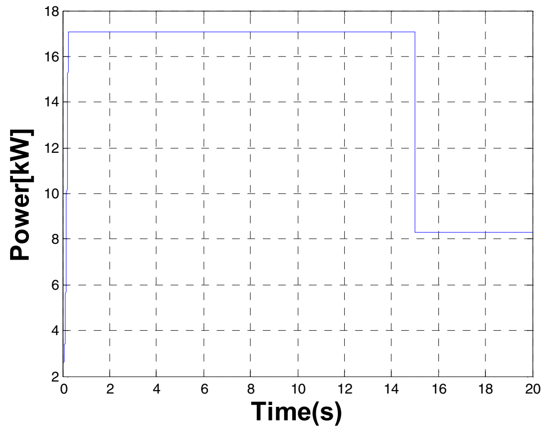


Figure 1. Maximum load requirement of the vehicle

equations of motion that are given in (1) and (2). The core mechanical parameters of the prototype vehicle are listed on the Table I. Fig. 1 shows the calculated load profile of the worst case. Therefore, the power system should be designed to meet this worst case load profile.

$$F = \mu_r mg + 0.5\rho C_d A v^2 + \delta ma \qquad (1)$$

$$P = F \cdot v \qquad (2)$$

where, F : $force\,[N]$, P : $power\,[W]$, v : $velocity\,[m/s]$

III. Power System Configuration

The overall power system configuration for the prototype vehicle is shown in Fig. 2. The vehicle has 6 wheels and 6 arms where each part is driven by an electric machine. Thus, the dc-bus voltage should be regulated well at any time for the system's stable and reliable operation. Even though, either the engine-generator (En-Gen) or the battery can regulate this dc-bus voltage, it is regulated by the En-Gen interfaced with a three-phase PWM boost rectifier considering lifetime of the battery and efficiency of the power system. Then, desired power can be drawn regardless of the engine speed. This

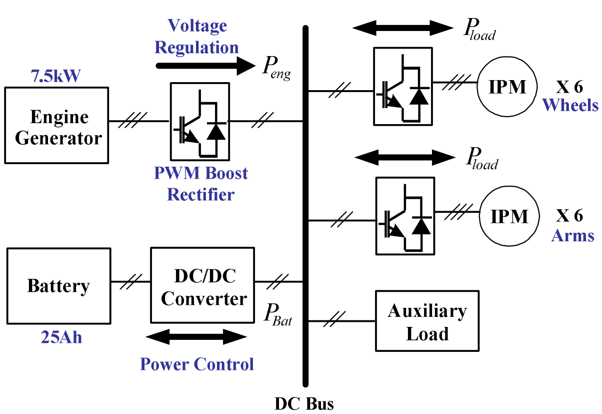


Figure 2. Configuration of power system of the vehicle under test

TABLE II. Power System Design Parameters

Parameters	Values
Engine rated power	9.39[kW]
Engine idle speed	1600[r/min]
Engine(generator) rated speed	3600[r/min]
Generator type	Permanent magnet synchronous machine
Generator rated power	7.5[kW]
Generator back EMF constant	0.057@25℃ [Vs/rad]
Generator synchronous inductance	1.2[mH]
Battery rated charge capacity	25[Ah]
Battery nominal voltage	245[V]

makes it possible that the engine operating speed can freely move to another point which yields better fuel efficiency. Also, the starting of the engine is possible through a motoring operation of the generator. The designed parameters for the En-Gen are listed in Table II. Battery is still needed to provide supplementary power for rapid load variation as well as to absorb regenerative braking power. A dc/dc converter is utilized to control its power bi-directionally.
The designed parameters for the battery are also listed in Table II.

IV. Specific Fuel Consumption(SFC) Map of the Engine

In order for the engine to be operated at its optimal efficiency points for the whole load conditions, its optimal efficiency points should be obtained preliminarily. However, they are not generally given by the engine manufacturers. Thus, the SFC map of the target engine has been obtained by off-line experiments. Fig. 3 shows the experimental setup for yielding the SFC map. At first, fuel consumption, i.e., mass difference under the constant load condition during a time unit has been measured by a precision scale shown in Fig. 3. Then, the same measurements have been repeated for different engine speeds from the idle to its maximum one. This

Figure 3. Experimental setup for yielding the SFC map

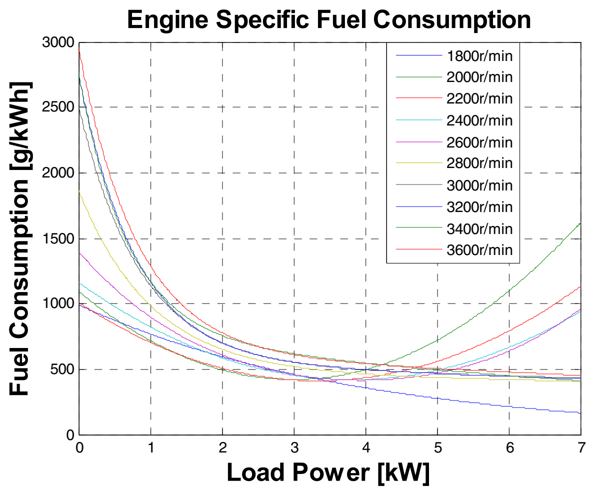


Figure 4. SFC map

procedure is repeated again for the different load conditions from the no load to the rated load. The experimental data for the whole operating points has been processed by the curve fitting tool in MATLAB software as shown in Fig. 4. Note that, each vertex of the curves in Fig. 4 is the optimal efficiency point with respect to given load conditions. Roughly, the En-Gen should operate at low speed for light load, and should operate at high speed for heavy load.

V. Control of Each Component of the Power System

In this section, basic control method for each component of the power system shown in Fig. 2 is described.

A. *Engine Speed Control*

In terms of speed of the engine, it should be able to vary according to the load conditions in order to match the operating point to the optimal one. Thus, the engine speed controller has been implemented by directly controlling its throttle valve. Fig. 5 shows an experimental result of the engine speed control response. The settling time of the step response is about 2[s].

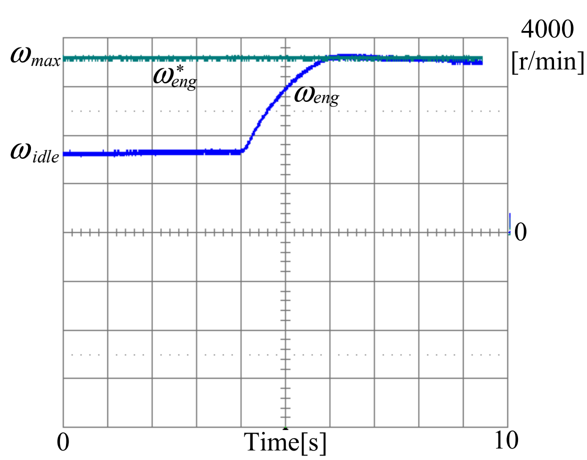


Figure 5. Engine speed control response

B. *DC-bus voltage regulation*

The dc-bus represented in Fig. 2 plays a very important role to decouple instantaneous power difference between the two power sources and the loads. Hence, its voltage should be regulated within the tolerance range even under the worst case load condition with variable back EMF of the En-Gen. If the battery interfaced with a DC/DC converter regulates the dc-bus voltage, it may be much easier than the En-Gen interfaced with a PWM rectifier does. In that case however, the lifetime of the battery would be shortened much faster due to frequent operations of the battery. Therefore, the dc-bus voltage is regulated by the En-Gen interfaced with a typical current controlled PWM rectifier [9,10]. Its input power can be described by (3).

$$P_{in} = \frac{3}{2} \cdot (E_d i^r_{ds} + E_q i^r_{qs}) \qquad (3)$$

where E_{dq} : back EMF, i^r_{dqs} : PWM rectifier current. Then, the input power can be controlled by both the back EMF voltage of En-Gen and the PWM rectifier current.

C. *Battery power control*

Supplementary power should be able to be drawn from the battery or regenerative power should be able to be stored to the battery during the vehicle's operation. This can easily be done by controlling the battery current with the bi-directional dc/dc converter shown in Fig. 2. The current reference is given by (4).

$$i^*_{bat} = \frac{P^*_{bat}}{V_{bat}} \qquad (4)$$

where i^*_{bat} : battery current reference, P^*_{bat} : battery power reference, V_{bat} : battery terminal voltage.

VI. Power Flow Control

The power system has two power sources. Thus, the required load power should be appropriately shared or supplied by these two sources to get desired dynamic performance. The basic scheme of the proposed power flow control method is that the dc-bus voltage is regulated by the three-phase PWM rectifier interfaced with the variable speed En-Gen, and the battery assists power for rapid load variation. The main objectives of the proposed power flow control method are as follows.

1) Optimal fuel efficiency operation
2) Maximum engine power utilization
3) Stable dc-bus voltage regulation(within ±15% of set point)

As described above, to achieve the optimal fuel efficiency operation, speed of the engine is controlled and its reference is obtained from the SFC map of the engine. To maximize engine power utilization, the engine supplies its power as large as possible not only at the transient state, but also at the steady state. This makes it possible that the lifetime of the battery can be increased as well as efficiency of the power system can be increased because the battery energy is originally from the engine. The 3rd objective is essential for the stable and reliable operation of the whole power system.

A. *Power flow control method*

Since the vehicle has two power sources, it is a key issue that how the two power sources share load power appropriately. For the worst case load profile shown in Fig. 1, the engine is operating at very low speed at standstill. As the load power requirement rapidly increases up to its maximum, the speed reference of the engine increases rapidly because its optimal operating point is somewhere in high speed region. However, the dynamic response of the engine speed control shown in Fig. 5 is too slow to meet the load variation rate which is shorter than 0.5[s]. Thus, only engine interfaced with the PWM rectifier may not be able to regulate the dc-bus voltage within the tolerance range due to current limitation of the PWM rectifier. Hence, the battery should provide supplementary power in this case. Three battery power reference generation algorithms are introduced in this section.

1) Battery power reference generation algorithm I

The best way to maximize the engine power utilization is shown in Fig. 6. The battery provides power only when the load power exceeds the engine's rated power. This can maximize the engine power utilization, but the dc-bus voltage cannot be regulated within the tolerance range because of the slow dynamic response of the engine speed control. Fig. 7 is its simulation result. The load variation rate is the same as the worst case load profile, but the maximum power is less than the engine's rated power. In Fig. 7, the dc-bus voltage is dropped down out of the tolerance range since the engine power (Peng) cannot meet the load power (Pload) during the rapid load variation region. The battery even starts to discharge (Pbat) when the dc-bus voltage is less than the battery voltage. Consequently, even though this algorithm can maximize the engine power utilization, this cannot be applied to the load variation which is faster than the dynamic response of the engine speed control.

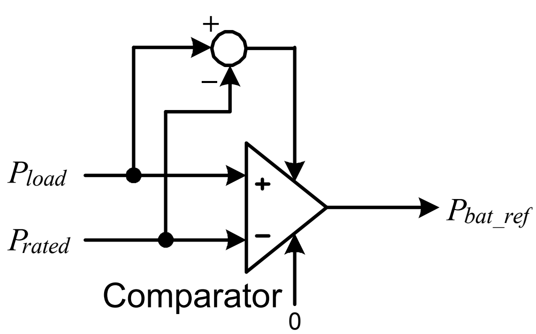


Figure 6. Battery power reference generation algorithm I

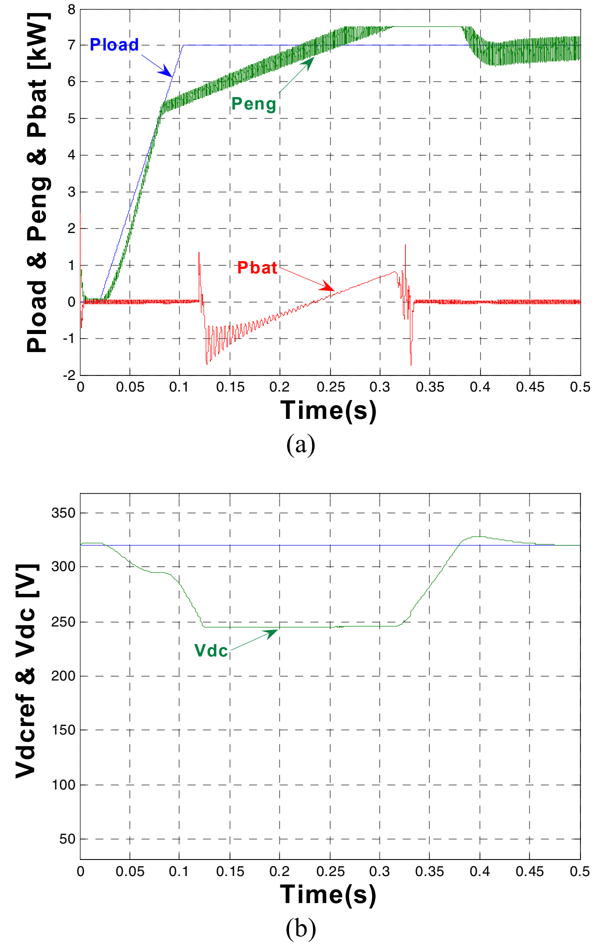


Figure 7. Battery power reference generation algorithm I (simulation result)

2) Battery power reference generation algorithm II

Fig. 8 shows another load sharing algorithm using battery's fast dynamic response. The power reference of the battery is from the difference between the load power and the En-Gen power. Fig. 9 shows its simulation result. The dc-bus voltage is regulated well, but the engine is almost rest state. This is because of the faster dynamic response of the battery power controller than that of the PWM rectifier. Therefore, with this algorithm, the dc-bus voltage can be regulated within the tolerance range easily. However, in terms of the engine power utilization, this is not preferable.

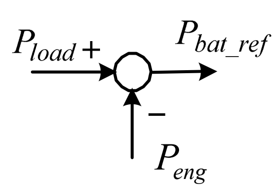
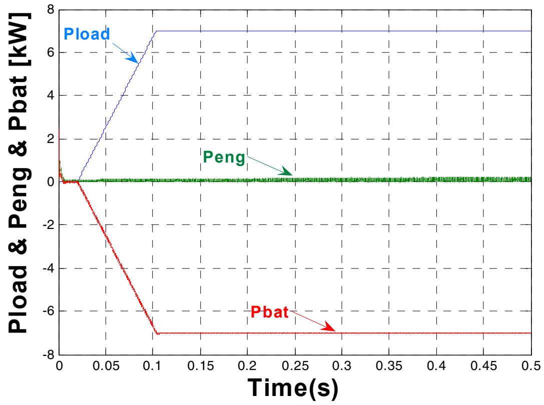
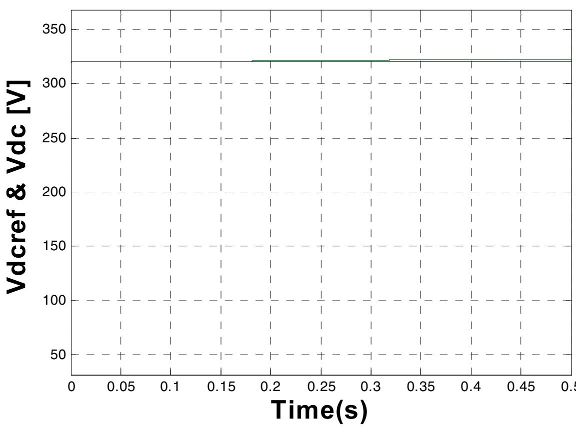


Figure 8. Battery power reference generation algorithm II



(a)



(b)

Figure 9. Battery power reference generation algorithm II(simulation result)

3) Battery power reference generation algorithm III (proposed method)

Fig. 10 shows the block diagram of the proposed battery power reference generation method. The engine speed reference is given from the SFC map obtained by off-line experiments using the load power information. Then, it is controlled by the speed control system mentioned above. The optimal power reference of the battery can be calculated using inverse function of the SFC map. Above all, the optimal input power value from the engine at the measured actual speed (ω_{eng}) point can be obtained from the inverse SFC map considering current limitation of the PWM rectifier. Then, the power reference of the battery which makes it possible for the engine to operate its optimal points without degrading the dynamic performance can be expressed by (5).

$$P_{bat\_ref} = -(P_{load} - P_{eng\_opt}) \quad (5)$$

where P_{bat_ref} : battery power reference, P_{load} :load power, P_{eng_opt} : optimal input power from the engine via the PWM rectifier at the measured speed.

Fig. 11 shows the simulation result for the proposed battery power reference generation method. As the load power increases rapidly, the engine power slowly increases with respect to its speed increasing rate. At the same time, the battery provides supplementary power while the engine power increases. After the engine power meets the load power, the battery does not provide any power. This is different with the battery power reference generation algorithm II. As a consequence, with the proposed battery power reference generation method, not only the dc-bus voltage is regulated within the tolerance range, but also the engine power is utilized maximally.

On the other hand, when the load rapidly decreases, the speed reference is used instead of the actual speed when obtaining the optimal input power value from the engine. This is also because of the slow dynamic response of the engine speed control. In this case, if the actual speed is used when calculating its optimal input power from the engine, unwanted battery charging may occur during the rapid load decrease.

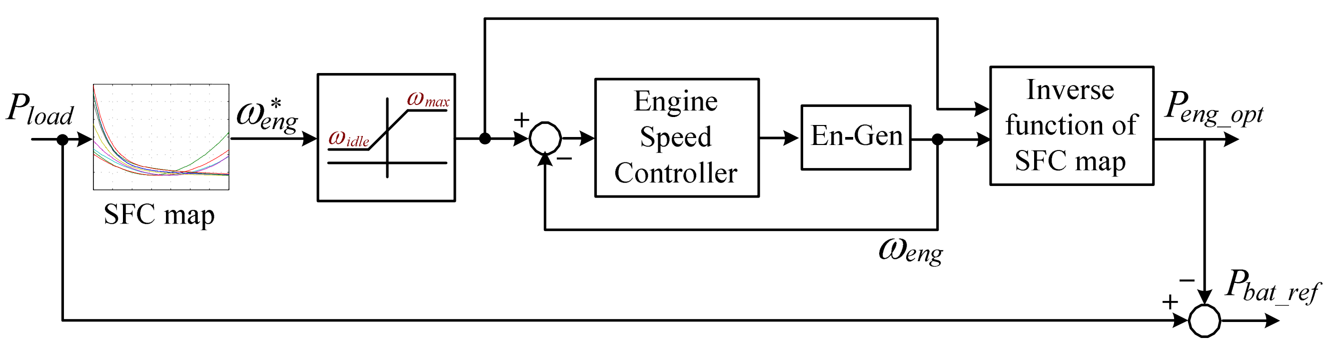
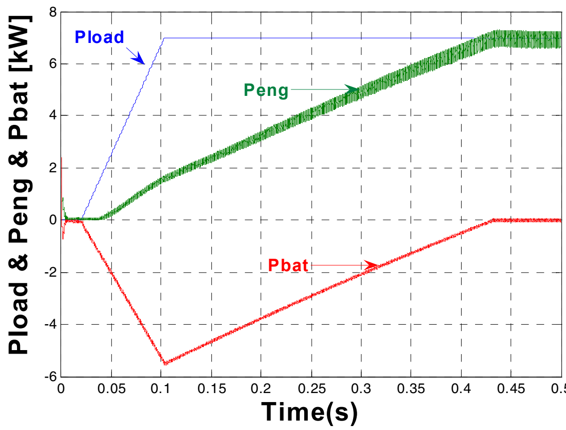
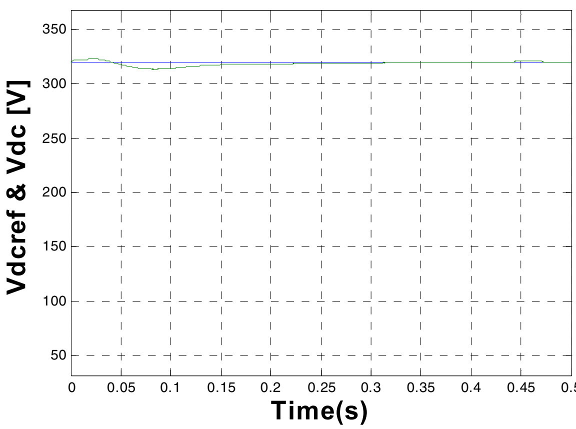


Figure 10. Proposed power flow control method



(a)



(b)

Figure 11. Proposed battery power reference generation algorithm (simulation result)

B. Regenerative braking

The proposed power flow control algorithm can be applied to the regenerative braking instant without modification. However, the optimal input power calculation using the inverse function of the SFC map during regeneration is always zero because the engine cannot absorb regeneration energy. Thus, the battery power reference is always the same as the load power. Furthermore, the battery charging capability is much worse than the discharging capability. Therefore, only the rated power of the battery can be absorbed to the battery, and then the rest of power should be dissipated on a braking resistor and the auxiliary load.

VII. EXPERIMENTAL RESULTS

To verify the validity of the proposed power flow control method, several load conditions including the estimated worst case load requirement shown in Fig. 1 have been simulated with a dc-ac converter interfaced to the 3-phase grid as shown in Fig. 12. Fig. 13 shows the experimental result for a load

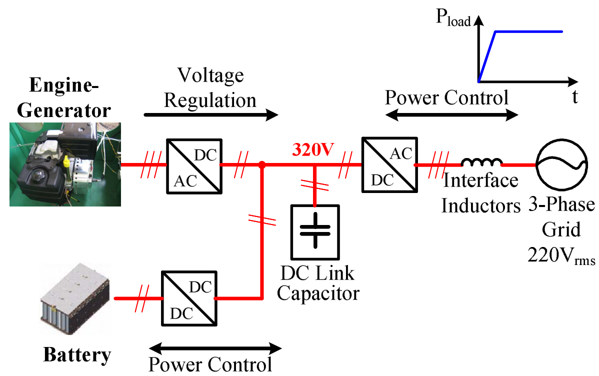
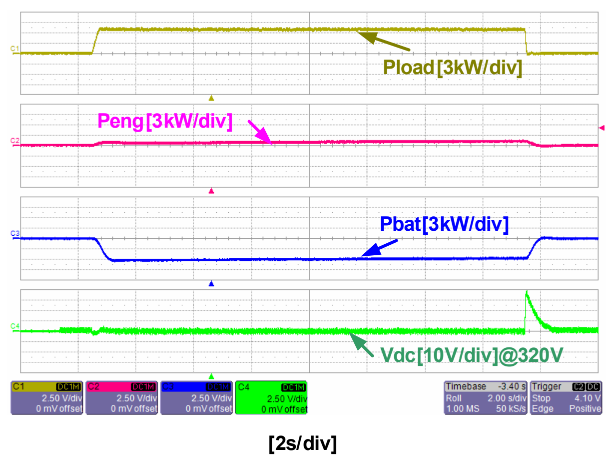
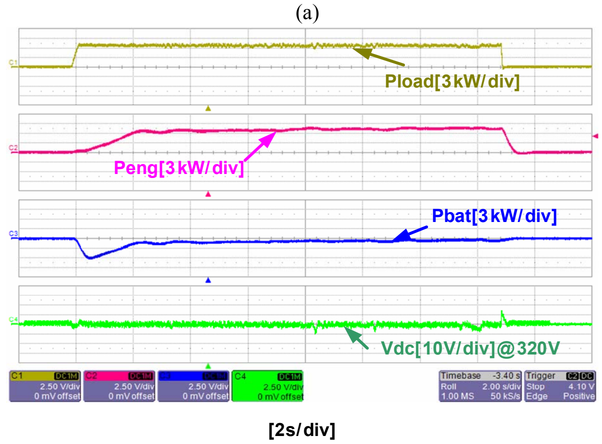


Figure 12. Experimental setup for load test

which can be covered by only the En-Gen. Fig. 13(a) shows the experimental result for the battery power reference generation algorithm II. The load power is almost covered by the battery because of its faster dynamic response than that of the PWM rectifier with the engine. Thus, the engine power utilization is very poor. Also, at the rapid load decrease, the dc-bus voltage exceeds its tolerance range. Fig. 13(b) shows the experimental result of the proposed power flow control



(a)



(b)

Figure 13. Proposed battery power reference generation algorithm (experimental result): (a) algorithm II; (b) proposed power flow algorithm.

method. As the load increases, the speed of the engine increases up to its optimal efficiency point obtained from the SFC map. The engine power is increased with the same rate of its real speed increase. Thus, the battery supplies supplementary power during only this period, and it diminishes to zero as the power from the engine increases. Hence, the dc-link voltage is well regulated within the tolerance range with the engine operating at its optimal efficiency point as well as the engine power is utilized maximally. For the case of the battery power reference generation algorithm I, the dc-bus voltage cannot be stable. Thus, the result is not shown here.

Fig. 14 shows the experimental result of the worst case load condition. The engine power is increased up to its rated value as its speed is increased. The battery supplies the difference power between the load power and the engine power during not only the transient state but also the steady state because the load power exceeds the rated power of the engine in this case. Thanks to the proposed power flow control method, the engine outputs its rated power at its optimal efficiency operating point without degrading the desired dynamic performance.

Fig. 15 shows the constructed prototype 6-wheeled-unmanned vehicle. The autonomous drive test result is shown in Fig. 16. As the load power in Fig. 15 varies rapidly and frequently, the engine tries to cover the load power as much as it can at its optimal operating points while the battery supplies supplementary power at any moment. As a consequence, the engine and the battery appropriately share the load power to achieve optimal fuel efficiency with maintaining the dc-link voltage within the tolerance range during the whole operation.

VIII. Conclusion

This paper has proposed a novel power flow control method to achieve optimal fuel efficiency of the ICE. The power system has been integrated that is appropriate for a variable speed En-Gen based series hybrid electric vehicle. The engine operating speed is varied according to the load power through directly controlling its throttle valve. A three-phase PWM rectifier regulates the dc-link voltage under the variable speed En-Gen. Also, the battery compensates insufficient power during the transient to get desired dynamic performance keeping up the optimal fuel efficiency. Experimental results based on the load simulation and on the actual vehicle tests reveal the superiority of the proposed power flow control method.

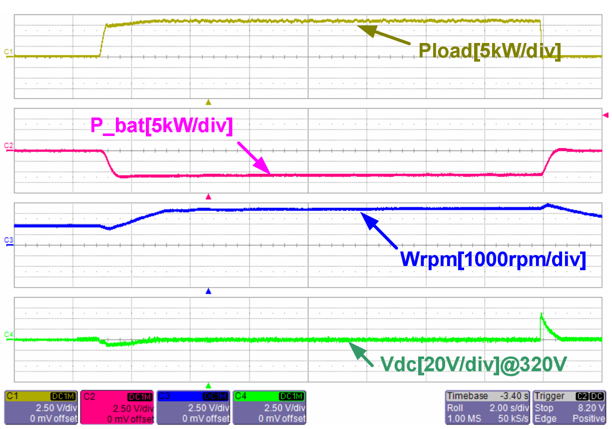


Figure 14. Experimental result for the proposed battery power flow control method (worst case load).

Figure 15. The prototype vehicle

References

[1] Z. Wang, W. Li and Y. Xu, “A novel power control strategy of series hybrid electric vehicle,” IEEE Conf. on Inteligent Robotics and Systems, San Diego, CA, USA, pp. 96-102, Nov. 2007.
[2] D. Prokhorov, “Toyota Prius HEV Neurocontrol,” IEEE Internaltional Joint Conf. on Neural Networks, Orlando, Florida, USA, Aug. 2007..
[3] S. Barsali, C. Miulli and A. Possenti, “A control strategy to minimize fuel consumption of series hybrid electric vehicles,” IEEE Trans. on Energy Conversion, vol 19, no. 1,pp. 187-195, March 2004.
[4] P. Stewart and R. Cowley, “Generator voltage stabilization for the series-hybrid vehicle,” IEEE Conf. on Industrial Electronics Society (IECON), Taiwan, pp274-279, Nov. 2007.
[5] M. Talib, A. Atabi and T. F. Yusaf, “Experimental investigation of a single cylinder diesel engine as a hybrid power unit for a series hybrid electric vehicle,” IEEE student Conf. on Research and Development, pp. 261-264, 2002..
[6] S. Barsali, M. Ceraolo and A. Possenti, “Techniques to control the electricity generation in a series hybrid electric vehicle,” IEEE Trans. on Energy Conversion, vol 17, no. 2,pp. 260-266, June 2002.
[7] X. Liu, Y. Xu and J. Duan, “Power split control strategy for a series hybrid electric vehicle using fuzzy logic,” IEEE Conf. on Automation and Logistics, China, pp. 481-486, Sep. 2008.
[8] C. Lin, H. Peng, J. W. Grizzle and J. Kang, “Power management strategy for a parallel hybrid electric truck,” IEEE Trans. on Control System Technology, vol 11, no. 6,pp. 839-849, Nov. 2003.
[9] N. R. Zargari and G. Joos, “Performance inverstigation of a current-controlled voltage-regulated PWM rectifier in rotating and stationary frames,” IEEE Trans. on Industrial Electronics, vol 42, no. 4, pp. 396-401, Aug. 1995.
[10] B. T. OOI, J. C. Salmon, J. W. Dixon and A. B. Kulkarni, “A three-phase controlled-current PWM converter with leading power factor,” IEEE Trans. on Industry Applications, vol IA-23, no. 1, pp. 78-84, Jan./Feb. 1987.

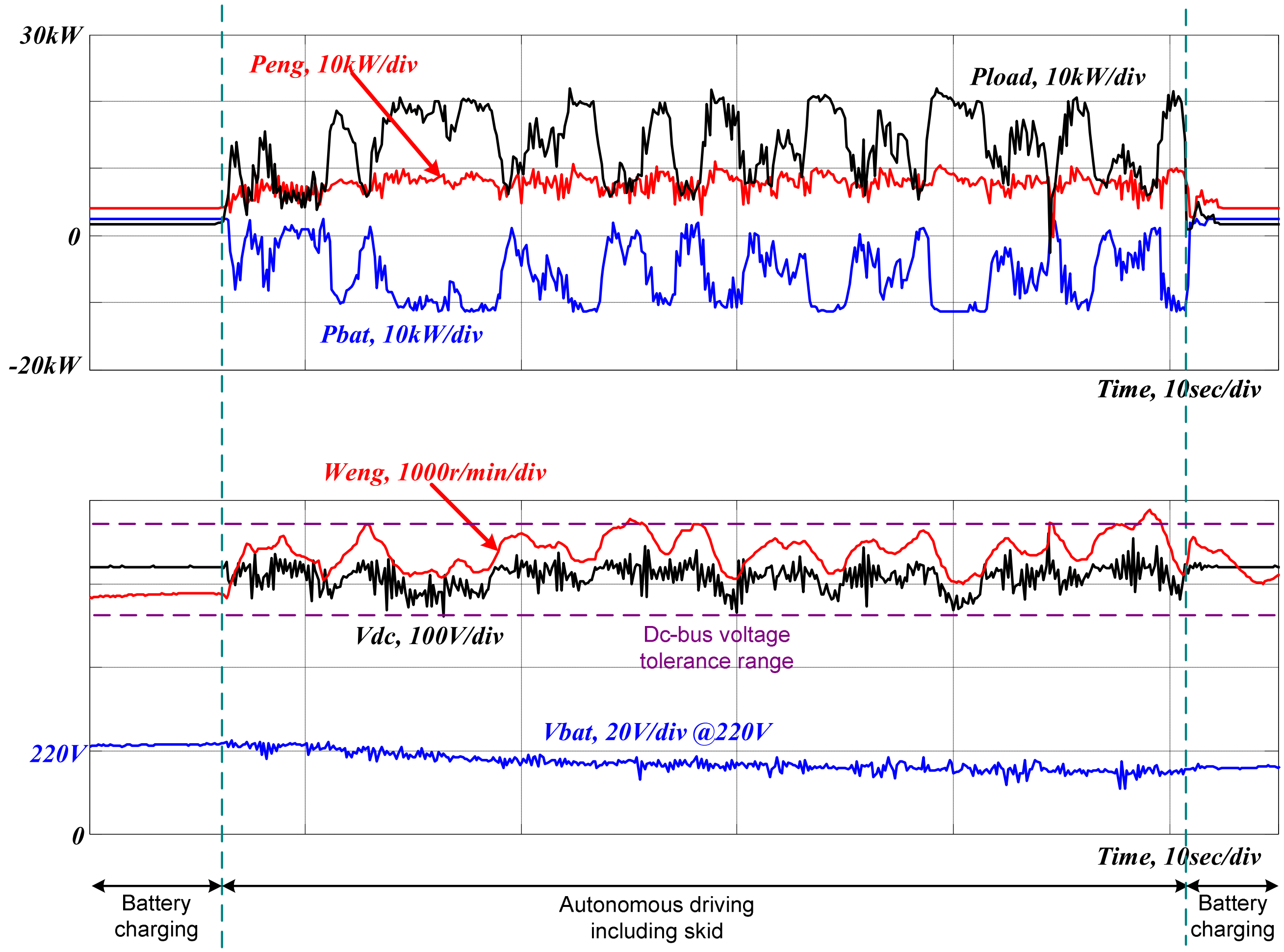


Figure 16. Autonomous drive test result