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Improvement of boom control performance for hybrid hydraulic excavator with potential energy recovery

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ABSTRACT

Potential energy recovery (ER) is an effective way to reduce energy consumption of hybrid hydraulic excavators; however, the ER system with a direct speed-control strategy is prone to oscillation of actuators due to the reduction of damping in comparison to the conventional throttle governing system. This paper aims to improve the boom control performance of a hybrid hydraulic excavator by properly designing the ER controller. Based on the dynamics of the system, mathematical modeling including hydraulic components and electrical components is carried out. A staged composite control strategy is proposed to achieve acceptable performance in the whole velocity range. Load torque observation is employed to increase the speed stiffness of the permanent magnet generator applied in the system as well as the stiffness of the boom motion. The leakage flow which affects the anti-disturbance capability and accuracy of the control system is compensated. Finally, the effectiveness of the proposed control scheme is verified by simulation and experimental results.

1. Introduction

Various technologies are developed to reduce energy consumption and emission with the raising demand of energy saving and environmental protection in the world range. Hybrid power system, which has been successfully applied to vehicles, is also paid much attention in the field of construction machinery, especially hydraulic excavators [1–6]. The hybrid system usually has two energy sources including a combustion engine and an electrical energy storage device. The fuel economy is improved by operating the engine in an optimum efficiency range with a proper control strategy. According to the structures of hybrid systems, hybrid hydraulic excavators (HHEs) can be categorized as series type, parallel type and compound type, of which the compound type hybrid structure is the best solution from the aspects of the fuel efficiency, the additional cost and the expected payback time [6].

In hydraulic systems, energy recovery (ER) is another energy saving method which can be realized by using hydraulic or electrical energy storage devices. The hydraulic approach is to convert the recoverable energy to hydraulic form, store it in a hydraulic accumulator and release it when there are requirements [7–9]. However, it needs additional components such as hydraulic pump/motors or transformers to reuse the recovered energy. The electrical approach, which converts the recoverable energy to electrical form, is more suitable for HHEs, for the hybrid power systems provide electrical energy storage devices such as batteries or super capacitors and the recovered energy can be delivered directly to any electrical actuators. In general, there are two kinds of ER systems in HHEs, including the braking kinetic energy of swings and the gravitational potential energy of booms. The former is similar to the energy regeneration system in hybrid or electrical vehicles which have been studied widely, so this paper concentrates on the latter.

A potential energy recovery system for hydraulic forklift trucks was developed and verified in [10]. In comparison to the conventional machines, the efficiency was increased from 56% to 74% at high velocity and from 39% to 69% at low velocity, but the boom response was more oscillatory. In [11], a similar system was studied and the efficiency evaluation of every component is carried out by theoretical analysis and experimental tests. It is reported that the maximum recovery efficiency was 66.2% and improvements could still be achieved. Researches have also been carried out on the HHEs. In [12], additional hydraulic motor-generator was installed in the return oil line of the boom circuit to recover the potential energy, for most hydraulic pumps could not be used in motoring mode. The results of experiment and simulation showed that the ER scheme was feasible in HHEs. Two different ER configurations were compared in [13]. The simulation results showed that the configuration with a hydraulic accumulator had better control performance; however, it was much more complex and its efficiency was only 41% due to the extra link of energy conversion in the accumulator.

This paper studies the boom control performance of the HHE with a potential ER system where an electrical generator is driven by a hydraulic motor in the return oil line. The control characteristics of the novel system are analyzed based on the dynamic model. In order to improve the comprehensive performance, solutions including composite control strategy, load torque observation, and leakage flow compensation are

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proposed. The effectiveness of the proposed control scheme is verified by simulations and experiments.

The paper is organized as follows. Section 2 presents the structure and parameters of the potential ER system and the experimental platform. Mathematical modeling and analysis are demonstrated in Section 3. Section 4 concentrates on the controller design with the assist of simulations in the MATLAB environment. Section 5 provides the experimental results. Finally, conclusions are drawn in Section 6.

2. Structure and parameters

2.1. System structure

The configuration of the compound type HHE with a potential ER system is shown in Fig. 1. It can be seen that the hydraulic pump is driven by the engine and the electrical machine together. The electrical machine behaves as a motor when the load is heavy and a generator when the load is light. By this way, the working condition of the engine is improved and the fuel consumption is reduced. The conventional hydraulic swing motor is replaced with the electrical motor which can be used to recover the braking kinetic energy. The capacitor's state of charge (SOC) is restrained by a dynamic-working-point control developed in [2].

The boom potential ER system is composed of a hydraulic motor, an electrical generator and a throttle valve. The gravitational potential energy can be converted to the electrical form and stored in the super capacitor when the boom is being lowered down, instead of being dissipated totally in the conventional throttle governing mode. In the proposed mode, the boom velocity is adjusted by controlling the rotational speed of the generator as well as the hydraulic motor. It should be noticed that the throttle valve is necessary in the system, for the oil line should be cut off when the boom is lifted up. Furthermore, the valve can be used to improve the dynamic performance at starting and the low velocity stage, as described in Section 4.

Generally, the energy conversion efficiency and the actuator control performance are two important evaluation indexes of the ER system. The total efficiency is mainly determined by the efficiencies of the recovering components and the hydraulic circuits. The control performance indicates the actuator responses to the movement commands which are usually conveyed through joysticks by drivers. Due to the introduction of the ER system, the operation mode becomes different from the conventional mode. Therefore, the velocity governing performance is also changed and should be reconsidered.

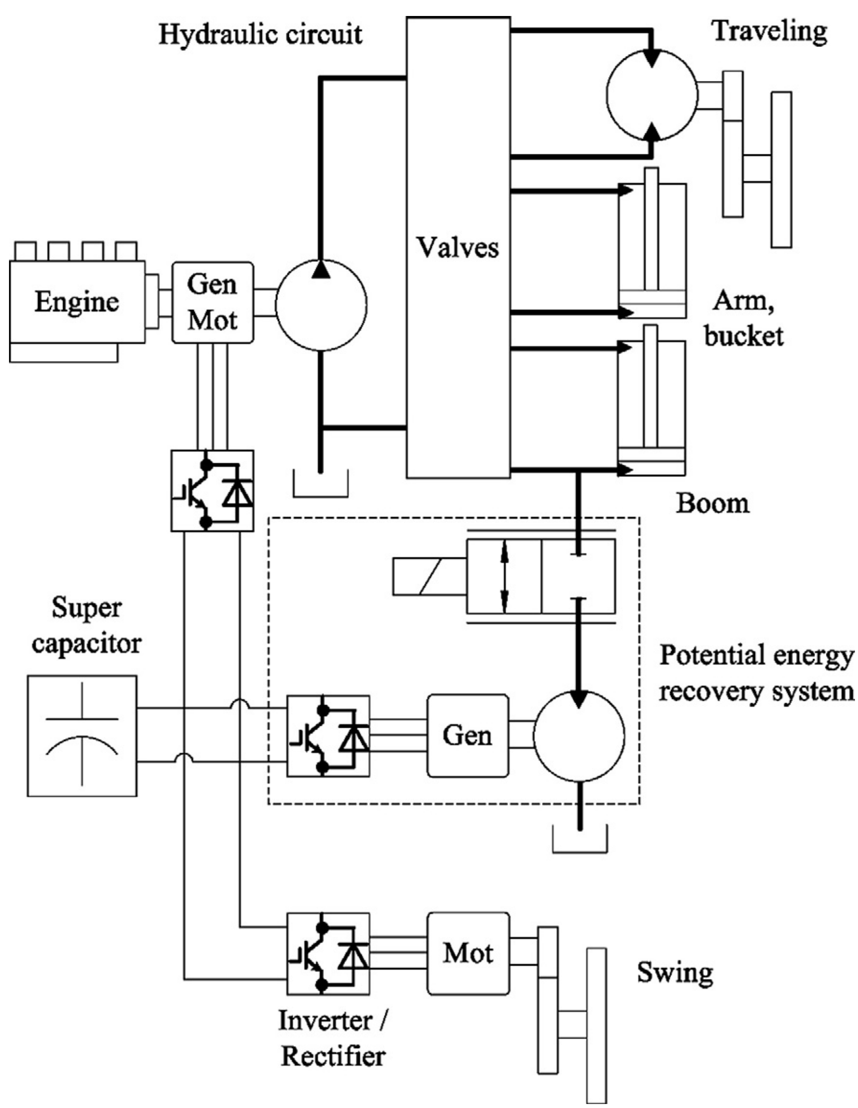

Fig. 1. Configuration of the compound HHEs with potential ER.