Energy Conversion and Management 150 (2017) 62–71

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Efficiency improvement and evaluation of electric hydraulic excavator with speed and displacement variable pump

Lei Ge, Long Quan*, Xiaogang Zhang, Bin Zhao, Jing Yang

Key Lab of Advanced Transducers and Intelligent Control System of Ministry of Education, Taiyuan University of Technology, 030024 Taiyuan, China

A R T I C L E I N F O

Keywords:
Electric excavator
Energy efficiency
Independent metering in and metering out
Speed and displacement variable concepts

A B S T R A C T

Hydraulic excavator driven by an internal-combustion engine is widely used in the construction field. However, some problems, such as high pollutant emissions, noise and low efficiency, exist universally. To address these problems, an electric hydraulic excavator configuration combining with an independent metering in and metering out system is proposed to improve the overall energy efficiency. In this paper, a displacement variable pump driven by a speed variable electric motor is used as power source, and a matching method based on the segmented speed and continuous displacement control of the pump is proposed to meet the requirements of high dynamic, high energy efficiency and zero emission of hydraulic excavator under different working conditions. Then, an independent metering in and metering out system is employed to reduce throttling loss. A test rig with a 6-ton hydraulic excavator was built up and used to validate the proposed scheme. The energy consumption characteristics of the electro-hydraulic power source under different rotational speeds and different loads are further investigated to provide analytical and experimental references for control strategy designing. Furthermore, the working performance and energy distributions of the excavator with the pure displacement variable concept, and speed and displacement variable concept are studied comparatively. Results show that, compared with pure displacement variable concept, the electric power consumption during the idle period can be reduced from 2.05 kW to 0.7 kW, the energy saving ratio under partial load condition can be up to 33%, while it is 28.5% under digging condition.

1. Introduction

Nowadays, hydraulic excavator is widely used in the construction field, and there are millions in use in the world, which is about 1.6 million in China in 2015. In the excavator system, a displacement variable pump driven by an internal-combustion engine is normally applied as power source to supply high-pressure oil, and the four-sides spool valves are used to distribute the flow and to control the actuators. However, the energy efficiency of the internal-combustion engine is poor when the load changes in a wide range, which is only about 35% [1], resulting in a huge waste of resources and serious environmental pollutions [2,3]. Besides, the average energy efficiency of the hydraulic system is only about 54%, and the energy efficiency of the whole machine is only about 10% [1]. Thus, energy saving and emission reducing have been the research focuses in the excavator.

For the power transmissions path, there are two approaches to increase the energy efficiency of hydraulic excavator: one is to improve the matching performance between the load and engine, and the other is to reduce the throttling loss.

In a conventional excavator system, the engine speed of excavator is selected by operator manually according to the excavating job at hand. Usually, there are five operating modes distinguished by the speed. It should be emphasized that load torque is distributed widely for each operating mode. Thus, the engine often works under partial load condition, during which the energy efficiency is poor. Many research efforts have been undertaken to address this issue. A conventional approach is to adjust the engine speed according to load condition [4]. The other is the diesel engine cylinder deactivation technology [5]. However, these two approaches can only improve the economy of the diesel engine in light load. An approach to comprehensively improve the engine efficiency is to add an auxiliary power unit to the system, called the hybrid technology [6–10]. Furthermore, a relatively thorough approach is to use some accumulators to separate the engine from the actuators, allowing optimal engine operation independent of the

Abbreviations: SVPS, pure speed-variable power source; SDVPS, speed and displacement variable power source; PSVC, pure speed variable concept; PDVC, pure displacement variable concept; SSCD, the segmented speed and continuous displacement concept of the pump; IMC, independent metering in and metering out circuit; PMAM, a permanent magnet asynchronous motor

* Corresponding author.
E-mail address: quanlong@tyut.edu.cn (L. Quan).

http://dx.doi.org/10.1016/j.enconman.2017.08.010
Received 3 July 2017; Received in revised form 2 August 2017; Accepted 4 August 2017
0196-8904/

Nomenclature

E_e	electric energy input to the inverter
P_{ei}	electric power input to the inverter
E_h	hydraulic energy output of the pump
p_p	pump pressure
q_o	pump flow
$\eta_{e\text{-}h}$	energy efficiency of the electro-power source
v_{be}	boom cylinder extending control signal
v_{br}	boom cylinder retraction control signal
p_{A1}	pressure of the rod-less cavity of boom cylinder
p_{B1}	pressure of the rod cavity of boom cylinder
q_B	flow into the boom cylinder
E_{hloss}	throttling loss of the hydraulic system
E_{Bhloss}	throttling loss of the boom system
E_{Ahloss}	throttling loss of the arm system
$E_{Buhloss}$	throttling loss of the bucket system
E_{Shloss}	throttling loss of the swing system
E_{Thloss}	throttling loss of the travel system
η_h	Energy efficiency of the hydraulic system
η_{total}	energy efficiency of the excavator
P_{loss}	power loss of the electric motor
P_{out}	power output of the electric motor
ω_m	rotational speed of the electric motor
Ψ_{rd}	rotor flux d axis component for induction machine
R_s	equivalent resistance of stator winding
R_r	equivalent resistance of rotor winding
R_m	equivalent resistance of stator core loss
L_m	mutual inductance between the stator winding and rotor winding
η_m	energy efficiency of the electric motor
η_p	energy efficiency of the hydraulic pump
η_{pv}	volume efficiency of the hydraulic pump
η_{pm}	mechanical efficiency of the hydraulic pump
n	rotational speed of the hydraulic pump
k	proportionality coefficient
C_s	Laminar leakage coefficient
Δp	pressure difference of the hydraulic pump
μ	kinematic viscosity of oil
β	Displacement factor, V/V_{max}
C_V	Laminar drag coefficient
C_f	coefficient of mechanical resistance
T_s	Torque loss independent of speed and pressure difference
V_{max}	maximum displacement of the pump

current power demand [11–16].

Although numerous technologies have been taken to improve the energy efficiency of the hydraulic excavator, this is not the eventual solution. Like the development direction of the automotive industry, the development direction of mobile machine is pure electric drive to eliminate emissions completely and to achieve low noise. And now, this system configuration is used in industrial equipments and some hydraulic shovels. In addition, there are some small hydraulic excavator productions with this configuration, such as Wacker Neuson dual-power 803 and Volvo EX2. This configuration is especially suitable for urban construction and water conservatory reconstruction projects with high environmental protection requirements. In these applications, the electric motor usually operates at its rated speed, resulting in large energy consumption under idle period and partial load conditions. What's more, the displacement-variable pump usually operates in small displacement condition, during which the energy efficiency is poor [17–19]. Currently, one of the ways to deal with this situation is to use a quantitative pump driven by a speed-variable motor, named pure speed-variable power source (SVPS) [20,21]. The other approach is to use a displacement-variable pump driven by a speed-variable motor, named speed and displacement variable power source (SDVPS). It is reported that the energy consumption can be reduced by 20% and more comparing to pure speed variable concept (PSVC) or pure displacement variable concept (PDVC) [22]. Therefore, improved efficiency and reduced energy consumption are two of the main goals during the design period of modern electrohydraulic systems.

However, when the speed-variable power source is applied to a mobile machine, there exist some problems such as dynamic response,

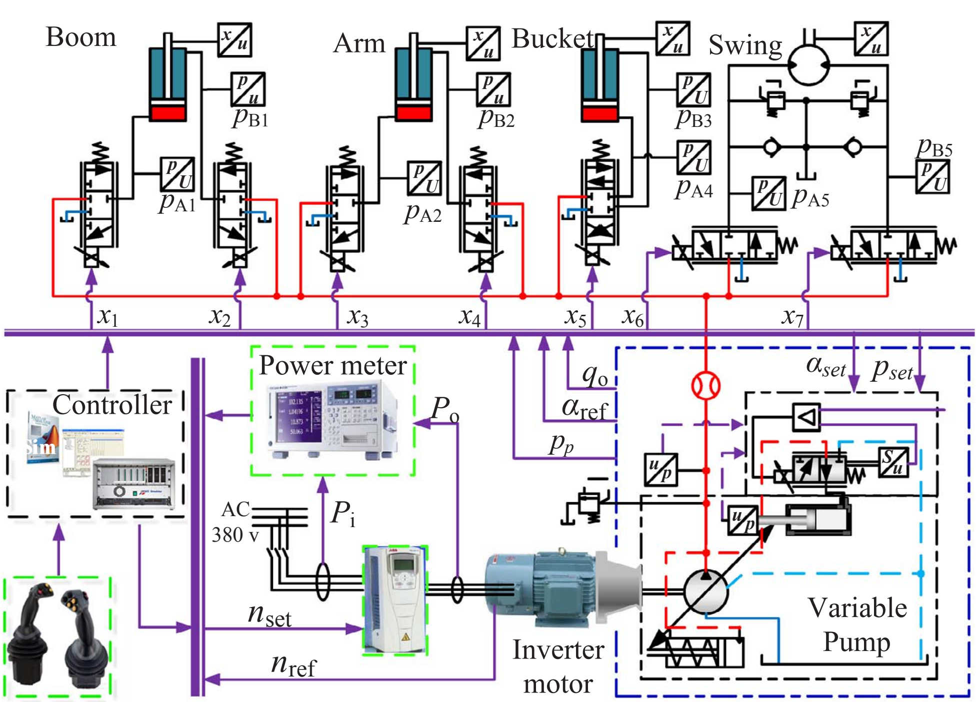

Fig. 1. System structure of electric excavator.