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Review

A review of developments in energy storage systems for hybrid excavators

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ABSTRACT

Hybrid technology applied to vehicles and construction machineries is one of the promising technologies to address environmental challenges. The energy storage system with higher power density, higher energy density, small size, long lifetime and low cost is essential for the hybrid system. This paper firstly analyzes the difference among the energy storing elements especially for battery and super capacitor (SC). Secondly, the advantages and disadvantages of different structures of energy storage systems are analyzed and compared. Thirdly, the energy storage systems and control strategies in hybrid excavators designed by different manufacturers and research institutions are analyzed in detail. Finally, the challenges in the energy storage system of hybrid excavators are discussed.

Contents

1. Introduction

As global warming and environmental pollution is getting increasingly serious, energy saving and emission reducing have become concerns all over the world [1,2]. As one of the most widely used construction machineries, the excavator usually consumes lots of fuel

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and produces a lot of emissions. To save energy and reduce emissions in excavators and other construction machineries, hybrid power technology is quite promising.

The ESS (Energy Storage System) is very important in a hybrid system with ICE (Internal Combustion Engine) and motors/generators. Due to the different power requirements and ESEs (Energy Storing Element) used in hybrid systems, different structures of ESS are proposed. The goal of this paper is to give a review of the ESS in hybrid excavators.

Initially, advantages, disadvantages and structures of different ESEs are analyzed and compared in this paper. In addition, the current research on ESS of hybrid excavators is discussed. Additionally, the paper focuses on the control strategy of ESS in detail. Finally, the challenges the ESS of hybrid excavators are facing are presented.

2. ESS of hybrid excavator

2.1. Comparisons of different ESEs

Different ESEs are adopted in different energy storing systems for energy demand. For example, flywheel is widely used in hydro systems, while accumulator is widely used in hydraulic systems [8], and battery or SC (Super Capacitor) is usually used in hybrid vehicles and construction machineries. Now people are exploring the combination of applications with a variety of energy sources, including electric power, wind power, solar energy, fuel cell and even superconducting magnetic energy [3–7]. As shown in Table 1, Nehrir et al. [9] summarized which type of energy storage devices is used in hybrid systems with different RE (Renewable Energy)/AE (Alternative Energy) power generation technologies. T. Bocklisch [9] compared various different energy storage technologies in terms of storage duration, energy density, power density, cycle efficiency, response time, cycle lifetime, costs storage duration, etc.

In a hybrid system, SC and battery are the two widely used ESEs. SCs have a higher efficiency and longer life cycle than batteries, while batteries have higher energy density than SCs [10–21]. As for the battery, there are mainly lead-acid batteries, Ni-MH batteries and the lithium batteries. The Ni-MH battery and lithium battery are the most commonly used batteries in hybrid systems [22]. Table 2 is the comparison among the common ESEs.

2.2. Structure of ESS of hybrid system

The structure of ESS can be determined only after determining the Bus type. Nehrir et al. [9] classified the ESS into three types: DC-Coupled systems, AC-Coupled systems and Hybrid-Coupled systems according to the type of the energy sources and loads.

Due to the structure complexity and space limitation of hybrid systems, DC Bus is widely used in hybrid vehicles and construction machineries. The main structure of DC Bus is shown in Fig. 1. In hybrid vehicles or construction machineries, the structure of ESS is decided by the type of the motor/generator. If a DC motor/generator is used in the hybrid system shown in Fig. 1(a), a DC-DC converter is necessary if the voltage between the DC motor/generator and the ESS doesn't match. In another situation, if an AC motor/generator is used shown in Fig.1(b), an AC-DC converter is necessary.

Regardless of the motor/generator type, the structures of the ESS are classified as these types as follows.

(1) ESS with single ESE

The biggest advantage of ESS with single ESE is its simple structure and less energy conversion as shown in Fig. 2. While batteries, according to the merits and drawbacks of batteries and SCs shown in Table 2, have enough energy density to supply the power requirements in acceleration of the vehicles, the situation in hybrid excavators is more complex. In small-size excavators, batteries are utilized widely. However, in the medium-size and large-size excavators, SCs are used more widely due to the complex working conditions and power requirements.

(2) Hybrid ESS

Hybrid ESS was used in hybrid vehicles earliest to meet the demands of high power density, high energy density, and also small size and weight [17–23]. In the study [24–27], a structure of ESS with batteries, SCs and fuel cells is adopted. While a structure only with batteries and SCs is much widely used and it makes full use of their merits [28–30].

Ostadi1 et al. [31] concluded seven types of structures about hybrid ESS. The battery, SC and AC electric motor are connected to the DC bus by means of one or two DC-DC converters and a DC-AC converter. Simply, these seven types can be divided into two types: direct connection structure and indirect connection structure [32,33].

The direct connection structure means the SC and the battery are directly connected to the DC bus with no converters shown in Fig. 3(a). The SC voltage and the battery voltage are equal to the DC bus voltage. Whether they absorb energy or release energy, the energy distribution ratio is determined by their internal resistance and it cannot be controlled [30,34].

If the SC or the battery is connected to the DC bus via some power converters such as DC-DCs, it is called an indirect connection structure.

• A structure of the SC connected to the DC bus with a DC-DC converter

Fig. 3(b) is the first indirect connection structure. While charging or discharging, the SC voltage fluctuates intensely which will lead to the voltage fluctuation of the DC bus if there is no power converter between the SC and the DC bus. In this structure, the battery is generally used to provide the average required power of the system and the fluctuation power is provided by the SC. When the SC charges and discharges frequently, the DC-DC converter switches frequently, too. So the system efficiency is reduced.

• A structure of the battery connected to the DC bus with a DC-DC converter

Fig. 3(c) is the second indirect connection structure. In this structure, the system efficiency can be improved because DC-DC switching frequency can be reduced when a battery provides required power and SC provides fluctuation power. Furthermore, input and output terminals of the DC-DC are not connected; the converter could realize input/output isolation. Then the DC-DC converter isolates the battery from the DC bus, so that the influence of current fluctuation on the battery is reduced, the life of battery is extended. However, the SC and the DC bus are connected directly, so the SC voltage changes sharply which will affect the efficiency of the motor/generator. The system efficiency will reduce and the fuel consumption will increase, too.

Table 1
Different energy storage devices used in different RE/AE power generation technologies [9].

Main RE/AE technologies	Energy storage types
Biomass	Battery
Geothermal	Compressed air
Hydro/microhydro	Flywheel
Ocean tidal/wave	Hydrogen
Solar PV/thermal	Pumped hydro
Wind	SMES(superconducting magnetic energy storage)
Fuel cell	Super capacitor
Microturbine	Thermal