EVS25

Shenzhen, China, Nov 5-9, 2010

An Efficient Energy Regeneration System for Diesel Engines

Ying HUANG[1], Fuyuan YANG[1], Minggao OUYANG[1], Lin CHEN[1], Guojing GAO[1], Yongsheng He[2]

[1] Department of Automotive Engineering, Tsinghua University, 100084, Beijing China, huang-y03@mails.tsinghua.edu.cn

[2]General Motors Global Research and Development, Warren, Michigan 48309, USA

Abstract

In order to further improve the fuel economy of vehicles, an efficient energy regeneration system for diesel engines is designed and constructed. An additional automatic clutch is added between the engine and the motor in a conventional ISG (Integrated Starter and Generator) system. During regenerative braking, the clutch can be disengaged and the engine braking is avoided. Control strategy is redesigned to determine the braking torque distribution and coordinate all the components. The generated electricity is increased and the fuel economy is improved. An experiment is designed to test the performance of the new energy regeneration system, and the result shows that during a regenerative braking test over 112% more electric energy can be regenerated without correcting for the fuel consumption at idle. Theoretical analysis also shows that the regenerated energy would be increased at least 63.1% for a single regenerative braking event with the new system, if we correct for the fuel consumption at idle.

Keywords: ISG, Regenerative Braking, Automatic Clutch, Control Strategy

1 Introduction

Fuel economy and environmental friendliness are becoming the major topics in vehicle technology nowadays. Research shows, almost the half of energy is consumed by braking in the EPA75 urban driving cycle [1]. Therefore, braking energy regeneration system has a great potential to enhance the energy efficiency and improve the fuel economy.

Energy regeneration technology is mainly used in hybrid propulsion systems. ISG (Integrated Starter and Generator) is a popular solution to achieve

hybrid power and energy regeneration due to its simple and low cost configuration.
Dr. Tian [2] has carried out some relevant research on regenerative braking technology in diesel engine ISG system. In the conventional ISG system wherein the rotor is directly connected to the engine crankshaft, engine braking cannot be avoided during braking process. This consumes a significant part of the braking energy and reduces energy regeneration efficiency in the hybrid power system.
To solve the problem, a new energy regeneration system configuration is constructed in this paper. Control strategy is investigated. Experiments and theoretical analysis are carried out to verify the new energy regeneration system and its control strategy.

2 New Energy Regeneration System Configuration

Figure 1 shows a schematic of a conventional ISG hybrid system. In the conventional ISG system, the ISG motor is integrated at the end of engine crankshaft. The rotor is connected to the crankshaft directly. The energy storage unit, either a battery or an ultra-capacitor, is connected to the motor through an inverter. This kind of configuration is compact and simple. But the engine speed and the motor speed remain the same all the time, which makes engine braking unavoidable and consumes energy during regenerative braking.

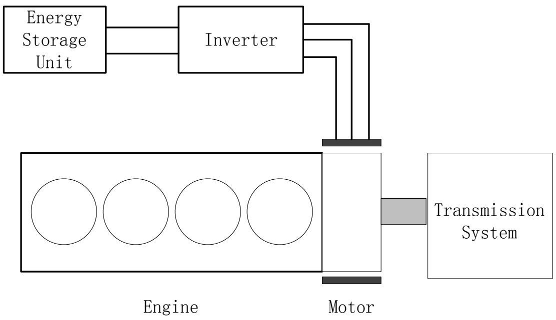
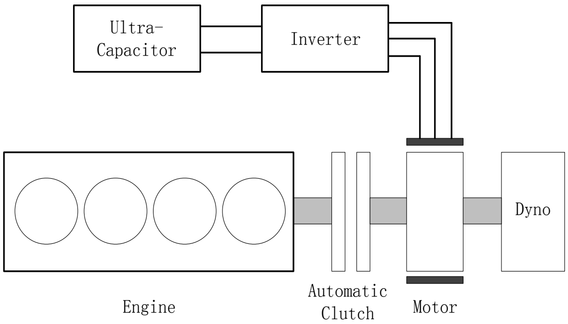
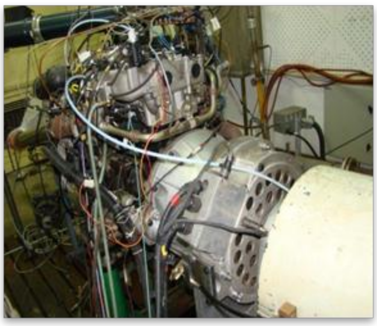


Figure 1: Conventional ISG hybrid system

In order to further improve the energy regeneration efficiency, an additional automatic clutch is added between the engine and the motor [3]. Therefore, the rotor of ISG system is no longer directly connected to the crankshaft of the engine. During regenerative braking, the clutch can be disengaged and the engine braking is avoided. Besides, the ISG motor can be supported at both sides to increase the rigidity. The vibrating impact from the crankshaft to the ISG rotor is decreased. The working environment for the ISG motor is improved and its lifetime can be extended. Figure 2 shows the new ISG hybrid system for diesel engines, with the system setup in the lab (a) and the actual picture (b). An ultra-capacitor is used as the energy storage unit and a permanent magnet brushless motor is used as the ISG motor.



(a)



(b)

Figure 2: New ISG hybrid system

The characteristics of relevant components and dynamometer are specified in Table 1.

Table 1: System specifications

Components	***Parameters***	***Value***
Engine	Type Max. Power / kW Rated Speed / rpm Max. Speed / rpm	Diesel Engine, 4 Cylinders, 2.5 L 87 3800 4250
ISG Motor	Motor Type Rated Power / kW Rated Voltage / V Base Speed / rpm Max. Speed / rpm	Permanent Magnet, Synchronous 15.7 250 1000 4000
Ultra-capacitor	Equivalent Capacitance / F Resistance / mΩ Max. Voltage / V	21 54 375
Dynamometer	Type Rated Power / kW Torque Precision / Nm	HORIBA Dynas3 HT350 350 1

3 Control Strategy

3.1 Braking torque distribution

During the braking process in a conventional vehicle without energy regeneration, the driver's braking torque demand T_{bk} is satisfied by the mechanical braking torque T_{mech} from the braking system and the engine braking torque T_{f_eng}.

$$T_{bk} = T_{mech} + T_{f\_eng} \quad (1)$$

With an ISG system, ISG motor can also contribute to the total braking torque demand through brake energy regeneration. But the engine braking torque still exists in the conventional ISG system.

$$T_{bk} = T_{mech} + T_{reg} + T_{f\_eng} \quad (2)$$

where T_{reg} is the regenerative braking torque from ISG motor.

The total braking torque demand T_{bk} is interpreted from the driver's intention. The engine braking torque T_{f_eng} is determined by the engine working condition. ISG system can distribute the braking torque between mechanical braking system and energy regeneration system, in order to maintain the total braking effect and maximize the regenerative energy.

In the new ISG system, the automatic clutch can be disengaged during braking. Engine crankshaft and vehicle transmission system are separated. Therefore, engine braking is avoided and no longer provides braking torque.

$$T_{bk}' = T_{mech}' + T_{reg}' \quad (3)$$

If the total braking torque demand keeps the same, the engine braking torque in the conventional ISG system should be compensated by the mechanical braking system and the energy regeneration system. The regenerative braking torque is increased. And more energy can be regenerated. As a result, new energy regeneration system provides a possibility to increase the regenerative braking efficiency of the ISG system.

3.2 Control Strategy

In the new energy regenerative system, with more control components, the system complexity is increased, and the control strategy should be redesigned in order to coordinate all these components and make the best use of its advantages.

When the system enters a state of regenerative braking, the engine should stop fuel injection immediately. At the same time, the automatic clutch should be disengaged. After the disengagement is accomplished, the engine braking torque disappears, and the total braking torque demand should be redistributed.

The redistribution of braking torque is determined by the state of the automatic clutch, as shown in Figure 3. When the clutch is engaged, the situation stays unchanged as in the conventional ISG system. The regenerative braking torque is still T_{reg}. When the clutch is disengaged, the engine braking torque no longer exists. And this part should be compensated as much as possible by the regenerative braking torque, so that the driver keeps the same feeling about the vehicle deceleration. Thus more braking energy can be regenerated. The engine braking torque is determined by the current engine speed and oil temperature through a calibration map, shown in Figure 4. Meanwhile, the regenerative braking torque is limited by the capacity of the ultra-capacitor and the motor speed. The ultra-capacitor cannot be overcharged and the motor braking torque cannot exceed its maximum value, shown in Figure 5. ECU recalculates the distribution of the braking torque, and controls the mechanical braking system and the ISG motor accordingly.

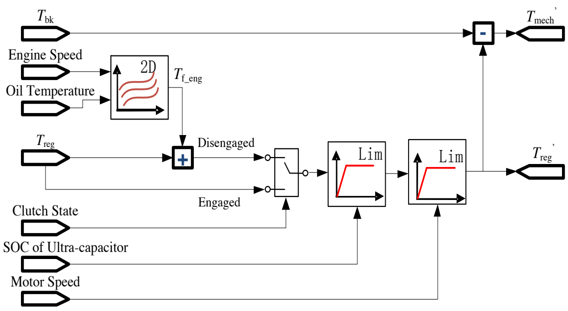


Figure 3: Braking torque redistribution algorithm

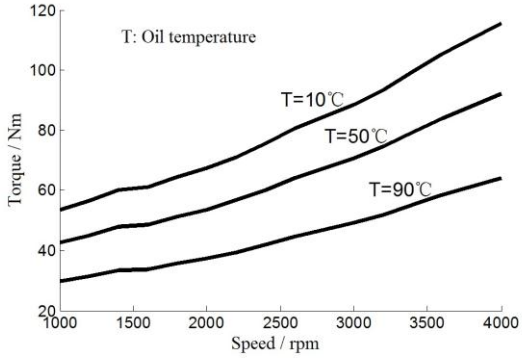


Figure 4: Engine braking torque characteristic

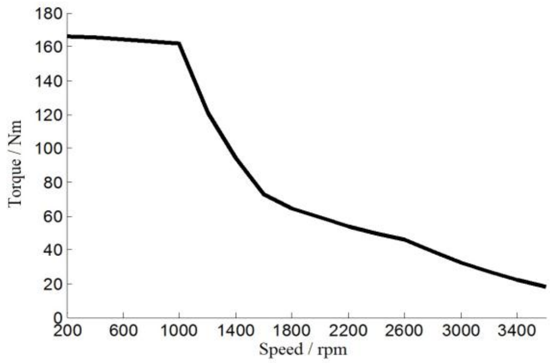


Figure 5: Maximum motor braking torque

4 Experiments and Results

An experiment is carried out to test the performance of the new energy regeneration system and its potential to increase the regenerative braking efficiency.

At first the engine runs at a speed of 3400 rpm. The required torque output drops to 0 suddenly, and the engine control system enters a state of “Overrun”. Regenerative braking starts and two strategies are used:

Automatic clutch control is enabled. The clutch would be disengaged during the state of “Overrun”, and engine braking is avoided.

Automatic clutch control is disabled. Engine braking is available during the state of “Overrun”.

The result is shown in Figure 6. With strategy ①, the automatic clutch is disengaged successfully at a speed around 3000rpm. And the curves of engine speed and ISG motor speed separate from each other. The regenerative braking torque is increased from around 30N·m to more than 60N·m. The clutch is engaged again when the ISG motor speed drops to near idle speed. During the whole process, the regenerative energy with strategy ① is $W_{\text{regen1}} \approx 256KJ$, and that with strategy ② when automatic clutch is disabled is $W_{\text{regen2}} \approx 115KJ$. Without considering the fuel consumption at idle, strategy ① can regenerate over 112% more energy.

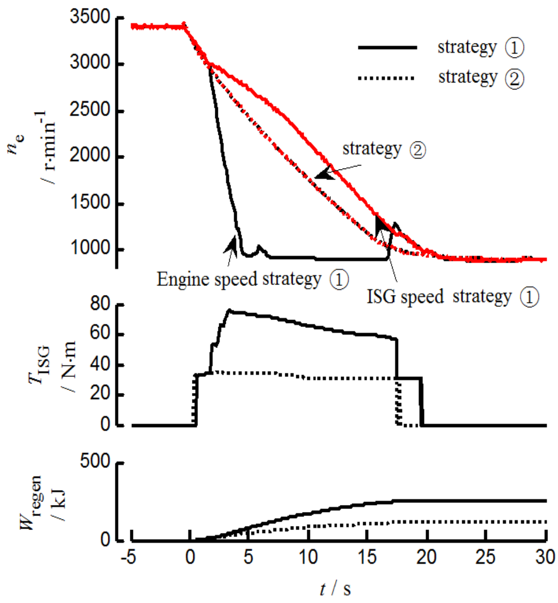


Figure 6: Energy regeneration process during "Overrun" (Comparison of two strategies)

However, it should be noticed that during the braking process, the engine maintains idle speed with strategy ①, while the fuel injection is shut off because of "Overrun" state with strategy ②. So the increase of regenerative energy is accompanied by increased idle fuel consumption. This fuel consumption should also be taken into consideration when the regenerative braking efficiency is evaluated.

5 Theoretical Analysis

With strategy ①, the engine runs at idle speed during the braking process, the consumed fuel quantity Q_1 is:

$$Q_1 = \frac{T_{f\_eng}(n_{idle})n_{idle}}{9550} b_i t_1 \qquad (4)$$

where b_i is indicated specific fuel consumption (ISFC, $g/(kW \cdot h)$)

The regenerated energy W_{reg1} with strategy ①:

$$W_{\text{reg1}} = \int_0^{t_1} \frac{T_{reg}' n_e(t)}{9550} dt$$

$$= \int_0^{t_1} \frac{[T_{reg} + T_{f\_eng}(n_e(t))] n_e(t)}{9550} dt \qquad (5)$$

With strategy ②:

$$Q_2 = 0 \qquad (6)$$

$$W_{\text{reg2}} = \int_0^{t_2} \frac{T_{reg} n_e(t)}{9550} dt \qquad (7)$$

The regenerated energy with strategy ① is increased by ΔW_{reg} . Considering the rotational inertia of the engine is much smaller than that of the vehicle, the deceleration of the vehicle can be taken as the same, i.e.: $t_1 \approx t_2$:

$$\Delta W_{\text{reg}} = W_{\text{reg1}} - W_{\text{reg2}}$$

$$= \int_0^{t_1} \frac{T_{f\_eng}(n_e(t)) n_e(t)}{9550} dt \qquad (8)$$

T_{reg} is the regenerative braking torque in the conventional ISG system. In the experiment described in section 4, $T_{reg} = 30Nm$. T_{f_eng} is the engine braking torque. Its characteristic curve is already shown in Figure 4.

Therefore it can be concluded:

$$T_{reg} < T_{f\_eng} \Rightarrow W_{\mathrm{reg2}} < \Delta W_{\mathrm{reg}} \quad (9)$$

$$\frac{\Delta W_{\mathrm{reg}}}{W_{\mathrm{reg2}}} > 100\% \quad (10)$$

Strategy ① can regenerate energy more than 100%.

However, with strategy ①, more fuel Q_1 is consumed.

If this amount of fuel is used to charge the ultra-capacitor, the corresponding electric energy can be described as:

$$E_1 = Q_1 H_u \eta_e \eta_{ISG}$$

$$= \frac{T_{f\_eng}(n_{idle}) n_{idle} t_1 \eta_e \eta_{ISG}}{9550 \eta_i} \quad (11)$$

where H_u is the lower heating value of diesel fuel, η_e and η_{ISG} are the effective efficiency and charging efficiency of ISG when the engine output power is used to charge the ultra-capacitor through ISG, η_i is the indicated efficiency at idle.

$$\begin{aligned}\frac{\Delta W_{\mathrm{reg}} - E_1}{W_{\mathrm{reg2}}} &> 1 - \frac{E_1}{W_{\mathrm{reg2}}} \\ &\approx 1 - \frac{T_{f\_eng}(n_{idle}) n_{idle} t_1 \eta_e \eta_{ISG} / \eta_i}{T_{reg} t_2 (n_{2\max} + n_{2\min}) / 2} \\ &= 1 - \frac{2 n_{idle}}{(n_{2\max} + n_{2\min})} \frac{\eta_e \eta_{ISG}}{\eta_i} \\ &> 1 - \frac{2 n_{idle}}{(n_{2\max} + n_{2\min})} \eta_m \eta_{ISG}\end{aligned} \quad (12)$$

With

$n_{idle} = 900 rpm$, $n_{2\max} = 3400 rpm$, $n_{2\min} = 900 rpm$, $\eta_m = 98\%$, $\eta_{ISG} < 90\%$ in this case:

$$\frac{\Delta W_{\mathrm{reg}} - E_1}{W_{\mathrm{reg2}}} > 63.1\% \quad (13)$$

Therefore, even when the fuel consumption at idle is considered, the regenerated energy is increased at least 63.1% with the new energy regeneration system.

6 Conclusion

In conclusion, a new energy regeneration system with an automatic clutch between the engine and ISG motor is investigated to avoid engine braking consuming energy during braking process. The control strategy is designed to coordinate all the relevant components to achieve an efficient braking torque distribution. Experiment and theoretical analysis both show that the regenerated energy would be increased significantly with the new energy regeneration system, even with the fuel consumption at idle. This fuel consumption at idle could be avoided by shutting down the engine with an appropriate algorithm in future research.

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Authors

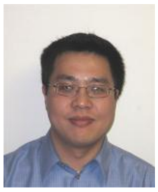
Mr. Ying Huang
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, 100084, Beijing, China
Tel: +86-(0)10-62781830
Email:huang-y03@mails.thu.edu.cn
Mr. Ying Huang is a Master's candidate in Tsinghua University working on Diesel Engine Management System.

Prof. Fuyuan Yang
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, 100084, Beijing, China
Tel: +86-(0)10-62795828
Email: fyyang@tsinghua.edu.cn
Major: Electronic Engine Control Technology

Prof. Minggao Ouyang
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, 100084, Beijing, China
Tel: +86-(0)10- 62785966
Email: ouymg@tsinghua.edu.cn
Prof. Minggao Ouyang is the director of State Key Laboratory of Automotive Safety and Energy. His research interests include Electronic Engine Control Systems, Hybrid Power Systems, and New Energy Power System.

Mr. Guojing Gao
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, 100084, Beijing, China
Tel: +86-(0)10-62781830
Email: ggj05@mails.tsinghua.edu.cn
Mr. Guojing Gao is a Master's candidate in Tsinghua University working on Hybrid Powertrain Control.

Dr. Lin Chen
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, 100084, Beijing, China
Tel: +86-(0)10-62781830
Email: chenlin00 @mails.thu.edu.cn
Dr. Lin Chen is recently graduated from Tsinghua Univ. He will be working at section of Powertrain Advanced Engineering in SAIC R&D center, focusing on the research of engine performance development.



Dr. Yongsheng He
Propulsion Systems Research Lab, GM Global Research & Development, MC: 480-106-252
30500 Mound Rd, Warren, MI 48090, USA
Tel: +1 (586) 291-6852,
Fax:+1 (586) 986-0176
Email: yongsheng.he@gm.com
Dr Yongsheng is a Staff Researcher at GM R&D working on Hybrid Powertrain, Automotive Engines, and Emission Control.