System Configuration and Control Strategy for Compound Type Hybrid Excavator with Ultra Capacitor

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***Abstract*-- This paper presents a power converter configuration for the compound type hybrid excavator with an ultra capacitor, which is directly connected in parallel to dc-link capacitor without DC/DC converter. With this structure, the efficiency of the system has been improved compared to the conventional compound type hybrid excavator where an ultra capacitor was connected via DC/DC converter. And, a power control strategy for the suggested configuration is described. To suppress the oscillation of the voltage of the ultra capacitor, an observer for the internal voltage of the ultra capacitor is devised. To evaluate the effectiveness of the proposed configuration and power control strategy, extensive computer simulations have been performed and the results are discussed. The feasibility of the simulation results is experimentally verified based on mid-sized excavator.**

***Index Terms*-- Power Control, Hybrid excavator, Ultra Capacitor, Super Capacitor.**

I. INTRODUCTION

Recently, due to the concern about global warming and air pollution resulted from the operation of the Internal Combustion Engine(ICE), a lot of efforts have been made to reduce the pollution from ICE by hybridization. The hybrid system has been already commercialized in the field of the passenger vehicle and transit bus, and the hybridization is extended to construction vehicles such as excavators, rubber tyred gantry cranes [1-4]. According to the study of [4], there are three types of hybrid excavator with the ultra capacitor. One is series type, another is parallel type and the other is compound type. Among them, the compound type of hybrid excavator is promising thanks to the shortest payback period and highest reliability with moderate fuel saving. In this paper, new power converter configuration for the compound type hybrid excavator without DC/DC converter is proposed. Additionally, the power control strategy associated with the proposed configuration is suggested. To enhance charging performance of the ultra capacitor, the power control strategy with an internal voltage observer for the ultra capacitor is employed. In order to verify the feasibility of the proposed strategy, computer simulations and experimental test are carried out.

II. SYSTEM CONFIGURATION OF POWER CONVERTER FOR THE COMPOUND TYPE HYBRID EXCAVATOR

A. Compound Type Hybrid Excavator

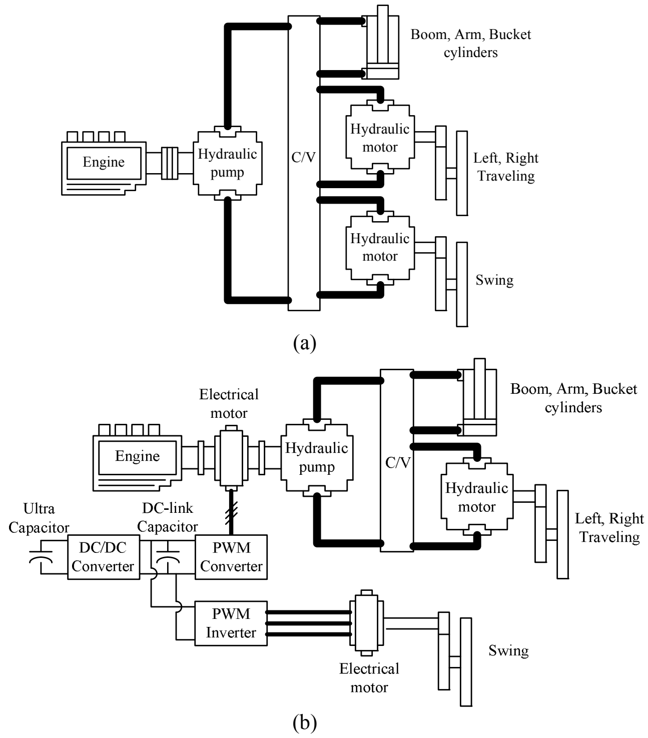

Fig. 1. (a) Structure of a conventional hydraulic excavator.
(b) Structure of a conventional compound type hybrid excavator.

Fig. 1(a) and Fig. 1(b) depict a block diagram of the hydraulic excavator and compound type hybrid excavator, respectively. As shown in the compound type hybrid excavator of Fig. 1(b), electrical power of an ultra capacitor is converted to mechanical power or vice versa, through the electrical motor/generator between ICE and the hydraulic pump. In addition, because the actuator for the swing motion has been replaced by an electrical motor, the regenerated energy from decelerating motion of the swing motor can be stored in the ultra capacitor. Afterward, the energy can be used to actuate the hydraulic pump or accelerate the swing motor. In the case that the required hydraulic pump power is greater than the maximum engine power, the ultra capacitor is discharged to supplement the insufficient engine power. The

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capacitor is charged by the surplus power of ICE or by the regenerated power from the swing motor. With this power control strategy, the ICE in the compound type hybrid excavator in Fig. 1 (b) operates at higher fuel efficiency point compared to the conventional hydraulic excavator in Fig. 1 (a). Furthermore, the losses from hydraulic control valve(C/V) are reduced conspicuously by separating the swing actuator from the hydraulic circuit. Hence, the fuel consumption of the compound type hybrid excavator could be saved by 24% compared to hydraulic excavator [4].

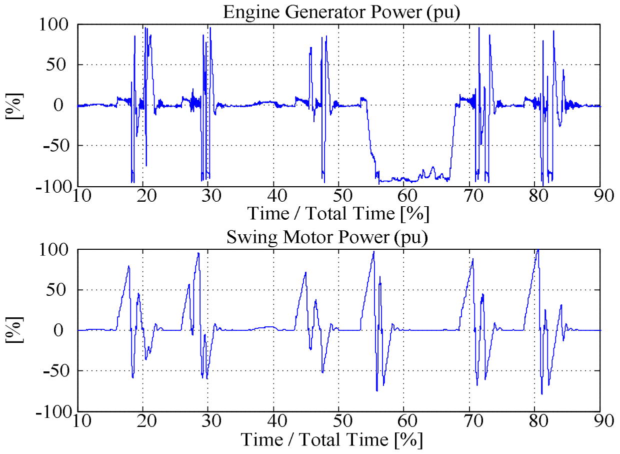


Fig. 2. Engine generator power and swing motor power of conventional compound type hybrid excavator.

Fig. 2 shows the experimental results of the traces of the power from the engine generator and the swing motor for the conventional compound type hybrid excavator in the standard excavating mode. In each figure, positive power means that the electrical machine works as a motor whereas negative power means that the electrical machine works as a generator. Correspondingly, the positive power from the engine generator means that the engine generator assists ICE as a motor. As shown in Fig. 2, there exist few assisting operations of the engine generator in the standard excavating mode. Some overshoots of the positive power from the engine generator are simply brake operation of the engine generator to consume the surplus regenerated power from the swing motor. This power is dissipated as heat inside the ICE or the hydraulic pump. Hence, it can be deduced that ultra capacitor was mainly used for the swing motion in the standard excavating mode. From the experimental results, it can be noted that the capacitance of the ultra capacitor can be optimized just to accommodate only the power fluctuation of the swing motor. Furthermore, the overall efficiency is increased as the efficiency of regeneration energy from the swing motor is increased. In this sense, the proposed configuration shown in Fig. 3, which is the direct connection of the ultra capacitor to DC-link, can be justified. This proposed configuration can improve overall efficiency and reliability of the excavator by saving the DC/DC converter.

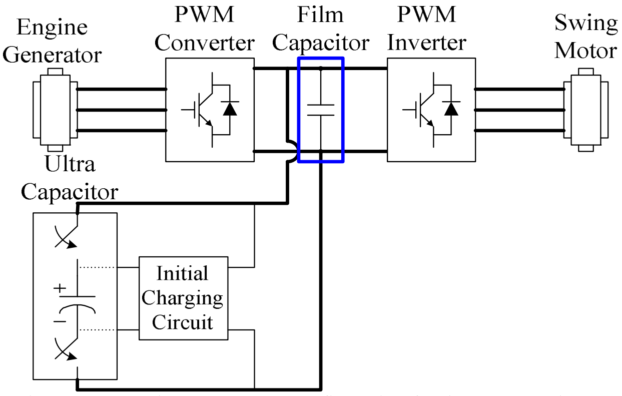


Fig. 3. Proposed power system configuration for the compound type hybrid excavator.

In the conventional hybrid excavator in Fig.1 (b), because of the DC/DC converter, electric machines always transfer energy to the ultra capacitor through the DC/DC converter. The energy from the ultra capacitor is also transferred to the swing motor or to the hydraulic pump through the DC/DC converter. That means the degradation of the overall efficiency of the hybrid excavator. The DC/DC converter also incurs packaging problems and cooling issues. So, it can be expected that the proposed system has higher reliability than conventional system.

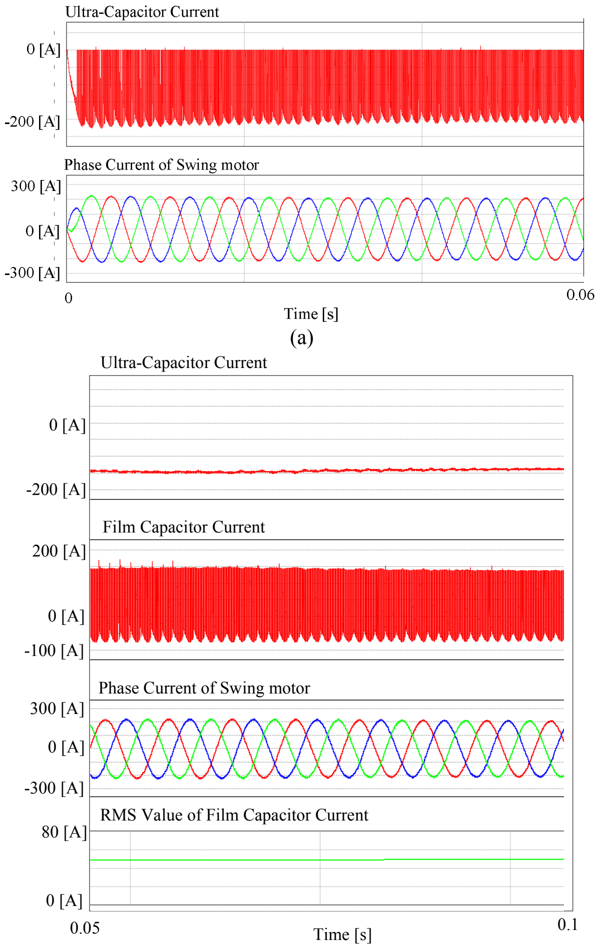


Fig. 4. (a) Simulation results without film capacitor.
(b) Simulation results with film capacitor.

In the spite of the virtues of the configuration in Fig. 3, there are several problems. First, large ripple currents from the switching of PWM inverter and converter may flow into the ultra capacitor because of the direct connection of the ultra capacitor to DC-link. Large ripple currents have negative effects on the life span of the ultra capacitor. Thus, it is necessary to connect the film capacitor, which has very low internal inductance, to the ultra capacitor in parallel in order to provide the path of the ripple currents. The computer simulation is performed to set the capacitance of the film capacitor at maximum load condition. As shown in Fig. 4, if the film capacitor is connected in parallel to the ultra capacitor, the ripple current of the ultra capacitor is drastically decreased. This film capacitor should be chosen to handle the required RMS value of ripple current.

Next one would be the initial charging problem of the ultra capacitor. When the ultra capacitor is charged by the engine generator, inrush current flows through the engine generator to the ultra capacitor if the ultra capacitor is not initially charged. In this case, the starting of engine would be extremely difficult because of the heavy load torque from the engine generator due to the inrush current. Hence, an additional initial charging circuit should be provided as shown in Fig. 3. The initial charging of ultra capacitor is only required when the ultra capacitor voltage is much lower than the rectified voltage of the engine generator. Thus, this additional initial charging circuit would be used infrequently. Therefore the size of the initial charging circuit can be minimized at the cost of charging time under the consideration of infrequent usage of the charging circuit.

Finally, because of the fluctuation of DC-link voltage, it is mandatory to synthesize the output voltage of PWM converter and inverter under this fluctuating DC-link voltage. Furthermore, the rated current of the engine generator and the swing motor should be set with the consideration of the minimum DC-link voltage due to the fluctuation to guarantee the same electric power of the electric machines at the minimum DC-link voltage. After the careful trade-off between the capacitance of the ultra capacitor and the range of the fluctuation of DC-link voltage, the overall system efficiency and the cost of the system might be optimized. To minimize capacitance of the ultra capacitor, the generator and motor would operate in flux weakening mode [5] to accommodate the reduced DC-link voltage.

III. POWER CONTROL STRATEGY

A. *Main concepts of the Power Control Strategy*

The main concepts of the proposed power control strategy are as follows.

1. ICE provides power for the required hydraulic pump power.
2. The ultra capacitor provides power for the swing motor.
3. The loss due to the swing action is charged to the ultra capacitor by engine generator during the swing action.
4. The voltage of ultra capacitor is always maintained to the maximum available voltage after the swing action is finished.

As mentioned before, the required pump power was under the maximum engine power at the maximum efficient operating point of ICE during the standard excavating mode. Thus ICE can fully provide required pump power during the standard excavating mode. In addition, as the ICE provides the required pump power, it is possible that the ultra capacitor provides only power for the swing motor. Because the swing action always includes regeneration mode, the engine generator provides only loss due to the swing action to keep the maximum available voltage of the ultra capacitor after swing motion.

In the proposed configuration, DC-link voltage is fluctuated. If DC-link voltage is lower than a certain value, the electric machines cannot provide sufficient torque for stable operation of hybrid excavator. Thus, in the proposed strategy, the ultra capacitor's voltage, which is the DC-link voltage, should be kept above the certain value. Because the ICE provides all of the required pump power, if the engine generator charges to the ultra capacitor during excavating action of excavator, ICE might provide the required pump power no longer. For this reason, the ultra capacitor should be charged only during the swing action.

B. *State Transit Diagram*

State transit diagram is applied to set up the control strategy for the proposed compound type hybrid excavator. Current state influences on output (or action). Additionally, both of current state and input (or condition) influence on next state. On the basis of these rules, the state transit diagram can be implemented as described in Table I-II.

TABLE I
STATE TRANSIT TABLE FOR CONTROL STRATEGY

Present State	Input (Condition)			Next State
xxx	$V_{sc} > V_{ref\_high}$	Power > 0	$Fabs(\omega_{rpm}^*) > \omega_{rpm\_low}$	010
			$Fabs(\omega_{rpm}^*) < \omega_{rpm\_low}$	000
	$V_{ref\_top} \leq V_{sc} < V_{ref\_high}$	xxx		010
	$V_{ref\_bottom} < V_{sc} < V_{ref\_top}$	Power > 0	$Fabs(\omega_{rpm}^*) > \omega_{rpm\_high}$	001
			$Fabs(\omega_{rpm}^*) < \omega_{rpm\_high}$	010
		Power ≤ 0	$Fabs(\omega_{rpm}^*) > \omega_{rpm\_low}$	010
			$Fabs(\omega_{rpm}^*) < \omega_{rpm\_low}$	001
	$V_{sc} > V_{ref\_low}$	xxx		001

V_{sc} = voltage of the ultra capacitor, V_{ref_high} = maximum acceptable voltage of the ultra capacitor, V_{ref_low} = minimum acceptable voltage of the ultra capacitor, V_{ref_bottom} and V_{ref_top} = operating voltage of the ultra capacitor, Power = power of the swing motor, ω_{rpm}^* = speed reference of the swing motor.

TABLE II
OUTPUT TABLE FOR CONTROL STRATEGY

Present State	Output (Action)
000	Discharging the ultra capacitor ($P^* = P_{max}$)
001	Charging the ultra capacitor ($P^* = -P_{max}$)
010	No Action ($P^* = 0$)

P^* = power reference of the engine generator, P_{max} = rated power of the engine generator.

It is necessary for the safe operation of the ultra capacitor that the voltage of the ultra capacitor can't be increased over the acceptable maximum value. In the reverse, the voltage of the ultra capacitor can't be decreased under acceptable minimum value due to rated currents of the ultra capacitor. Thus, V_{ref_high}, V_{ref_low} can be set by above rules. Each voltage reference exists for the protection of the ultra capacitor, and if the ultra capacitor's voltage is in the acceptable range, the control strategy is performed to maximize the fuel efficiency. To achieve maximum efficiency, the regenerative energy should be maximally recuperated from the swing motor to the ultra capacitor and the waste of energy by the engine generator should be minimized. Thus, the speed reference for charging, ω_{rpm_high}, is set with the consideration of loss in the swing action. Because the swing motor has the variable inertia, the loss in the swing action is unpredictable. If the ultra capacitor is charged in advance, the ultra capacitor might not receive the regenerative energy fully due to the variable inertia of swing motor, and all of the surplus regenerative energies are wasted by the engine and overall system efficiency would be degraded. Thus the speed reference for charging should be set as described in Table III.

TABLE III
SPEED REFERENCE FOR CHRAGING

Present State	Output (Action)
000	$\omega_{rpm\_high} = \omega_{rpm\_high} + K * T_{samp}$
001	$\omega_{rpm\_high} = \omega_{rpm\_high} - K * T_{samp}$
010	$\omega_{rpm\_high} = \omega_{rpm\_high}$

K = gain for integral term, T_{samp} = sampling time.

"000" state means that there is the surplus regeneration energy because the ultra capacitor is charged in advance. Thus ω_{rpm_high} should be increased in "000" state. "001" state means that the insufficient energy is charged to ultra capacitor during swing action. So ω_{rpm_high} should be decreased in "001" state. According to Table III, the speed reference for charging of the ultra capacitor can be set adaptively.

Considering the aforementioned conditions, the state diagram is configured such as the Table I-III. In the case of the proposed configuration, there are total 3 states since the primary energy source is only the engine generator.

C. *Voltage Observer of Ultra Capacitor*

Since the swing motor is operated independently from the hydraulic pump in the standard excavating mode, the maximum pump power is required for the excavating action, not for the swing action. So, it is necessary to charge the ultra capacitor rapidly not to incur the influence on the excavating action when the ultra capacitor is charged by engine generator. When the control strategy is performed based on dc-link voltage and the power is applied to the ultra capacitor for the rapid charging of the capacitor in step manner, there are severe oscillations of the ultra capacitor voltage and current due to the large ESR (Equivalent Series Resistance) as shown in Fig. 5. In order to avoid these oscillations, the hysteresis band might exist at each state. However, because of the hysteresis band at each state, it is impossible to maintain the maximum acceptable voltage of the ultra capacitor. Additionally, the power control strategy is much complicated than Table I-III. In this paper, an observer of internal voltage for the ultra capacitor is devised to avoid severe oscillations of the ultra capacitor voltage. Thus the rapid charging of the ultra capacitor can be used with the proposed simple control strategy thanks to this estimated internal voltage of the ultra capacitor.

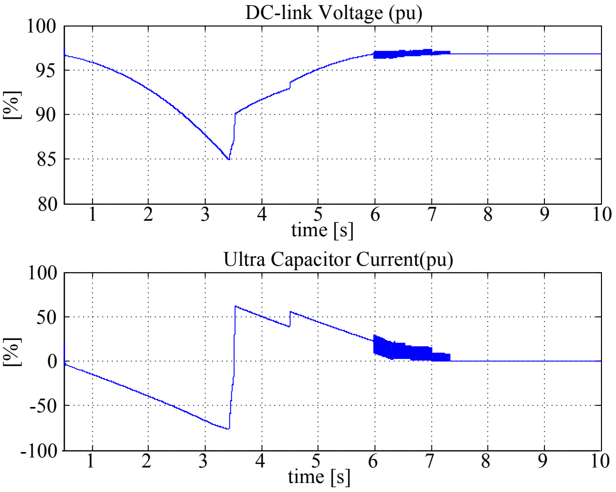


Fig. 5. DC-link voltage and ultra capacitor current when the power is applied to the ultra capacitor in step manner.

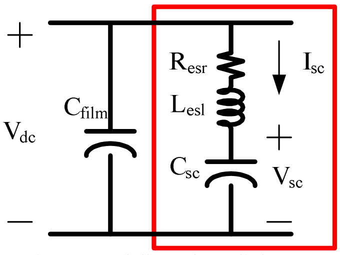


Fig. 6. Modeling of DC-link part.

Fig. 6 depicts the modeling for the dc-link part of the proposed configuration where R_{esr} stands for the Equivalent Series Resistance of the ultra capacitor, L_{esl} stands for the Equivalent Series Inductance of the ultra capacitor, and the C_{sc} stands for the capacitance of the ultra capacitor. The measured output is the ultra capacitor current, I_{sc}, the measured input is the DC-link voltage, V_{dc}, and the estimated state is the internal voltage of the ultra capacitor, V_{sc}.

The voltage and current equation of the ultra capacitor in Fig.6 can be deduced as follows.

$$V_{dc} = V_{sc} + L_{esl}\frac{dI_{sc}}{dt} + R_{esr}I_{sc}$$
$$I_{sc} = C_{sc}\frac{dV_{sc}}{dt} \tag{1}$$

Then the state equation can be presented as (2)-(5).

$$\begin{aligned}\dot{x}&=Ax+Bu\\ y&=Cx\end{aligned}\ , \tag{2}$$

$$A=\begin{bmatrix}0 & \dfrac{1}{C_{sc}}\\ -\dfrac{1}{L_{esl}} & -\dfrac{R_{esr}}{L_{esl}}\end{bmatrix}, \tag{3}$$

$$B=\begin{bmatrix}0\\ \dfrac{1}{L_s}\end{bmatrix}, \tag{4}$$

$$C=\begin{bmatrix}0 & 1\end{bmatrix}, \tag{5}$$

where $x=\begin{bmatrix}V_{sc} & I_{sc}\end{bmatrix}^T$ and $u=V_{dc}$.

In order to implement the closed-loop observer, the observer gain matrix L can be made up such as (6). The closed form of the observer can be deduced as (7) and (9).

$$L=\begin{bmatrix}L_1 & L_2\end{bmatrix}^T. \tag{6}$$

$$\dot{\hat{x}}=\hat{A}\hat{x}+\hat{B}u+L(y-\hat{y}). \tag{7}$$

$$\hat{A}=\begin{bmatrix}0 & \dfrac{1}{\hat{C}_{sc}}\\ -\dfrac{1}{\hat{L}_{esl}} & -\dfrac{\hat{R}_{esr}}{\hat{L}_{esl}}\end{bmatrix}. \tag{8}$$

$$\hat{B}=\begin{bmatrix}0\\ \dfrac{1}{\hat{L}_{esl}}\end{bmatrix}. \tag{9}$$

The transfer function between real value of ultra capacitor voltage and estimated value of ultra capacitor voltage can be expressed by (10)-(12).

$$\frac{V_{sc}}{\hat{V}_{sc}}=\frac{num(s)}{den(s)}. \tag{10}$$

$$num(s)=\hat{C}_{sc}s^2+2\hat{C}_{sc}\beta s+\hat{C}_{sc}\beta^2. \tag{11}$$

$$\begin{aligned}den(s)&=(C_{sc}+C_{sc}\hat{C}_{sc}L_s\beta^2-C_{sc}\hat{C}_{sc}\hat{L}_s\beta^2)s^2\\ &+(2C_{sc}\beta+C_{sc}\hat{C}_{sc}R_s\beta^2-C_{sc}\hat{C}_{sc}\hat{R}_s\beta^2)s+\hat{C}_{sc}\beta^2\end{aligned}\ . \tag{12}$$

The block diagram of the observer for the ultra capacitor voltage is shown in Fig. 7.

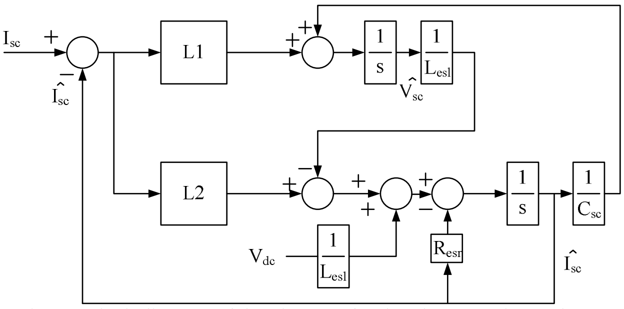


Fig. 7. Block diagram of the observer for the ultra capacitor voltage.

D. Control for the Whole of the system

With consideration of all the factors of the control strategy such as Table I-III and Fig. 7, control method for the whole of the system can be depicted as shown in Fig. 8.

The state transit diagram, Table I-III, decides the power reference of the engine generator and this power reference is converted to the current reference of the engine generator. In order to decide the power reference, the state diagram uses the information of the swing motor and internal voltage of the ultra capacitor. The swing motor power is calculated with the current controller of the swing motor and the internal voltage of the ultra capacitor can be obtained by the ultra capacitor voltage observer. The DC-link voltage and the ultra capacitor current are used to calculate the internal voltage of the ultra capacitor in the voltage observer.

IV. SIMULATION RESULTS

An extensive computer simulation is performed to evaluate the proposed control strategy. For the simulation, it is assumed that there is one cycle of swing motion at maximum inertia. Vdc, Vsc, Vsc_{est}, Isc, Isc_{est} stand for DC-link voltage, real value of internal voltage of the ultra capacitor, estimated value of internal voltage of the ultra capacitor by the observer, real value of current of the ultra capacitor, and estimated value of current of the ultra capacitor by the observer, respectively. To apply the control strategy in Table I-III, it is assumed that there is quite small loss due to the swing action. So, ω_{rpm_high} is set as 200 % of the rated speed of the swing motor and ω_{rpm_low} is set as 0 r/min. Fig. 8 shows that the estimated voltage tracks the real value of the internal voltage well. Contrast to the results in Fig.5, there is no oscillation in the voltage and current of the ultra capacitor. Under the maximum inertia condition, due to the inherent power shortage the swing motor has insufficient output torque to follow the speed reference, ω_{rpm}*. Hence, the real speed of the swing motor, ω_{rpm}, cannot follow the speed reference.

As shown in Fig. 8, in the section of "010" state (1), the estimated voltage of ultra capacitor is in the acceptable voltage range. Also the speed reference of the swing motor is lower than ω_{rpm_high} and higher than ω_{rpm_low}. Thus the "010" state is decided by this condition. At this state, the engine generator is just in idle state.

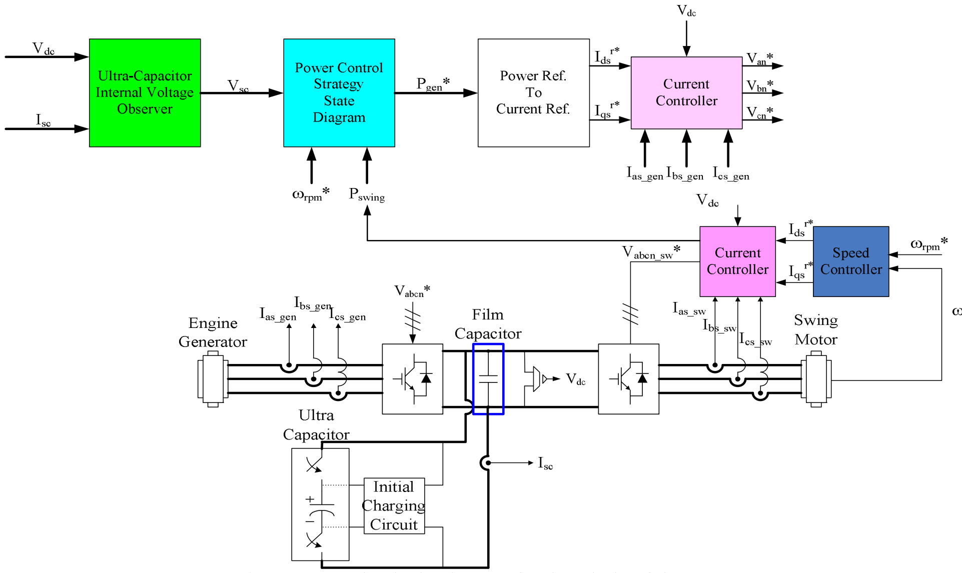
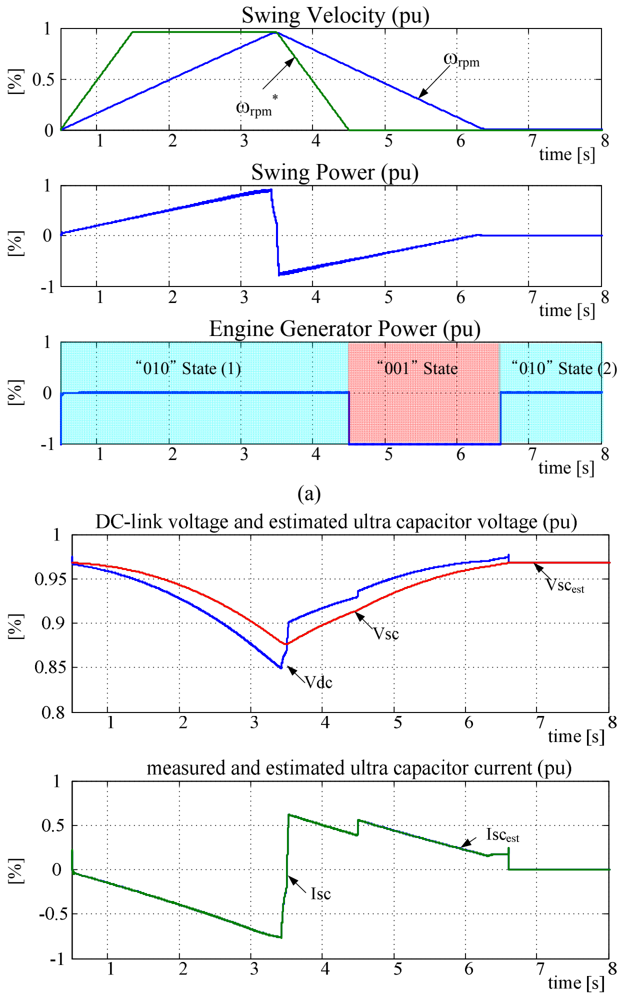


Fig. 8. Control Block Diagram for the whole of the system.



(b)

Fig. 9. Simulation results of the proposed power control strategy.

In "001" state, the estimated voltage of ultra capacitor is in the acceptable voltage range and the speed reference of the swing motor is lower than ω_{rpm_low} where the swing motor produces negative power. When the speed reference is under the ω_{rpm_low} and the swing motor produces regenerative power or zero power, "010" state switches to "001" state. At this state, the engine generator charges the ultra capacitor.

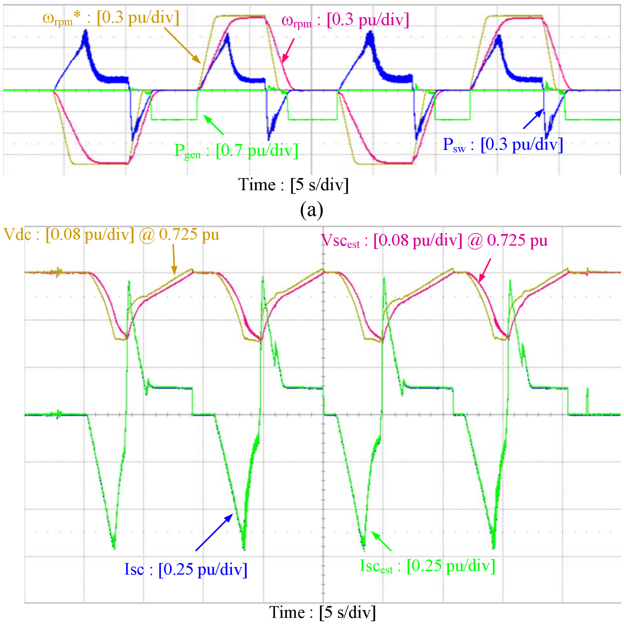
Just before the latter "010" state, designated as (2) in Fig. 9 (a), the estimated voltage of ultra capacitor attains to the maximum acceptable voltage. Hence "001" state switches to "010" state, and the engine generator finishes the charging action.

V. EXPERIMENTAL RESULTS

To verify the feasibility of the simulation results, several experiments have been performed at the maximum inertia of the swing motor. The constructed compound type hybrid excavator is shown in Fig. 10.

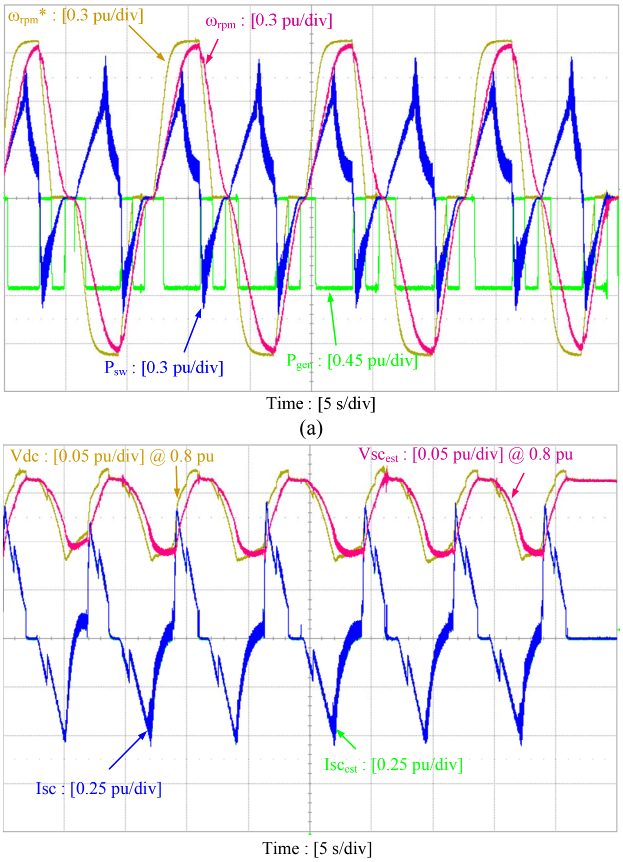
Fig. 10. The compound type hybrid excavator.

As shown in Fig. 11, the experimental results are almost the same with the simulation results. The power reference of the engine generator is generated by the state diagram, Table I-III. The estimated ultra capacitor current tracks well the real ultra capacitor current. At the constant speed of the swing motor, P_{sw}, the power of swing motor, is quite large due to the friction in Fig. 11. At this experiment, ω_{rpm_high} was set 200 % of the rated speed of the swing motor. But there is quite large loss due to the swing action. Because of the increased loss, the time to charge the ultra capacitor is relatively large compared to the simulation results. So, it was necessary for fast charging to change ω_{rpm_high}.



(a)

Fig. 11. The experimental results for the proposed power control strategy : $\omega_{rpm\_high} = 2$ pu.



(a)

(b)

Fig. 12. The experimental results for the proposed power control strategy : $\omega_{rpm\_high} = 0.625$ pu

In the case that the initial value of the ω_{rpm_high} was set as 62.5 % of the rated speed of the swing motor, the experimental results were shown as Fig. 12. The charging of the ultra capacitor is finished as soon as the swing speed is zero. It means that the loss during the swing motion is fully compensated.

VI. CONCLUSION

In this paper, the power converter configuration of a compound type hybrid excavator without DC/DC converter is proposed in order to maximize the efficiency and to achieve the higher reliability of the excavator. In addition, the control strategy using state diagram is proposed. An observer for the estimation of the internal voltage of the ultra capacitor is devised to charge the ultra capacitor to the maximum available voltage as soon as possible while suppressing the oscillation of the voltage. To evaluate the proposed strategy, an extensive computer simulation is performed. And the experimental results have been shown to verify the feasibility of the simulation results based on the actual mid-sized excavator. A measurement of fuel efficiency for the constructed hybrid excavator is now on the process to verify the validity of the proposed system configuration.

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