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Development of a Mid-Size Compound Type Hybrid Electric Excavator

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Abstract

Regulations on emission gases and ever-increasing fuel costs call for environmentally friendly and energy efficient machines in industries worldwide. To meet these requirements, a hybrid excavator prototype has been developed where an electric swing motor, an engine assist motor, and an ultra-capacitor module are incorporated into a conventional hydraulic excavator of 22-ton class. The developed hybrid excavator benefits from the regeneration of swing energy when decelerating and the efficient operation of the engine, eventually achieving the enhanced energy efficiency and reduction of emission gases. Based on the authors' as well as the co-workers' previous efforts developing the hybrid excavator prototype, this paper will introduce a few techniques to optimize its energy efficiency. These include the 1) engine speed control in proportional to the load torque, 2) pump displacement control when driving the electric swing system, 3) ultra-capacitor voltage management minimizing the electrical energy loss, and 4) cooling fan speed reduction designed for the system with improved energy efficiency. The first three of these techniques are realized into the control algorithm, while the last is implemented through the design modification based on the estimation model of the engine coolant and hydraulic oil temperature according to the fan speed. The gross impact of these techniques on the energy efficiency is validated through the test.

Keywords: hybrid, excavator, efficiency

1 Introduction

The regulations on emission gases have been spreading ever strictly from on-road vehicles to off-road vehicles, including construction equipment. After the introduction of off-road Tier 1 regulations in 1996, much more rigorous Tier 4 regulations will come into effect from 2015. Because US environmental Protection Agency (EPA) demands a stringent reduction on diesel engines, construction equipment companies are forced to reduce the emission level of their diesel engines in accordance with the regulations.

In construction equipment industry, the customers' key buying criteria are energy efficiency, productivity and reliability. Since the dependence on fossil fuels throughout the world is not predicted to dramatically decrease, construction equipment manufactures are devoting their efforts in developing more energy efficient machines to survive in the market.

To cope with these market and environmental needs, hybrid electric excavators have been developed in which an electric swing motor, an engine assist motor, and an ultra-capacitor module are incorporated into a conventional hydraulic excavator of 22-ton class [1], [2].

The developed hybrid excavator benefits from the regeneration of swing energy when decelerating and the efficient operation of the engine, eventually achieving the enhanced fuel performance and reduction of emission gases.

Based on the authors' as well as the coworkers' previous works [1] - [7], this paper presents a few efforts made to optimize the energy efficiency of the hybrid excavator prototype.

First, the target speed of the engine is controlled in proportional to the hydraulic pump torque and the electric power generation requirement. The control strategy is keeping the engine speed low, if the machine's load power is not high nor the ultra-capacitor is fully charged. This reduces the energy loss in the idling periods albeit short in a typical excavation cycle.

Second, the displacement of the hydraulic pump is controlled to be decreased in proportional to the swing motor torque and speed. Utilizing this control strategy, the user controllability of the hybrid excavator prototype can be tuned to be similar to that of the conventional excavator when manipulating the boom and swing simultaneously. The overall energy efficiency is improved by restricting excessive hydraulic pump power when driving the electric swing motor.

Third, the state of charge(SOC) of the ultra-capacitor is managed high to reduce the electric energy loss which is proportional to the square of the current. The target voltage of the ultra-capacitor is derived from the estimated energy which will be regenerated by the swing motor. This flexible target voltage, considering the swing regeneration energy prevents the excessive charging of the ultra-capacitor.

Finally, the cooling fan speed is reduced thereby reducing the cooling power. Based on an empirical model estimating the engine coolant and the hydraulic oil temperature according to the fan speed, the minimal speed of the cooling fan and the required pulley are designed that fit to the developed energy efficient power train.

The gross impact of these techniques on the energy efficiency is validated through the test.

This paper starts with the overview of the developed hybrid excavator prototype. The details of the above efficiency improving techniques are given in section 3, with the illustrative control block diagrams and the relevant control maps. Field test results and conclusion are given in section 4 and 5, respectively.

2 Prototype Hybrid Excavator

2.1 Overview of the power train structure

The power train of the developed prototype hybrid excavator is depicted in figure 1, where the electric swing motor and the engine assist motor are incorporated into the conventional drive train [2].

In this architecture, one of the primary functions of the engine assist motor is to supply the additional propelling power to drive the pumps in case of high-load operation mode. The other function is to generate the electrical power to charge the energy storage device or to supply the driving power to the electric swing motor. By replacing the hydraulic swing motor with an electric motor, it is possible to regenerate the kinetic energy of the excavator's turning body as well as to remove the hydraulic meter-in or meter-out loss.

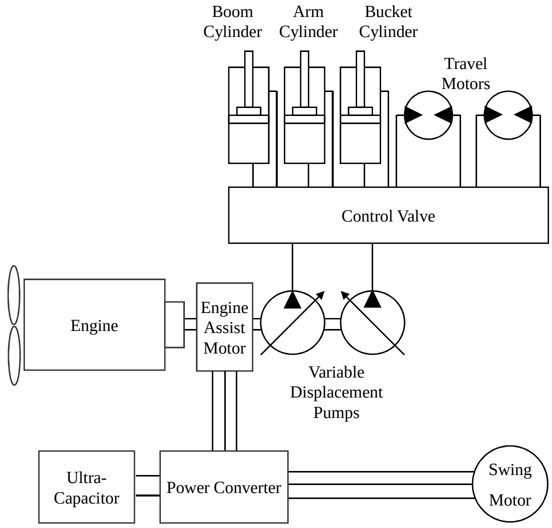

Figure 1: Power train of the prototype hybrid excavator

2.2 Energy efficiency of the prototype hybrid excavator

The major contributing factors improving the energy efficiency of the prototype hybrid excavator over the conventional one is the (1) efficient operation of the engine and the (2) swing energy regeneration.

By replacing the conventional hydraulic swing motor with an electric one, the system can convert kinetic energy into electric energy when decelerating, which will be wasted otherwise in the conventional system. The stored energy can be utilized when accelerating the swing motor or to assist the engine if necessary.

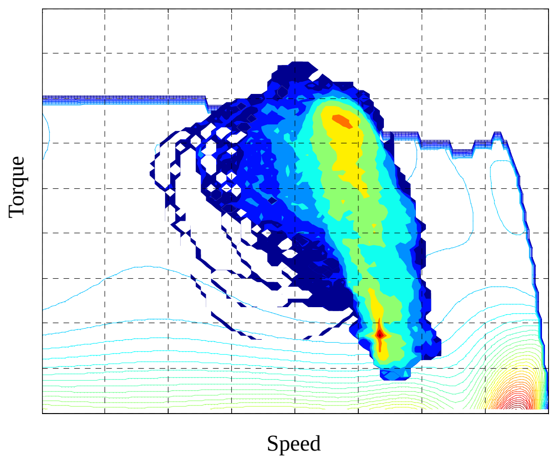

Figure 2: Operating points of the engine

Figure 2 shows the operating points of the engine for the prototype hybrid excavator. The prototype hybrid excavator restricts the maximum engine speed within the optimal efficiency region.

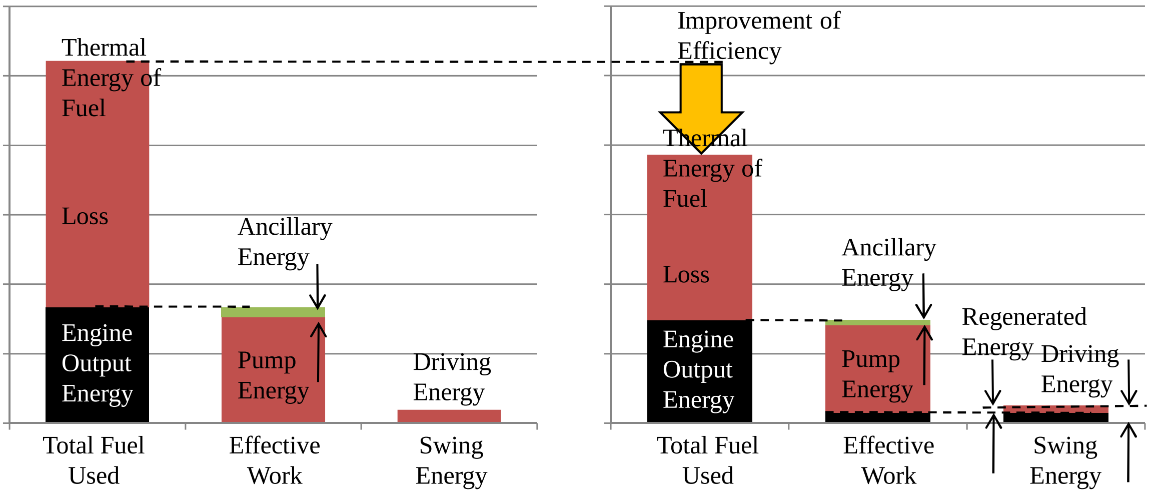

Figure 3: Comparative analysis of the fuel usage - (L) conventional excavator, (R) hybrid excavator

The displacement of the hydraulic pump is increased to maintain the equal amount of the flow rate, while the excessive load torque due to the increased pump displacement is compensated by means of the assist motoring. This feature enables the prototype hybrid excavator exhibits the equivalent rated power while operating the engine in the optimum operation line.

Figure 3 compares the consumed energy of the conventional excavator and the prototype hybrid excavator when performing the same excavation tasks. The analysis shows that the regenerated swing energy reduces the engine output energy and the engine is operated more efficiently thereby the overall efficiency of the hybrid excavator is superior to the conventional one.

3 Improving Energy Efficiency

In addition to the fuel saving ability benefited from swing energy regeneration and efficient operation of the engine, the energy efficiency of the prototype hybrid excavator is improved further by means of the 1) engine speed control, 2) pump displacement control, 3) ultra-capacitor voltage management and 4) cooling fan speed reduction.

3.1 Engine speed control

For a conventional excavator, the speed of the engine is regulated at the target value determined by the operator's dial input. Keeping the engine speed high even though the load torque at hand is not considerable, the energy loss takes place in the idle periods.

Despite this kind of energy loss, the reason for keeping the engine speed high regardless of the load is to guarantee the fast responsibility.

On the other hand, the engine assist motor improves the responsiveness of the prototype hybrid excavator such that the engine can recover

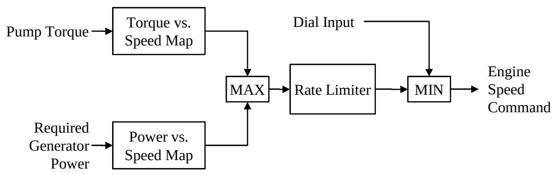

Figure 4: Block diagram of the engine speed controller

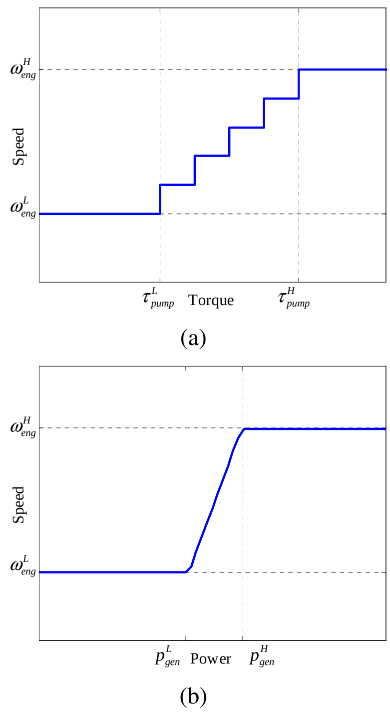

Figure 5: Control maps for the engine speed controller

its speed quickly from the lower speed. This facilitate the variable speed control of the engine for the hybrid excavator.
Charging the ultra-capacitor is another major function of the engine assist motor of which the detailed control algorithm is given in section 3.3. In order for the engine assist motor to generate the requested electric power, the engine should rotate at a sufficiently high speed to produce the required back EMF voltage.
Figure 4 is the block diagram of the designed engine speed controller. Figure 5 is the instantiations of the control maps in figure 4 which show the required engine speed according to the pump torque and the generator power, respectively. The dial input of the conventional excavator then limits the maximum engine speed.

3.2 Pump displacement control

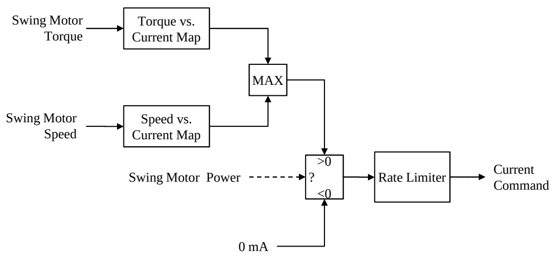

Figure 6: Block diagram of the pump displacement controller

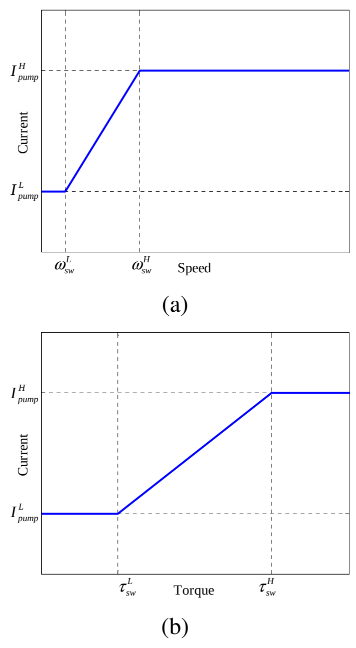

Figure 7: Control maps for the pump displacement controller

The hydraulic pump of the conventional excavator supplies the flow to the multiple actuators such as the boom, arm, bucket cylinders and the hydraulic swing motor. Therefore, the maximum speed of each actuator is reduced when simultaneously manipulated with other actuators.
On the other hand, the speed of the electric swing motor for the prototype hybrid excavator can be controlled independently of the hydraulic actuators.
The independent swing system of the hybrid excavator can be advantageous over the conventional one since the machine's productivity can be higher. However, this can cause unfamiliarity to the operators when controlling the machine with the same level of proficiency as they manipulate the conventional excavator.
The excessive power of the hybrid excavator when the swing system is controlled with other hydraulic actuators can also sacrifice its efficiency.
These necessitate the pump control algorithm for the hybrid excavator, that limits the maximum hydraulic pump power when the electric swing system is simultaneously controlled.
Figure 6 is the block diagram of the designed pump displacement controller. The pump displacement is decreased in proportional to the control current. Depending on the state of the electric swing motor, the pump power is restricted according to the control maps in figure 7.

3.3 UC voltage management

The ultra-capacitor module is used to supply the necessary energy to the swing motor and the engine assist motor, and its energy is obtained from the generation of the engine assist motor and the regeneration of the swing motor.
Since the swing instantaneous power is very high, when the ultra-capacitor voltage is low a large current flows, and this leads to a considerable energy loss due to the internal resistance of the ultra-capacitor. Therefore, in order to reduce the energy loss it is necessary to maintain the ultra-capacitor voltage as high as possible.
On the other hand, the regenerative swing energy should be fully absorbed by the ultra-capacitor. For this purpose the SOC should be low enough to store the regenerated energy.
To meet the above requirements, the target voltage of the ultra-capacitor is determined from the estimated energy which will be regenerated by the swing motor.
The algorithm is displayed in figure 8. The cell voltage is calculated according to the model in figure 9. The generating power of the engine assist motor is determined from the sum of the swing system loss and the required power to follow the target ultra-capacitor energy.

3.4 Cooling fan speed reduction

A conventional excavator has a forced air cooling system that comprises a cooling fan directly con-

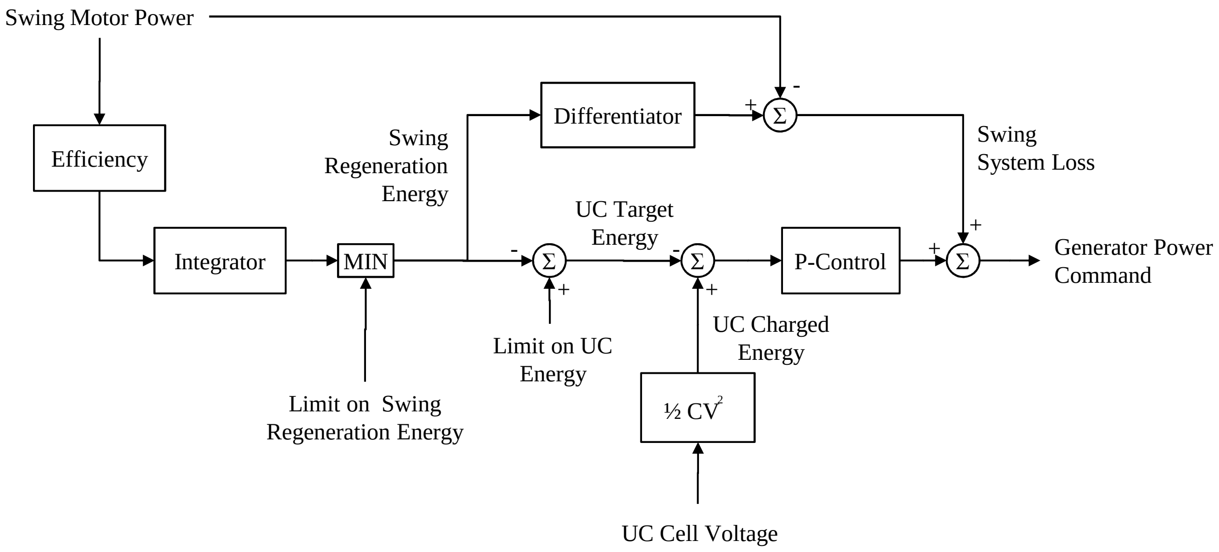

Figure 8: Block diagram of the UC voltage controller

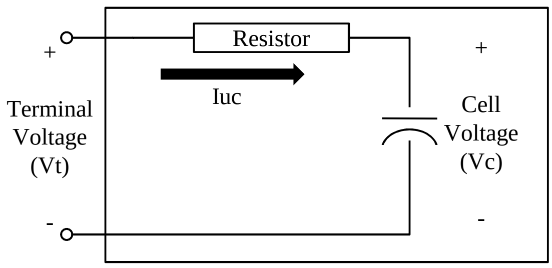

Figure 9: Model for the ultra-capacitor

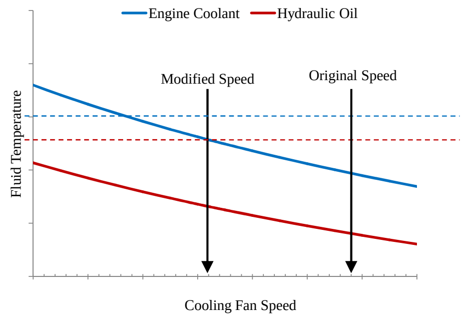

Figure 11: Fan speed vs. coolant and oil temperature

nected with the engine crank shaft through pulleys and radiators that coolants pass through. Powered by the engine, the cooling fan inhales outside air into the radiator room, and the coolants passing through the radiators release heat gained at each component including the engine, hydraulic pump, valves.

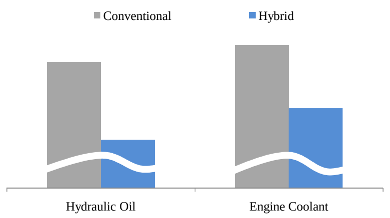

Figure 10: Comparison of the temperature

The cooling system for the prototype hybrid excavator is composed of the conventional one and an additional one for the electric components. Although the hydraulic pump load was decreased by separating swing power from the hydraulic system and the heat released from the engine was reduced by lowering the average engine power, the cooling performance still remains at the previous level. Therefore, the conventional cooling system is over-designed for the hybrid excavator thereby deteriorating the fuel economy.

The saturated temperatures from a test are charted in figure 10. The conventional cooling system of the hybrid excavator chills the cooling fluids below the required level.

By adjusting the pulley size, thus lowering the fan speed, the fan power consumption can be reduced. However, there needs a trade-off between the fan speed reduction and the thermal stability of the cooling system because excessively small air flow can overheat the machine's components.

Thus, an empirical heat transfer model is used to predict the saturated coolants' temperature according to the fan speed and to impose the lower limit on the fan speed.

Figure 11 shows calculated temperatures of the engine coolant and hydraulic oil from the heat transfer model. Based on the curve, the fan speed for the hybrid excavator prototype is reduced to the limit where neither of the coolants is overheated.

4 Test Results

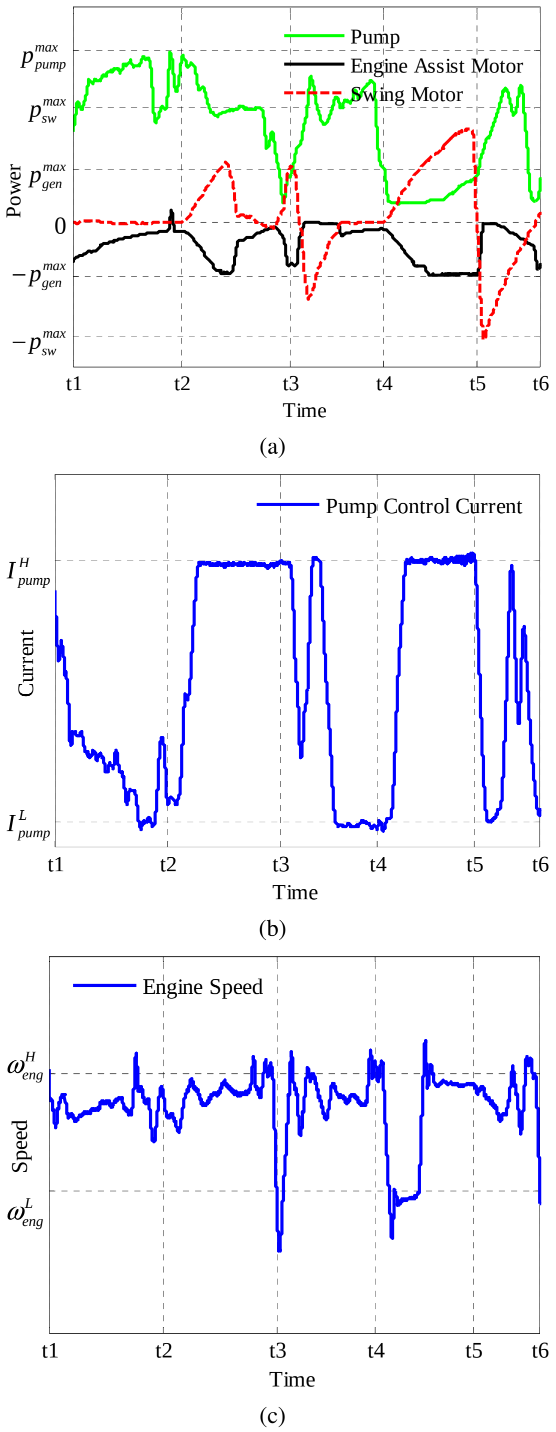

Figure 12: Test result for a typical excavation cycle

Figure 12 indicate how the engine speed controller as well as the pump displacement controller respond when performing a typical excavation cycle.
In figure 12 (a) and (b), during the time internal $t_2 \sim t_3$ of the boom-up and swing acceleration, the pump control current suddenly rises to decrease the displacement of the hydraulic pump in order to control the boom speed to meet the user controllability as the same level with the conventional excavator. In 12 (c), during the time internal $t_4 \sim t_5$ and in the vicinity of t_3, the engine speed is lowered because both of the pump torque and the generating power are not significant.

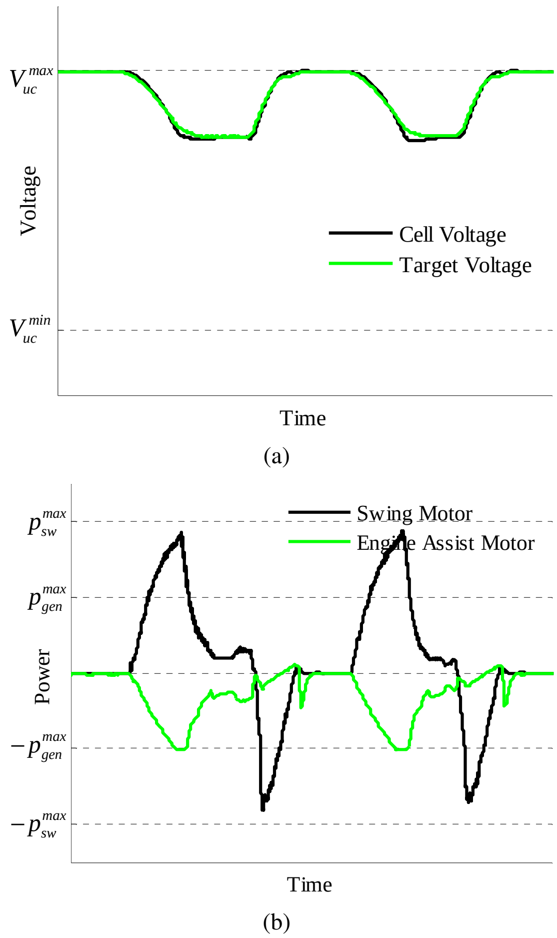

Figure 13: Test result for the UC voltage controller

Figure 13 shows the test results of the ultra-capacitor voltage controller. The target voltage of the ultra-capacitor is shown in (a) and the swing motor power is depicted in (b). The target voltage is maintained high considering the swing energy regeneration. The measured voltage closely follows the target without exceeding the target value in (a). Otherwise, the engine assist motor will dissipate the regenerated swing energy, which is not detected in (b).
Figure 14 shows the operating points of the engine when performing the excavation task. Compared to figure 2, the engine speed controller moves the operating points of the low torque region, to the lower speed region improving the energy efficiency of the prototype hybrid excavator.

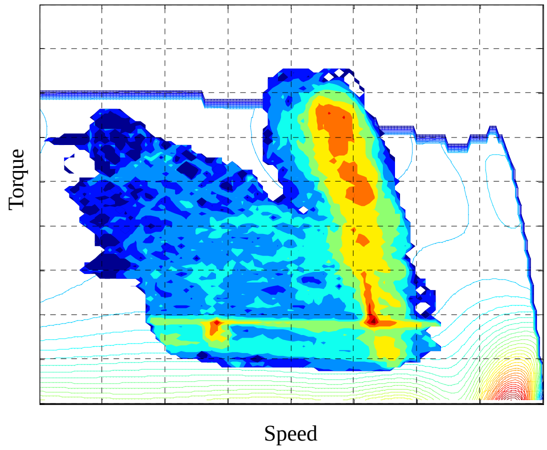

Figure 14: Operating points of the engine

Figure 15: Prototype hybrid excavator

5 Conclusion

In this paper, a prototype hybrid excavator that incorporates an electric swing motor, an engine assist motor and an ultra-capacitor is presented.
Besides the main features of a hybrid excavator such as swing energy regeneration, engine operating point shifting and reduction of hydraulic energy loss, various methodologies and control algorithms are applied in order to improve fuel efficiency as well as controllability: engine speed control, pump displacement control, ultra-capacitor voltage management, and cooling fan speed reduction.
The test results show that the energy efficiency of the prototype hybrid excavator is improved further in a typical excavation cycles.
For a future research, a boom regeneration system is considered to be integrated to enhance the fuel economy.

Acknowledgments

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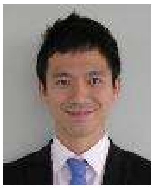

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