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Energy saving in working hydraulics of long booms in heavy working vehicles

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Hybridization of heavy off-highway working vehicles brings considerable energy savings in the form of a downsized internal combustion engine (ICE) by means of reduced no-load losses. In this paper, a novel energy saving opportunity in working hydraulics at the end of long booms of working vehicles is proposed. In traditional off-highway working vehicles, the working hydraulics is supplied through pipes, hoses, and valves by a hydraulic pump located near the main engine. A significant amount of energy is lost in long pipelines and hoses as well as in valve throttles. A new topology is introduced to supply the power along the long boom; the power for a hydraulic actuator is supplied by an integrated electro-hydraulic energy converter (IEHEC), which is located at the boom end. The electrical energy to the converter is supplied through electrical cables, which have negligible losses compared with a conventional fluid power supply with long pipelines. The converter transforms the electrical energy into hydraulic energy at the end of the boom, and may also recover energy for additional energy savings.

1. Introduction

The development of energy saving technologies for off-highway heavy working vehicles has received increasing interest over the last few years [1–3]. In off-highway heavy working vehicles, work actions require high forces. Because of the high power density, the use of fluid power is a key factor in mobile working vehicles [4]. Components and system designs affect the efficiency of a fluid power system [5]. The efficiencies of individual components such as pumps, hoses, and valves have an impact on the efficiency of the whole fluid power system, but it is also important to consider how these components are combined to meet the load demands [6].

There is also a demand for the development of new electrical components that can better meet the requirements of heavy mobile working vehicles [7]. Especially regenerative braking [8], operation in power-split modes [9], and development of novel types of hybrid transmissions [10] have been in the focus of interest. A common factor for these studies is that the attention is paid to the regeneration of kinetic energy of the chassis powertrain. This requires a higher level of optimization of the power control in order to fully benefit from the savings potential [11]. It has to be noted that in many types of heavy working vehicles, the major losses (but also the largest potential for energy regeneration) occur in the working hydraulics.

Fig. 1 shows a typical off-highway working vehicle with an actuator at the end of a telescopic boom. Conventionally, the actuator at the end of a long boom is supplied by long flexible fluid power transmission lines, Fig. 2. These lines can produce significant losses during the operation. Actuator cylinders are also controlled by valves, which act as fluid resistances, adapting the supply pressure to the load pressure by restricting the flow and converting fluid power into heat [12]. For instance, in hybrid electric trucks, the high-pressure hydraulic transmission lines can be eliminated, and thus, the manufacturing and maintenance of the steering system is simplified by using electric steering systems [13,14]. The hybrid reach stacker by Konecranes saves fuel 30%–50% compared with conventional reach stackers [15].

The energy efficiency of the boom end actuator can be enhanced by using an integrated electro-hydraulic energy converter (IEHEC) [16], which is placed directly at the end of the telescopic boom, see Fig. 3. On the scale of the machine under study, the weight of the IEHEC can be considered almost negligible in comparison with the mass of the gripper and the attached load. The IEHEC is supplied through electrical cables, which have negligible losses compared with a conventional fluid power supply with a long hose. The adverse phenomena of a hydraulic tank moving along the working machine are widely recognized [17]. These include for instance sizing, thermal and suction properties, cavitation, aeration, and filtration. As a rule of thumb, the hydraulic

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Fig. 1. Example of an off-highway working vehicle with a telescopic boom and a massive stacking gripper with its actuators [21].

tank has to be redesigned in order to meet the requirements of the heavily moving environment.

The use of an electro-hydraulically driven actuator fits well the concept of a hybrid diesel-electric drivetrain with an electrical energy storage (e.g. ultra-capacitors or lithium-titanate batteries because of their high peak power capabilities required in heavy off-highway working vehicles) [18–20].

This paper presents an investigation of the energy saving opportunities enabled by the use of a new topology of the long-boom-actuator power line with a new electro-hydraulic device. In Section 2, the parameters of the IEHEC are described. In Section 3, the measured losses in a conventional valve-controlled boom end actuator are analyzed. In Section 4, the energy saving potential achievable by the IEHEC is evaluated.

2. Integrated electro-hydraulic energy converter

The IEHEC consists of a hydraulic machine capable of working in both the pumping and motoring modes without significant charging of inlet pressure and an integrated tooth-coil permanent magnet synchronous machine (TC-PMSM) directly operating on the shaft of the hydraulic machine [16,22,23]. The TC-PMSM is controlled by a frequency converter. Fig. 4 illustrates a cut-away design view of the IEHEC and the first prototype. The main parameters of the IEHEC are given in Table 1.

High power density can be achieved by integration, compact electrical machine construction, and by using effective direct-immersion liquid cooling in the electrical machine. The integrated design allows significant space savings in mobile applications. The savings in length and weight of the motor-pump assembly example of Fig. 5 are 61% and 51%, respectively (the clutch needed in the conventional version is not taken into account).

3. Measurements of the conventional system

The measurements of the conventional system were made under actual working conditions [24]. The pressures and flow rates of a conventional hydraulic system with long hydraulic hoses were defined to determine the power consumption of the boom end actuator, losses in the hydraulic hoses, and throttling. Pressures are measured with Trafag (0…250 bar) pressure sensors, and the position of the cylinder (x) was measured with position sensors. The accuracy of the pressure sensor was 0.3%, and it was assumed that the maximum error of the cylinder position measurements was 0.015 m. The flow rates on piston-side Q_2 and rod-side Q_3 were defined with respect to rate of change of the cylinder length.

$$Q_2 = \frac{\mathrm{d}x}{\mathrm{d}t} \cdot A_{\mathrm{piston}} \quad (1)$$

$$Q_3 = \frac{\mathrm{d}x}{\mathrm{d}t} \cdot A_{\mathrm{rod}}. \quad (2)$$

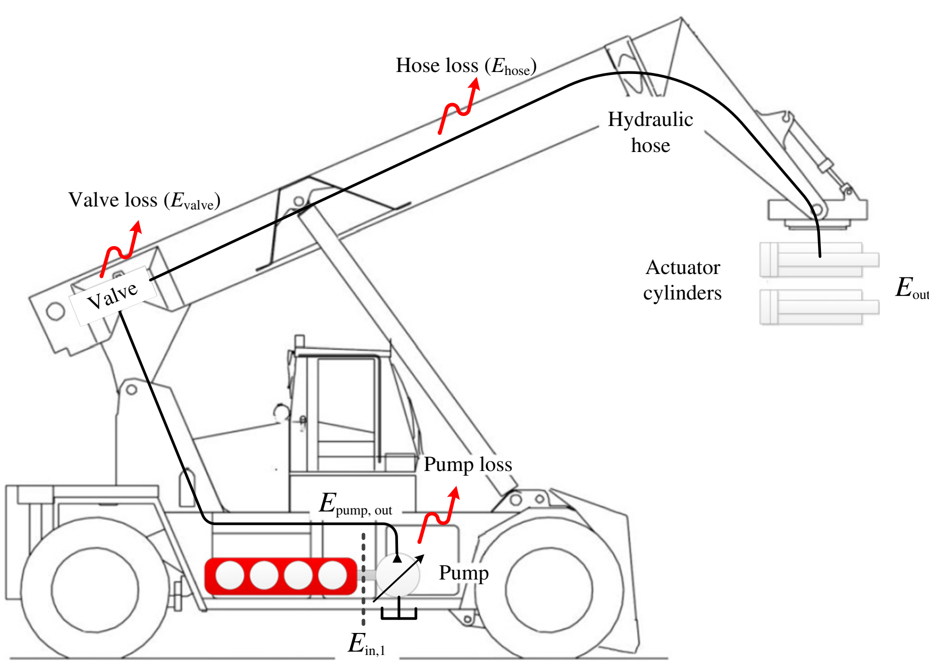

Fig. 2. Conventional boom end actuator, which is supplied by long hydraulic hoses.