Energy Efficiency Comparison of Electric-Hydraulic Hybrid Work Implements Systems

Björn Eriksson , Vivek Bhaskar*, and Ralf Gomm*

Global Mobile Systems (GMS), Parker Hannifin, Borås, Sweden
E-mail: bjorn.eriksson@parker.com
*Technology, Commercialization and Support team (TCS), Parker Hannifin, Charlotte, U.S.A.

Abstract

Increasing attention of electromobility creates new opportunities and even requirements to electrify traditional work implements of mobile machinery. Four possible implement system architectures are presented and compared regarding energy efficiency performance in this paper. The goal of this work is to frame the upper and lower end of system value versus complexity characteristics. Thus, an electrically powered load sensing circuit, E-LS, serves as a reference system (low added complexity, low added value) while a four quadrant electro-hydrostatic actuation, EHA, system (high added complexity, high added value) is found in the other end of the comparison. An electrically powered flow controlled system, E-IFC, and a electrically powered pump controlled system, E-PCA, are also investigated in the same framework to make the study comprehensive. A two actuator wheel loader system and a short cycle loading drive cycle serves as the platform for comparison. The results yield a 45% reduction of energy consumption with the EHA system compared to the E-LS system. This is equivalent to 82% fuel efficiency improvement.

Keywords: Hydraulics, Fluid Power, Electromobility, Efficiency, Electric Systems, Hybrid, e-LS, e-IFC, e-PCA, EHA

1 Introduction

Fuel efficiency has in the late years become a driver of technology development in the industry. Research and development in the area are extensive in both academia and industry. To minimize the dependency of fossil fuel many OEMs are investigating the use of electricity as energy carrier and storage. The electromobility era is here.

Mobile applications use internal combustion engines, ICE, as primary power source. During a work cycle, flow and pressure demands vary. The ICE efficiency is a function of the operating point, i.e. speed and torque at the engine shaft. Typically, with hydraulic implements the pump units are mechanically directly connected to the ICE. This implies that the ICE torque and speed vary with the load during operation.

A common approach when designing energy efficient mobile systems today is to decouple the load from the ICE. This can be done in various ways. The decoupling opens up the opportunity to run the ICE in or close to the efficiency sweet-spot. From a general perspective, a transmission of some kind is needed that is able to transform between the flow and effort variables. Either between torque and speed, pressure and flow or voltage and current. The criteria is that the product of the two is constant[1]. Further, if a large enough energy storage is included in this transmission both speed and torque can be chosen freely by the control system, independent of the load. Smoothing the power demand from the ICE avoiding peak demands.

This paper is limited to and focused on electric supplied hydraulic implement systems. Further, the drive-line is not studied. The systems are supplied from a common electric supply, a direct current bus, DC bus.

The systems in this paper can be split into two groups

Central pump without recovery The E-LS and the E-IFC systems use a single centralized pump approach where the functions share the supply. The pump handles only power in one direction with no recovery to the DC bus through the electric machine.

Independent pumps with recovery The E-PCA and EHA systems use one pump for each function and these pumps are also able to recover power back to the DC bus.

Hybrid mobile vehicles also often include redesigned drive-lines for the same reasons mentioned above.

The aim of this work is to compare different systems solutions electrifying the implements in a mobile application. The ap-

[1]Constant product of flow and effort variable is equivalent to constant power.

plication in this study is a wheel loader. The electric supply is not considered. System boundaries start at the DC bus and end at the function cylinders, see Figure 1.

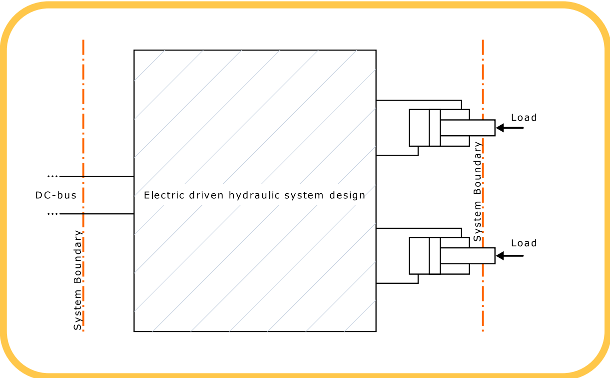


Figure 1: System boundary of studied system

The following studied systems take origin in conventional architectures presented in earlier works, but now with electrification. The exception is EHAs, which are not commonly used in traditional mobile hydraulic systems and are already electrified in all existing applications. The studied systems are

Electric load sensing, E-LS LS systems are considered as the state-of-the-art systems of today in mobile machinery, see for example [1] in [2], [3] in [4] and [5]. The most straight forward way of implementing an electric supplied system is to connect the pump in a state-of-the-art LS system to an electric motor. In this paper it is denoted by E-LS. The E-LS system serves as the reference system in this study.

Electric flow controlled system, E-IFC Flow controlled systems have gained increased popularity among researchers in the field of fluid power in the last decade, see for example [6] and [7]. Among the benefits are lower metering losses and open loop pump control, see [8] and [9].

Electric pump controlled actuators, E-PCA The approach to use displacement control instead of valves for implements has been subject for research a number of years, see [10] and [11] in [12]. This approach can be electrified similar to the E-LS system by connecting the hydraulic machine to an electric machine instead of the ICE. Here denoted E-PCA.

Electro-hydrostatic actuators, EHA One electric and one hydraulic machine are used at each function. The similarity with E-PCA is the decoupling of the functions. The use of fixed hydraulic machines removes control losses, idling losses as well as low efficiency when partly stroked. EHA was first seen in the aerospace industry, see for example [13].

Another system layout which would also fit in the comparison is the independent metering valve system, IMV. However, the IMV class of systems are excluded. The reason is that there exists a number of different approaches in the IMV area both in hardware and in controls. For some different approaches see [14], [15], [16] in [17], [18] in [19].

2 Modeling and Simulation

The evaluation is based on a combination of measurements and simulations. The loads are extracted from measurements and used as input to a simulation model. The input signals to the models are cylinder speeds and forces. The speeds are derived from filtering the position measurements. The forces are derived with chamber pressures and areas.

Static backward simulation is deployed, see Figure 2. The results, in a way, capture the dynamics of the system since measurements from a duty cycle are used. Dynamic characteristics from the cycle are therefore included through the measurements.

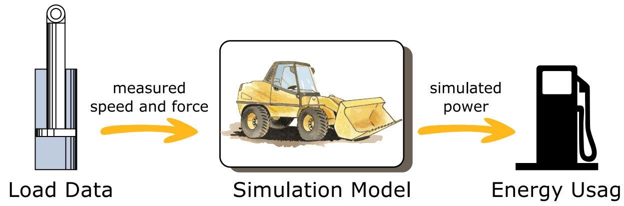


Figure 2: Explanation of backward simulation

The E-LS, E-IFC, E-PCA and EHA simulation models have been used on the same load data set to obtain a comparison in terms of power and energy consumption.

2.1 Duty Cycle

When a mobile system is to be evaluated, the load profile, work cycle or duty cycle, is as important as the fidelity of the simulation model itself. A certain system design can show completely different energy efficiency performance if the duty cycle is unrepresentative for the application.

This paper uses a wheel loader as the example application. A typical production cycle of this type of machines is the short load cycle, see Figure 3.

2.2 Modeling Description

The simulation models are simplified in a number of aspects.

Loads Inputs to the models are forces and speeds extracted from position and pressure measurements at a wheel loader running short loading cycles, see Section 2.1.

Cylinders Frictions are not part of the model since the load inputs are measured by pressure sensors. Flow losses in the cylinders are considered insignificant and are ignored.

Valves Metering out losses are estimated as function of flow. Pilot losses are ignored.

Pumps Flow and pressure dependent efficiency maps of the pumps are used. Controls losses are ignored.

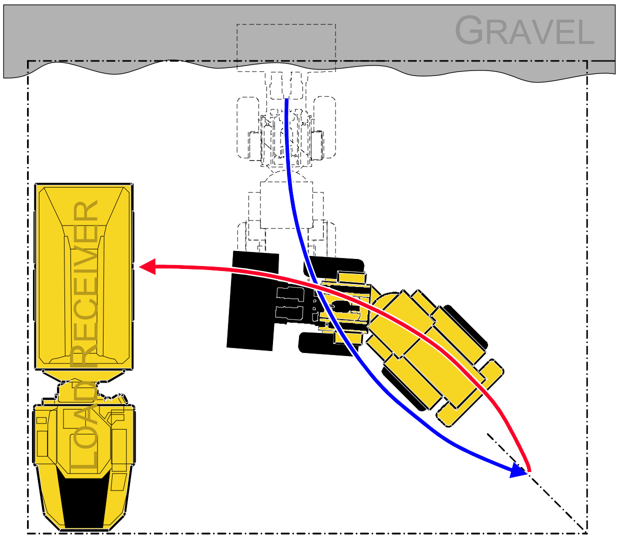


Figure 3: A short loading cycle (Reprinted from [20] with permission.)

Electric machines Permanent magnet alternating current motor, PMAC, is used for this comparison. Electric motors are modeled by accounting for current and temperature depending winding losses, rotor and stator iron losses as well as viscous damping losses.

Inverters Insulated gate bipolar transistor, IGBT, inverters serve as motor controllers to enable variable speed and torque control. A generic inverter model is used for this analysis, with losses being a function of motor current, switching frequency and supply voltage.

2.3 Electric Load Sensing Systems, E-LS

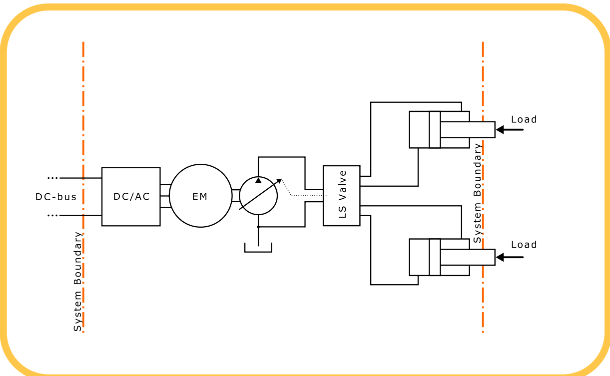


Figure 4: An E-LS system approach

The first system is an electrically driven conventional LS system, E-LS. The pump is a variable displacement pump run at constant speed. The only difference from conventional LS is that the hydraulic system is supplied from an electric motor instead of an ICE. The modeled system is shown in Figure 4. This is the reference system in this paper.[2]

[2]This is chosen as a reference system since it is the closest electrically driven hydraulic system to a conventional state-of-the-art approach.

2.4 Electric Intelligent Flow Control, E-IFC

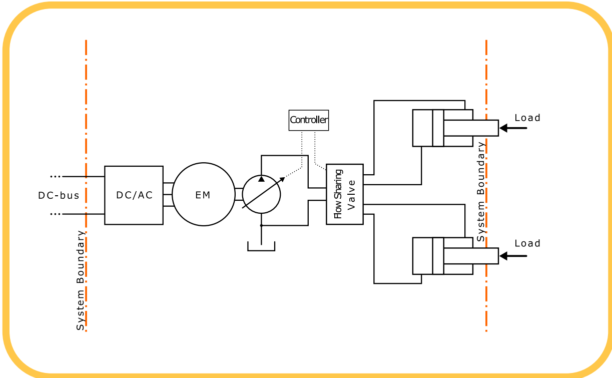


Figure 5: An E-IFC system approach

An alternative to conventional LS systems is flow controlled systems. The main difference is that the pump is controlled in an open loop flow control mode directly by the controller/joystick instead of in a closed loop with the load pressure. This is referred to as intelligent flow control, IFC. Here it is supplied with an electric pump and called E-IFC.

2.5 Electric Pump Controlled Actuation Systems, E-PCA

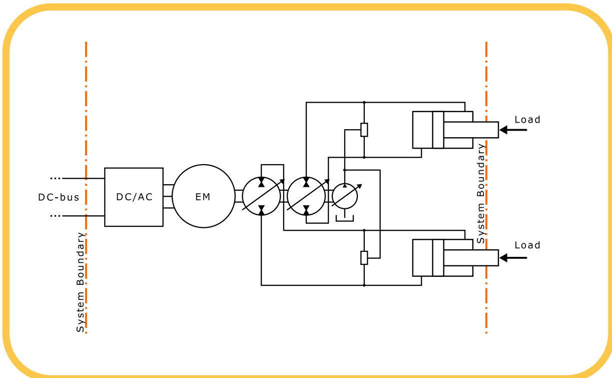


Figure 6: An E-PCA system approach

This approach uses over center hydrostatic pumps. One pump is used at each function. The loads are controlled in a decoupled manner with respect to the displacement settings. This approach is called pump controlled actuator, PCA. In this paper an electrical machine is used at the supply side instead of a ICE. It is here denoted E-PCA. See Figure 6.

2.6 Electro-Hydrostatic Actuation Systems, EHA

A system utilizing decoupled functions with fixed machines with separate electric supplies is studied as well, EHA. A benefit compared to the E-PCA is that the hydraulic machine efficiency is higher because of the use of fixed machines. The speed of the hydraulic machines is controlled independently. Compared to the E-PCA approach this allows uses of smaller machines.

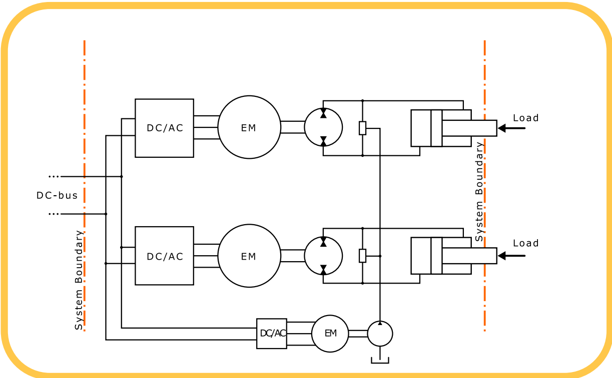


Figure 7: An EHA *system approach*

3 Simulation Results

The simulation models were run with identical input[3]. The bar diagram in Figure 8 shows the energy used with the different system layouts described in Sections 2.3-2.6. All results in the diagram are normalized to the energy input to the E-LS system. Hence, the output work is the same for all systems.

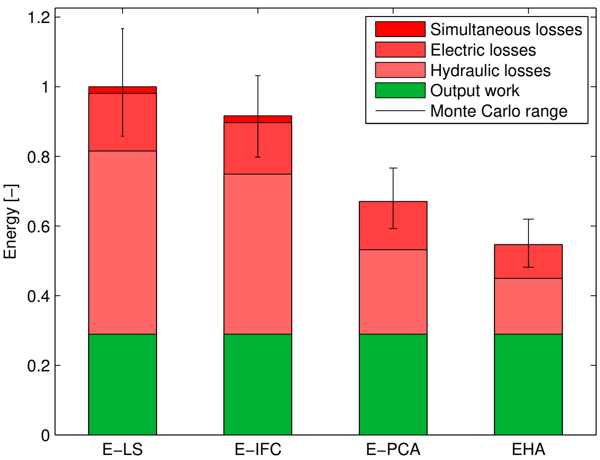
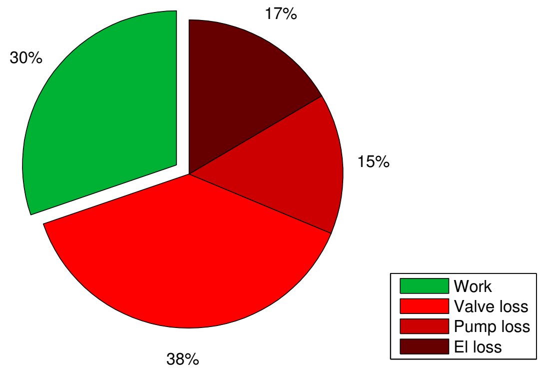


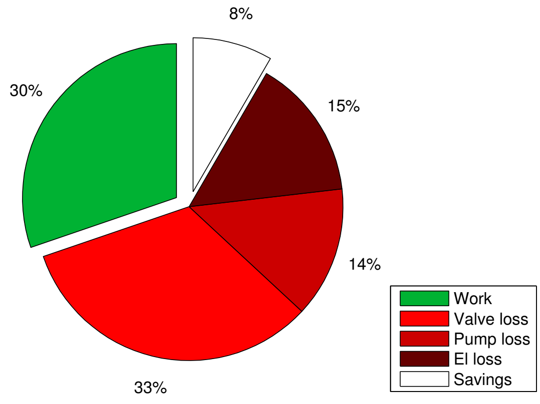
Figure 8: Relative comparison of used DC *energy in a short load cycle, see Section 2.1 (boom and bucket functions only)*

It can be seen that there are grades of potential energy savings depending on the chosen concept, the EHA system shows highest saving potential.

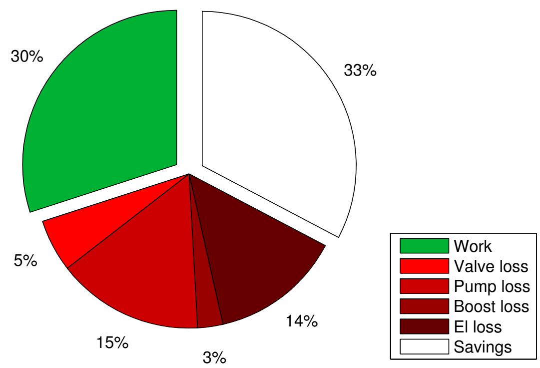
Systems with a centralized pump approach, such as E-LS and E-IFC, suffer from pressure losses when actuating more than one load at different load pressure levels. These types of losses are often caused by an interaction between the steering and the rest of the implements. Since steering is not a part of this study this effect is minor. This explains the low values of simultaneous losses in Figure 8.



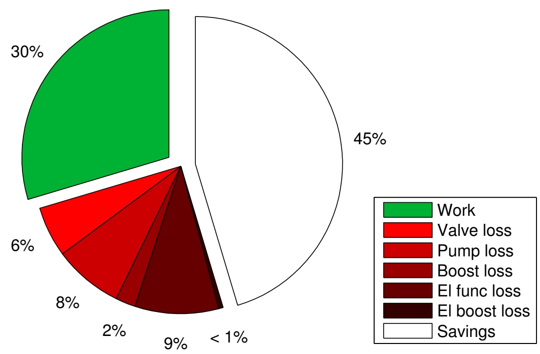
(a) E-LS system



(b) E-IFC system



(c) E-PCA system



(d) EHA system

Figure 9: Energy distribution with savings compared to E-LS*, "el" losses include inverter and electric machine losses*

[3]Forces and speeds as described in Section 2.