Development of Power Train of Hybrid Power Excavator

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Abstract

In this paper, a 20-ton prototype compound hybrid excavator is presented which includes assisting electric motor, swing electric motor, a super capacitor pack, an engine and negative flow hydraulic system. The energy-saving principle of hybrid excavator is introduced as well. The development rules of power train which include parameter design rules of key components and hierarchical structure of control strategy of hybrid power system are presented. By developing the electric swing control strategy and power management algorithm, experiments show that the developed hybrid power system can significantly improve the fuel economy of the excavator.

Key words: hybrid power, excavator, power train, swing system

1 Introduction

Energy is consuming up and pollution is more and more serious nowadays, so research on energy saving of hydraulic excavators has great significance because of their large application quantities, high energy consumption and bad exhaust. The efficiency of hydraulic excavators is only 22%[1], because of the lower efficiency of the engine and hydraulic system. To raise the system efficiency of excavators, hybrid power system, which is successfully applied in automobile industry, has been already introduced into construction machinery. In construction machinery industry, researchers also actively developed various kinds of construction machines based on hybrid concept. KOMATSU construction machinery company is the first one which promoted hybrid excavator into the market in 2008.

A lot of research work has been conducted in automobile industry, but those research achievements cannot be directly applied in the development of hybrid excavators because of the difference of working condition and load. However, only a few literatures on hybrid excavators which focus on the research of power train system configuration[2], simulation research[3] and control strategy[4,5,6] can be retrieved. Few reports on the development rules of hybrid excavators can be found.

In this paper, the development rules of parameters design and control strategy in hybrid excavator are presented. A 20-ton hybrid excavator is the design target, in which a compound hybrid power configuration is applied, a negative flow hydraulic system is adopted, the hydraulic swing motor is substituted by an electric motor and the super capacitor pack is used as an energy accumulator. According to the typical work condition of heavy mode and the measured load profile, the key parameters design of the power train is proposed and a control strategy characterized by hierarchical structure is presented. Experiments show that the designed compound hybrid excavator can effectively reduce fuel consumption and emission.

2 Configuration and principle

Several kinds of power train architectures of hybrid excavator are presented in[6,7,8,9]. According to the power flow structure of drive train, the hybrid drive train can be classified into three categories such as parallel, series and compound type. The most popular structure is shown in fig. 1 and also adopted as the target excavator structure in this paper. The hybrid excavator includes an engine, a hydraulic pump connected to an output shaft of the engine, hydraulic actuators (bucket cylinder, arm cylinder, boom cylinder and traveling motors) driven by the hydraulic pump, a generator motor connected in parallel to an output shaft of the engine to perform both a generator function and a motor function, a swing motor driving the upper structure of the hybrid excavator, an electric storage device(super capacitor pack) which supplies and receives electric power to and from the generator motor and the swing motor, and a hybrid power controller for coordinating the entire power train composed of the engine, the hydraulic pump, electric actuators and the capacitor pack. The engine, engine assist motor, pump and super capacitor constitutes the parallel hybrid power train; the engine assist motor, swing motor and capacitor constitutes the serial hybrid power train. So this kind of power train is called compound hybrid power system.

The negative flow hydraulic system is adopted in this paper and shown in fig. 2. The pump displacement is controlled by the negative flow pressure pm1, pm2, pump output pressure p1, p2 and proportional valve pressure pf1, pf2. The limit displacement of the pump is determined by pf1 and pf2 which are controlled by the current I. And the relationship of limit input torque and current is depicted in fig. 3.

Negative control metering valve PN1 and PN2 are placed between the control valve and the tank for reducing the loss of the discharge flow rate of the hydraulic pump1 and pump2 returning to the tank. Specifically, in a case where the hydraulic load is not in an operating state, said differently, there is no supplying the operating oil to the cylinders, the amount of the operating oil to be recovered to the tank without being used for the operation becomes great. In this case, because the oil passage is choked by the negative control metering valve PN1 and PN2, the negative control pressure Pm1 and Pm2 becomes higher than a predetermined value, the operating oil is supplied to the regulator to reduce the swash plate of the hydraulic pump. With this, when the hydraulic load is not in the operation state, the flow rate Q of the hydraulic pumps is decreased to restrict circulation of useless operating oil.

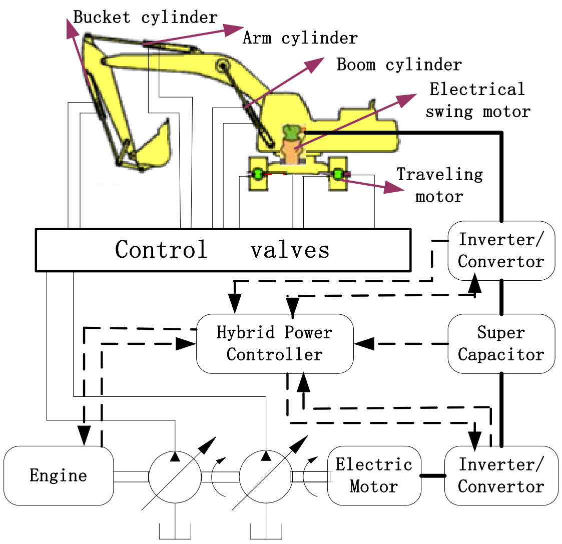


Figure 1: Configuration of hybrid powertrain

According to different working condition and requirements, excavators have various operation modes such as a heavy digging mode(H mode), a standard digging mode(S mode), and a finishing leveling mode(L mode). For different operation mode, excavators have different maximum output power. So the power output of the engine and hydraulic pumps are adjustable according to the operation mode.

The rotational speed of the engine is set by the engine controller which is mounted on the engine. Further, an electromagnetic proportional valve which controls the pressure Pf1 and Pf2, is connected to pump regulators, and the regulators control the displacement of the hydraulic pumps. A pump control current I for adjusting the tilting angle of the swash plates of the hydraulic pumps is controlled by the hybrid power controller.

In the case of performing a light-load operation, the motor-generator is operated to generate power to charge the super capacitor pack using a portion of the engine output, while in the case of performing a heavy-load operation, electric energy is provided from the super capacitor to supplement the engine. At a time of a driving operation, the swing motor works in the motor operation and the super capacitor pack supplies energy to the swing motor to drive the upper structure. At a time of braking revolution, the controller switches the swing motor into the power generating operation and inertia energy of the upper structure is regenerated and charged into the super capacitor pack. In such a way, the load exerted on the engine is leveled into the economical area and kinetic energy of upper structure is regenerated, so the hybrid excavator should work more efficiently than hydraulic excavators. But the system is also more complex, so how to design the key parameters of components and control strategy is a puzzling problem.

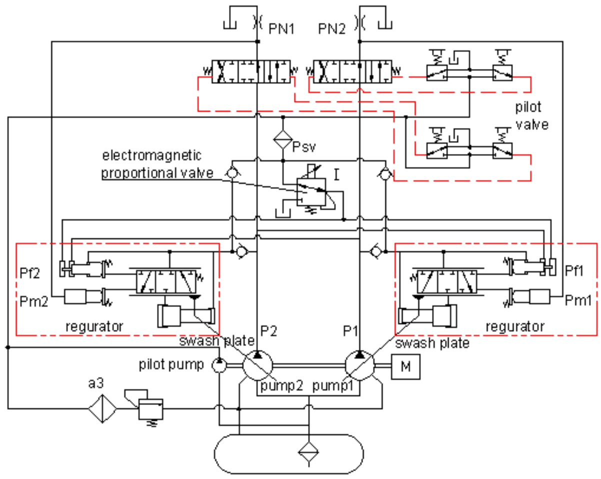


Figure 2: Negative flow hydraulic system

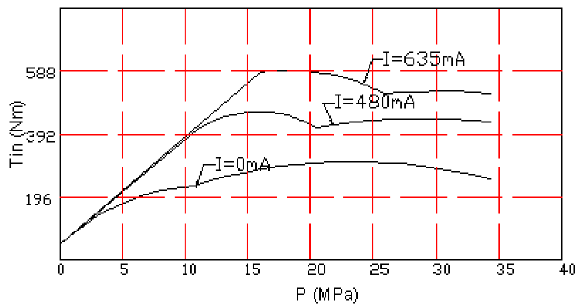


Figure 3: Relationship of torque and pressure of pump

3 Key parameters design

Fig. 4 is a graph showing a transition of absorption power of the hydraulic pump in one cycle when “an excavating and loading operation” in which excavated earth and sand are rotated and loaded into a damp vehicle is carried out in “H mode”. The red solid line is the total power output used for boom, arm, bucket, and swing motor; and the blue dash line is the power output for driving the upper structure. The characteristics of the load profile: (1) Load change is very sharp as compared with a passenger car; (2) Work capacity of the excavator is not fully utilized at all time; (3) Kinetic energy of upper structure is substantial and occupies 12% of the total energy. How to design the key parameters according to the load profile is described below.

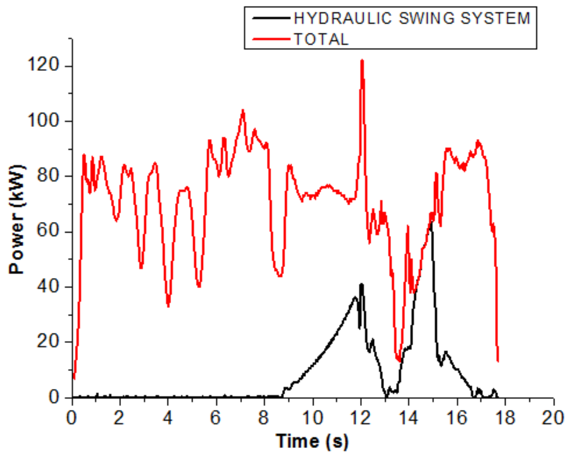


Figure 4: Load profile of 20-ton hydraulic excavator

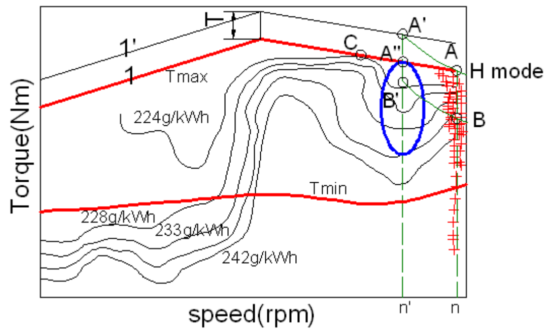


Figure 5: Operation points of engine

3.1 Engine

Engines of excavators are usually constantly rotated at a predetermined speed which set by operators manually according to the excavating job at hand. Usually, there are five engine speeds or five operating modes. It should be emphasized that load torque is distributed widely from very low torque to very high torque for each operating mode. In fig. 5, the operation points of the engine of hydraulic excavators during a cycle of "excavation and loading" in H mode are plotted on the brake specific fuel consumption map. In this case, the operators set the engine speed at its rated point, namely n, to utilize the full extent of working capability of the conventional excavators. The red-cross signs indicating operation points are strayed from the optimum area which is indicated by blue ellipse. The objective of the hybrid power is to improve the fuel consumption rate during the whole excavating operation. So, moving the engine operating region to high efficiency region on the fuel map from the low efficiency region operation via elaborate use of the hybrid structure is natural and reasonable. Therefore, setting the engine speed at n' is more reasonable.

The maximum system power of the hybrid excavator is determined based on the maximum power (i.e., maximum engine power)of the hydraulic excavator with equivalent operating capabilities and is typically set to be higher than the maximum power of the hydraulic excavator due to the efficiency of energy transfer. As shown in fig. 5, AA' and BB' are equal power curves. Point A is the maximum power and Point B is the average power for the engine operation in H mode of hydraulic excavators. In order to retain the same operating capabilities, Point A and Point B are shifted to Point A' and Point B'. The engine torque at the speed n' T(A'') should conform to Equation (1).

$$T_{B'} < T_{A''} < T_{A'} \qquad (1)$$

The hybrid excavator can assist the engine by the electric motor, Therefore, the maximum output required by the engine can be decreased. Thus, a small engine or smaller power may be utilized.

3.2 Pump

In order to retain the same output power of the pump, the set engine speed is lowered to n', meanwhile the limit input torque point is shifted from A to A'. Therefore the limit displacement of the pump is increased according to Equation (2).

$$D' = D\frac{n}{n'} \qquad (2)$$

3.3 Engine assisting motor

By enlarging the pump displacement, the maximum absorbed torque of the pump is increased beyond the maximum available torque of the engine at the speed n', therefore the generator /motor torque should compensate for the excessive power. Besides, the dynamics of the power train has to be taken into consideration. For example, the engine operation is to set engine to the point shown as A''. When load occurs, the engine operation droops to Point C, due to the delay of the compensation and the dynamics of drive train, which causes the machine response to suffer, excessive fuel consumption and more emission. In such a case, if the generator/motor performs a "transient torque assist" function, the engine can operate at a more fuel efficient speed and maintain machine response. Therefore T_m should satisfy Equation (3) and Equation (4).

$$T_m = T + J\alpha \qquad (3)$$

The first term on the right side of Equation (3) is the increased torque, and the second term is determined by the acceleration and equivalent inertia when the engine decelerates.

For a typical excavation and dumping operation, energy balance equation (4) also should be conformed to.

$$\int_{t_0}^{t_f} T_g \omega dt \eta_g \eta_c = \frac{\int_{t_0}^{t_f} T_m \omega dt}{\eta_m \eta_d} + \frac{\int_{t_0}^{t_f} T_s \omega_s dt}{\eta_{sm} \eta_d} - \int_{t_0}^{t_f} T_s \omega_s dt \eta_{sg} \eta_c \qquad (4)$$

3.4 Swing motor

The maximum equivalent inertia of the upper structure can be obtained through the hydraulic motor displacement, the cracking pressure of the relief valves installed in the swing circuit and the acceleration time. Therefore, the maximum torque and speed of the swing motor can be estimated as in Equation (5) and Equation (6).

$$T_{s\max} = \frac{P_r q_m}{2\pi} \quad (5)$$

$$n_{s\max} = \frac{n_{rated} q_p}{q_m} \quad (6)$$

3.5 Super capacitor

In order to meet the demand of supplying or receiving electric energy to generator/motor and swing motor together, the power of super capacitor should satisfy Equation (7).

$$P_c \geq P_s + P_a \quad (7)$$

During a working cycle, the energy charged into super capacitor is shown in Equation (8), therefore the capacity of has to satisfy Equation (9).

$$E_{c\max} = \int_{t_0}^{t_f} T_g \omega dt \eta_g \eta_c + \frac{\int_{t_0}^{t_f} T_s \omega_s dt}{\eta_{sm} \eta_d} \quad (8)$$

$$C = \frac{2E_{c\max}}{V_{\max}^2 - V_{\min}^2} \quad (9)$$

According to the rules and load profile, key parameters are shown in table 1:

Component	Parameter	Value
Engine	Rating power	113kW
	Rating speed	2000rpm
Assist motor	Rating power	30kW
	Rating speed	2000rpm
Swing motor	Rating power	60kW
	Rating speed	3800rpm
Super capacitor	Rating capacity	10F
	Maximum voltage	350V
	Minimum voltage	280V

4 Control strategy

The hybrid excavator is an integrated system that consists of many sub-systems including engine, generator/motor, capacitor pack, swing motor and pump. Each sub-system is also a complex system that has its own functionality and desired performance. In this case, almost every subsystem is equipped with its behavior. Moreover, all sub-systems need to be coordinated in an optimal manner to achieve different objectives, e.g. fuel economy, emissions reduction, charge balance, and drivability. With this increasing complexity of power train system and the need of achieving multiple objectives, an integrated machine-level controller is required to accomplish the task.

4.1 Hierarchical structure

The hierarchical structure of control strategy is proposed in fig. 5. It is decomposed into three layer, management layer, control layer and executor layer.

Based on the working condition and driver's expectation, drivers operate the excavator, such as pilot handles, and mode selection switch and increase power button, which produce corresponding signals. The hybrid power controller represents a high-level control system that can coordinate the overall power train to satisfy certain performance target such as fuel economy and emissions reduction. The high-level power controller must determine the desired output to be generated by the sub-systems (e.g. engine speed, motor torque, proportional valve current for pump, etc.). These desired output signals are sent to the corresponding sub-systems and become the commands for the lower-level control system of each sub-system. The executor layer controller include engine electronic control unit, generator/motor controller, swing motor controller, and super capacitor monitor unit, which are normally provided by sub-system supplier. The data exchange between control layer and executor layer is implemented through CAN BUS communication.

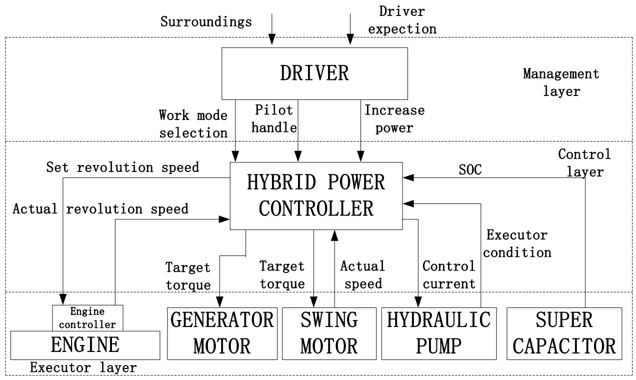


Figure 6: Hierarchical structure of control strategy

The hierarchical structure makes it possible to simplify and expedite the control design. However, a systematic design approach for the high-level control system in hybrid excavator is still lacking and needs to be developed.

4.2 Power management strategy

The term "power management" refers to the design of the higher-level control algorithm that determines the proper power (torque) level to be generated, and its split between the generator/motor and the engine while satisfying the power (torque) demand from the pump and the swing motor, maintaining adequate energy in the super capacitor.

The intuition of "hybrid power" is based on the concept of "load leveling", which attempts to operate the irreversible energy conversion device such as engine in an efficient region and uses the reversible energy storage device as a load-leveling device to compensate the rest of the power demand. However, due to the unknown nature of future power demand, a charge sustaining strategy is needed to maintain the SOC level of the super capacitor. The voltage range of super capacitor is separated into three regions, as shown in (9), and the normal range is from SOC_L to SOC_H. The other two regions are retained for swing motor in such cases that the generator/motor and the swing motor work together. Control strategy based on rules is designed below.

$$SOC_{\min} < SOC_L < SOC_H < SOC_{\max} \qquad (9)$$

（1） If $SOC > SOC_H$, then

If $T_{pump} > T_{\max}$， then $T_m = T_{pump} - T_{\max} + a \cdot \Delta\omega$;

If $T_{\max} > T_{pump} > T_{\min}$， then $T_m = a \cdot \Delta\omega$;

If $T_{pump} < T_{\min}$， then $T_m = 0$;

（2） If $SOC_H > SOC > SOC_L$, then

If $T_{pump} > T_{\max}$， then $T_m = T_{pump} - T_{\max} + a \cdot \Delta\omega$;

If $T_{\max} > T_{pump} > T_{\min}$， then $T_m = a \cdot \Delta\omega$;

If $T_{pump} < T_{\min}$， then $T_g = T_{\min} - T_{pump}$;

（3） If $SOC < SOC_L$， then

If $T_{pump} > T_{\min}$， then $T_m = 0$;

If $T_{pump} < T_{\min}$， then $T_g = T_{pump} - T_{\min}$;

4.3 Control strategy of swing system driven electrically

The upper structure is characterized by the large and variable swing inertia which varies with the posture of the upper structure and payload in the bucket. Most researchers are only interested in the swing speed control of the upper structure [5,6]. But some occasions on which the motor torque need also to be controlled are neglected, therefore in this paper a compound(speed mode and torque mode) control strategy is proposed, and the control scheme is shown in fig. 7.

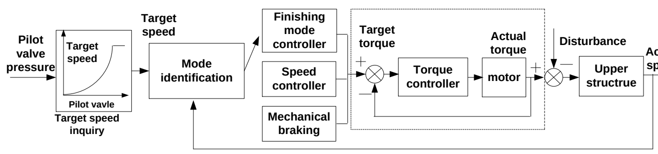


Figure 7: Control strategy of swing system driven by electric motor

Mode identification method and corresponding controller are shown below:

1, If $n_0 - n > \varepsilon$, then torque control mode is applied;

$T_0 = (n_0 - n)k$;

2, If $n_0 - n < \varepsilon$, then PI(proportional integral) is applied;

3, If $P_1 = 0$ and $P_2 = 0$ and $n < n_m$ then mechanical braking is applied;

5 Experiment results

The prototype of 20-ton hybrid power excavator and power train are shown in fig. 8 and fig. 9 respectively. The prototype excavator is equipped with the aforementioned electrical components, which are a generator/motor, an electric swing motor, a super capacitor pack and a hybrid power controller.

Figure 8: Prototype of 20-ton hybrid power excavator

Figure 9: Swing motor and engine assisting motor

Fig. 10 shows the swing control performance for PI controller and the presented compound strategy. It is obvious that during the acceleration the speed overshoot is produced for PI controller while for the compound strategy it accelerates smoothly. Moreover, the swing motor is controlled to stop more smoothly than the hydraulic swing motor, without any jerks that a driver might feel discomfort. fig. 11 shows the experiment results for 180^{o} swing operation. The motor speed and torque are shown in (a), and the current and voltage of super capacitor are shown in (b). The swing motor accelerates and decelerates smoothly and the kinetic energy can be recovered during the deceleration.

For the excavation and dumping operation, engine operation points of the 20-ton hybrid power excavator are shown in fig. 12. Compared to the operation points in fig. 5, the operation points of hybrid excavator engine are converged around the high efficiency area. Except that, for the same capacity, the energy used to drive the auxiliary components such as cooling fan, cooling pump, etc also can be reduced due to engine speed is lowered.

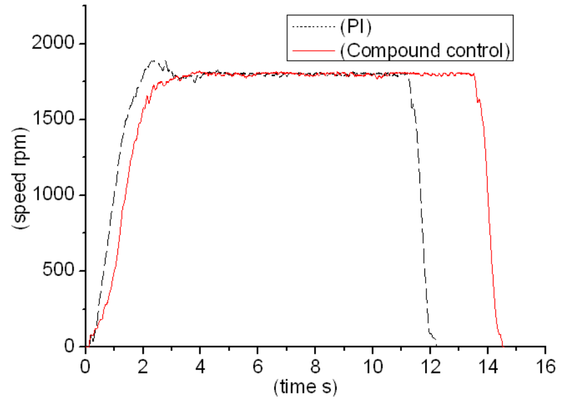
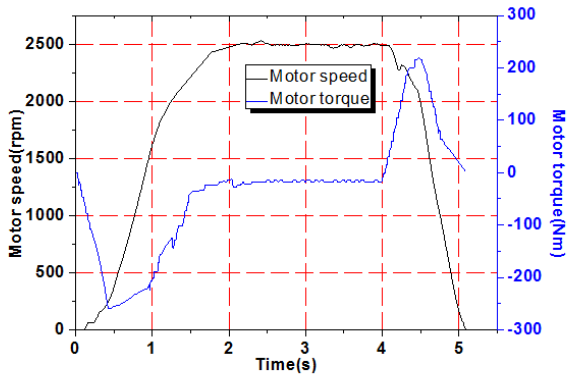
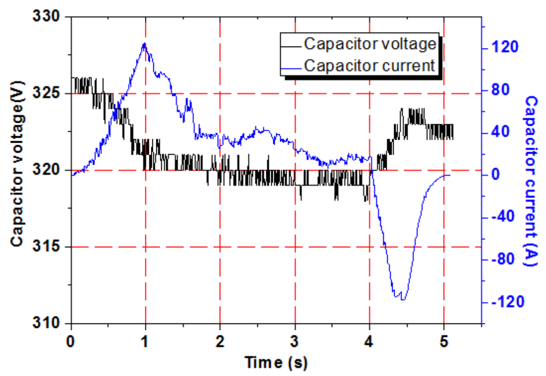


Figure 10: Swing motor speed



(a) Speed and torque of motor



(b) Voltage and current of super capacitor

Figure 11: 180^o swing operation

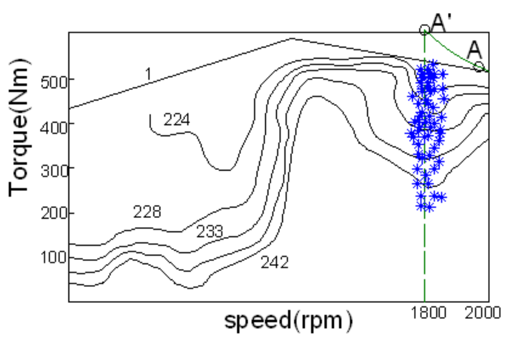


Figure 12: Engine operation point

6 Conclusion

In this paper, a 20-ton prototype compound hybrid excavator is presented which includes assisting electric motor, swing electric motor, a super capacitor pack, an engine and negative flow hydraulic system. The energy-saving principle of hybrid excavator is introduced as well. The development rules which include parameter design rules of key components and hierarchical structure of control strategy of hybrid power system are presented. By developing the electric swing control strategy and power management algorithm, experiments show that the swing motor accelerates and decelerates smoothly and the kinetic energy can be recovered during the deceleration, the developed hybrid power system can significantly improve the fuel economy of the excavator without any performance degradation or drivability deterioration.

Nomenclature

Designation	Denotation	Unit
D'	limit displacement of hybrid excavator	$[cm^3/r]$
D	limit displacement of hydraulic excavator	$[cm^3/r]$
T_m	maximum torque as motor	[Nm]
J	equivalent rotary inertia of drive train	$[kgm^2]$
α	acceleration of drive train	$[rad/s^2]$
T_g	maximum torque as generator	[Nm]
ω	engine revolutionary speed	[rpm]
η_g	mean efficiency as generator	[%]
η_m	mean efficiency as motor	[%]
η_c	mean charge efficiency of super capacitor	[%]
η_d	mean discharge efficiency of super capacitor	[%]
T_s	torque of swing motor	[Nm]
ω_s	rotary speed of swing motor	[rpm]
η_{sm}	mean efficiency as swing motor	[%]
η_{sg}	mean efficiency as swing generator	[%]
$T_{s\max}$	maximum torque of swing motor	[Nm]
$n_{s\max}$	maximum rotary speed of swing motor	[rpm]
P_r	cracking pressure of relief valve	[Mpa]

q_p	displacement of pump	[cm^3/r]
q_m	displacement of hydraulic motor	[cm^3/r]
P_c	power of super capacitor	[kW]
P_s	power of swing motor	[kW]
P_a	power of generator/motor	[kW]
$E_{c\max}$	Maximum storage energy	[J]
C	Capacity of super capacitor	[F]
$V_{\max}$	Maximum voltage of super capacitor	[V]
$V_{\min}$	Minimum voltage of super capacitor	[V]
n_0	Target speed of swing motor	[rpm]
n	Actual speed of swing motor	[rpm]
n_m	Mechanical braking speed	[rpm]
ε	Swing speed threshold	[rpm]
P_1	Pilot valve1 pressure	[Mpa]
P_2	Pilot valve2 pressure	[Mpa]

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