THE POTENTIAL OF ENERGY RECUPERATION IN VALVE CONTROLLED MOBILE HYDRAULIC SYSTEMS

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ABSTRACT

In this study the individual metering valve technology is put forward as a suitable base for a complementary energy recuperation system (ERS). The meter-out port of such a valve arrangement interconnects to the ERS that consists of a rotary hydraulic machine controlling the port pressure. The emphasis is on reducing the losses in overrunning load conditions and parallel actuation of multiple loads. In such load cases, the pressure drop across the valve is relocated to the hydraulic machine within the ERS. The ERS is controlled with the objective of reducing the throttling losses without sacrificing the advantageous dynamic characteristics of a valve controlled system. This article addresses relevant control strategies and presents methods to evaluate different types of ERS with regard to energy efficiency.

KEYWORDS: energy recuperation, hydraulic hybrid systems, individual metering valve

1 BACKGROUND

Mobile hydraulics are used in applications in many different industrial sectors, for example construction, forestry, agriculture and transportation. In some applications, the hydraulics are used to perform the work required for material handling; in others it is used for propulsion, and in some cases for both. Common to all these examples is the fact that the hydraulic system is often classified as one of the major energy consumers, considering both its useful and non-useful energy consumption. Figure 1 (left) shows the magnitude and distribution of engine power in a typical duty cycle in a wheel loader (commonly referred to as the Y-cycle). Here, approximately 50% to the energy is consumed by the hydraulic system. Figure 1 (right) show the hydraulic energy distribution, including useful work and losses. The machine is equipped with a load-sensing system, which for almost a decade has been considered to be the state-of-the-art in commercially available mobile hydraulics as regards energy efficiency. Nonetheless, more than half of the hydraulic energy consumption in this system is related to losses in this particular duty cycle.
For the purpose of describing potential improvements in energy efficiency, the hydraulic energy consumption is broken down into a number of categories relevant to this study. The “pump losses” category in the figure refers to the mechanical and volumetrical losses in the pumps. The power loss in pumps naturally varies throughout the duty cycle depending on supply pressure, shaft speed, and relative displacement. For any given task, the magnitude of this loss category will therefore depend on what other losses occur in the system. Another significant loss category here referred to as “losses in overrunning load conditions”, refers to the energy loss at the meter-out orifice occurring in load conditions where force and velocity has the same sign. For this particular cycle, the predominant part of this loss is associated to lowering of loads with gravity assistance. The category “losses in parallel operation” refers to the losses in simultaneous actuation of work functions with unequal pressure levels. The loss occurs over all meter-in orifices except for the one controlling the function operating at the highest pressure level. The magnitude of this loss naturally depends on both the pressure drop and the flow through the work section. Any other throttling losses over valves are included in the category “other losses”, for example losses related to the pump control pressure margin (LS-margin) and meter-out counter pressure. Losses in cylinders, hydraulic lines and cooling are also included in this category.

In the academic world throttling losses are frequently addressed and solved by introducing alternative system solutions. In for example displacement controlled hydraulic systems, separate rotary hydraulic machines are used for each hydraulically actuated function. This type of system eliminates valve throttling and enables energy recuperation in overrunning load conditions [1], [2], [3]. Also, systems based on secondary control, using different arrangements of rotary hydraulic machines will eliminate throttling losses and enable both energy recuperation and energy storage [4, 5]. If these solutions are implemented to replace a valve controlled system, substantial modifications to the current design will usually be necessary. In some applications, this could be an option. In larger versions of construction machinery, these alternative solutions often require very large or several rotary hydraulic machines (pumps/motors, transformers) to meet flow capacity requirements. Sometimes this can be solved by complementing the “throttle-free” approach with valves that take the excess...
flows [6]. However, compared to a system where the pump flow is shared by several drives, the utilization factor of the total installed hydraulic displacement tends to be low for throttle-free systems. This is generally seen as a drawback in a direct cost perspective as the installed hydraulic machines will often operate at partial displacement. Other drawbacks might include operating range, uncertainties in concept reliability, initial development cost, and manufacturer’s know-how.

Instead, looking at what can be done using a valve controlled solution as the baseline, many opportunities are still available. An interesting track is the independent metering valve technology. In contrast to valve arrangements using mechanically coupled metering orifices, this technology separates the meter-in and meter-out orifices. This provides a higher degree of freedom as regards control since these orifices can be controlled individually. Much work has been done on such concepts, both in the academic world and in industry [7, 8]. Some systems based on this technology have reached the market over the years, even if the focus has not always been on saving energy. More recent studies, for example [9, 10, 11], place a greater emphasis on efficiency aspects. When the appropriate hardware is combined with sophisticated control strategies, these systems can save a considerable amount of energy in mobile machines. The state-of-the-art systems in this field of research reduce both meter-in and meter-out losses and enable “return flow regeneration” which refers to letting back pressurized flow to the supply line to be shared by other actuators. Studies also show how efficiency may be improved during parallel operation using an asymmetrical cylinder as a discrete transformer. However, in many load cases, significant throttling losses still occur.

2 COMPLEMENTARY ENERGY RECUPERATION SYSTEMS

This chapter describes how a valve controlled system can be complemented with an energy recuperation system, here referred to as an ERS. The valve system can be either of a conventional type or the individual metering type. Figure 2 (left) shows a schematic of an individual metering valve system complemented with an ERS. An intermediate valve arrangement, here referred to as a priority shunt, may be used to select which hydraulic drive to connect to the energy absorber within the ERS. The priority shunt connects either directly to the existing main valve meter-out ports or to separate meter-out ports mounted in parallel with the existing ones. The general idea is to reduce the pressure drop over the metering valves. Figure 2 (right) shows how energy, which in a conventional system would be regarded as losses, is instead transferred to the ERS to be recuperated by its energy absorber. The label “net work” in this figure includes both energy supplied to the load and energy generated by the load (potential energy). Consequently, these losses may include power from the supply as well as from an external load. The energy absorber in the ERS comprises at least one rotary hydraulic machine with variable or fixed displacement. Its drive shaft interconnects to another device which may be hydraulic, electrical or mechanical. Some examples are shown in Figure 3.
In the hydraulic case, the solution assembles what is known as a hydraulic transformer, which in itself has many variations [12]. The second machine in the transformer interconnects either to an energy storage facility or back to the supply side. In the electrical case, the recuperated energy is transformed into electrical energy available to an electrical power grid, potentially connected to an energy buffer. In the mechanical case the recuperated power is transferred back to the prime mover without any preceding energy storage [13].
Figure 4 - Validation of simulation result where the machine is operating in a typical Y-cycle. Left: Lift function, Right: Tilt function. Dashed line is from measurement and continuous line is from simulation.

Of special interest in this model is how well the power losses over the control valves match the losses found in real measurements. The result shown in Figure 5 indicates a good match, both as regards the total input energy and the distribution between defined loss categories.

Figure 5 – The distribution of energy in the hydraulic system comparing simulation to measurement. The diagonally striped bars represent energy input and the others the distribution of this energy input. The percentage shows the difference to measurement data.
In Figure 6 the two predominant throttling losses are shown for the same simulated duty cycle. Worth mentioning is that in this particular application the throttling losses related to the different drives seldom coincide over time. This may be seen as an advantage considering that one ERS unit is therefore enough to satisfy most losses. This will also result in a maintained high degree of utilization of hydraulic machine displacement.

![Graph showing power losses and energy distribution](image)

**Figure 6** – Left: Simulated power losses in parallel operation and overrunning load cases. Right: Energy distribution between the lifting, tilting and steering drives.

### 2.1 Reducing losses in parallel operation

In machines where pumps are shared by several actuators, losses in parallel operation take place. Parallel operation refers to multiple hydraulic functions being simultaneously actuated, each subjected to a resistive load. This is a well known fact and can to some extent be considered when dimensioning the cylinders. However, the result will always be a compromise between efficiency and component size. If the hydraulic system uses a flow sharing mechanism, these losses are often significant as the available pump flow is divided between the drives, ideally independently of the pressure level. In systems without flow sharing, the drive subjected to the lowest pressure level will receive all flow when the pump becomes saturated, preventing any parallel operation and thereby also losses.

The desired system characteristics naturally depend on the application but also on operator behavior, which is most often task oriented and therefore adapts to the characteristics the machine offers [14].

In previous studies, losses in parallel operation are solved by introducing meter-out flow control to relocate the meter-in losses to the meter out-port [15]. The meter-out pressure drop is then relocated to a hydraulic motor generating a torque that propels an electric motor. The principle is illustrated in Figure 7.

Alternatively, flow may be controlled by the meter-in orifice while the meter-out port counter-pressure is controlled directly by the hydraulic motor. The pressure drop over the meter-out orifice should in this case be as low as possible.
Given the control objective of minimizing the power losses during parallel operation, the following questions have to be answered:

- What is the optimum ERS counter-pressure level considering efficiency in recuperation and to which meter-out port does this pressure level relate?
- How should the ERS pressure be controlled to achieve the desired pressure level?

An approach to the first question is to derive a “loss gradient” indicating whether the power loss in parallel operation increases or decreases with changes in pressure. The efficiency gradient should also include the change in losses in components, for example the hydraulic motor and the cylinder. Given the optimum pressure level with regard to efficiency, this is used as the reference pressure for the pressure controlled hydraulic motor. Depending on the bandwidth of the ERS, an additional pressure margin can be used to avoid disturbances in flow control.

Another approach to suppress losses in parallel operation is presented in [16] where a dedicated meter-out orifice is used to divert pressurized flow to a mechanical ERS which couples directly to the supply pump shaft. The solution is based on a completely hydro-mechanical controller for systems with two drives and an electro-hydraulic solution for systems with more than two drives.

### 2.2 Reducing losses in overrunning load cases

In overrunning load cases, the ERS increases the meter-out counter-pressure, leading to reduced throttling losses. The pressure level should be of such magnitude that a minimum sufficient pressure drop exists to achieve the desired flow.

In construction machinery the desired lowering speed can be relatively high, often twice as high as the lifting speed. If a recovery system is dimensioned to handle the complete lowering
flow, the rotary machines in the ERS unit will need to be unreasonably large. In the presented solution, the priority shunt may be used to throttle any flow exceeding the maximum flow capacity of the rotary machines. However, this leads to losses, especially under high flow conditions. If an asymmetrical cylinder is used, another approach is to connect its two cylinder chambers, allowing a transformation in pressure and flow, here referred to as a differential state of operation. In this state of operation, the effective pressurized area is only the piston rod area, resulting in a higher pressure level for a given force compared to a non-differential state of operation. The switching between the differential state and the normal state implies an abrupt change in pressure and flow and it is therefore desirable in many cases to instead remain in the differential state. The difficulty here is to avoid exceeding maximum pressure at higher actuation forces [17].

2.3 Minimum load sensing margin

To achieve a desired flow through any orifice, a certain pressure drop is required. The magnitude of the pressure drop depends on the opening area of the orifice. In a conventional load-sensing system, the pump controller will try to maintain a fixed pressure differential sufficient to achieve maximum flow at maximum valve opening. If the pressure differential is instead adjusted as a function of flow, these control losses can be kept to a minimum [18]. Figure 8 shows a principle comparison between a solution using a fixed LS pressure margin and a system using a variable pressure margin. In the illustrated load scenario, the pressure subjected on the lowest load will determine the pump pressure due to its higher flow and consequently reduce the throttling losses.

![Figure 8 - Principle comparison between variable and fix load sensing margin](image)

However, the load sensing margin is also an important parameter affecting both the steady state and the dynamic performance of an LS system. A system operating with a small margin tends to enter an unstable region [19]. The system damping, however, also depends on several other factors that can be elaborated in order to gain in amplitude margin. In [20], six different measures are suggested to avoid instability in an LS system.

1. Increase the pressure drop over the flow control orifice (meter-in) which would be at the expense of energy loss.
2. Increase the pressure drop over a meter-out orifice if one exists (also at the expense of energy loss).
3. Use pressure compensated valves. The system might be highly under-damped but would not be unstable.
4. Incorporate a pump-regulator with a high gain. This would have to be done with care in order to avoid high frequency instabilities.
5. Design a “low pass filter” on the load sensing line.
6. Actively damp the load by means of pressure or acceleration feedback.

The two first options are of least interest as the pressure drop over both meter-in and meter-out is supposed to be kept to a minimum considering power losses. The third might be an option if pressure compensated valves suit the application at hand. Depending on the selection of valve technology and how the load-sensing signal is created, option five might also be of interest. Relating to the sixth option, an interesting idea is to use the ERS to dampen the load. This can be achieved if a high-pass filtered pressure feedback signal is added to the ERS reference pressure signal.

A completely different approach would be to abandon the conventional type of load-sensing system for a displacement control type of system. A promising example of such a system is presented in [21], where load compensated control valves equipped with prime pressure compensators are controlled together with an electrohydraulically displacement controlled pump.

3 EFFICIENCY IN RECUPERATION

Figure 9 shows a simulation result where only the tilt drive is connected to the ERS, leaving the other drives almost unaffected. The ERS controls the meter-out pressure in a way that will reduce the meter-in pressure drop during parallel operation and also the meter-out pressure drop during regenerative lowering. Furthermore, the individual metering valves are so controlled that the pump is prevented from supplying flow to the piston rod chamber during overrunning load conditions. The remaining tilt drive throttling losses seen in the figure are a result of a mismatch in the ERS pressure control due to system dynamics.

![Figure 9 – Simulation result illustrating the remaining throttling losses over the control valve with an ERS implemented on the tilting drive only](image-url)
The pressure drop has now been relocated from the meter-out port to the ERS and the priority shunt, where some of the power will be recuperated and some lost in the form of heat. Recuperation efficiency will thus depend on the design and control of the ERS and a number of other factors, for example:

- How many ERS units are connected to the system?
- Does the potentially recuperable energy coincide over time?
- What are the physical limitations of the ERS unit as regards flow and pressure?
- How efficient are the components in the ERS unit?

When choosing between conceptually different concepts it is important to find a method to evaluate them from an application perspective. The method presented in this section is based on the definition of recuperation efficiency, given by Figure 12 and Eq.1-5.

\[
P_{in} = q_{in}P_{in} \quad (1)
\]

\[
P_{out} = P_{in} - P_{loss,s} - P_{loss,m} \quad (2)
\]

\[
E_{in} = \int_{t_{start}}^{t_{stop}} P_{in} \, dt \quad (3)
\]

\[
E_{out} = \int_{t_{start}}^{t_{stop}} P_{out} \, dt \quad (4)
\]

\[
\eta_{recup} = \frac{E_{out}}{E_{in}} \quad (5)
\]

Figure 10 - Power distribution in the ERS

Calculated for a selected duty cycle, Figure 11-13 illustrates how the recuperation efficiency in three different concepts varies with parameters relevant to dimensioning components. Which parameters are considered as relevant will differ between the solutions and may be selected from case to case. The boundary conditions considered in the efficiency calculation are the following:

- Maximum machine speed
- Maximum torque
- Maximum power
- Maximum flow
- Maximum pressure

Figure 11 (right) shows how the recuperation efficiency is affected if recuperated power is mechanically fed back to the power take out and no energy storage facility is available. The axes in the figure show how this efficiency varies with hydraulic machine displacement and a certain gear ratio to the prime mover (a diesel engine in this case). The recuperation efficiency is limited by the momentary prime mover’s torque and speed. There are also limitations as to what speed can be achieved for a certain machine displacement (mapped...
from manufacturer data sheets), shown in the figure as a black field at high gear ratios and high displacements.

![Figure 11 - Left: Schematic of a mechanical ERS system. Right: Recuperation efficiency including machine efficiency and conceptual limitations](image1)

In Figure 12, the same method is applied to a hydraulic solution comprising a hydraulic transformer. As the solution uses two hydraulic machines, both axes in the figure denote machine displacement. The recuperated energy is fed back hydraulically to the supply line, reducing the amount of energy supplied by the prime mover. If recuperated flow is not needed on the supply side, flow must instead be throttled to tank, decreasing the recuperation efficiency. The solution may be complemented with an energy storage facility, potentially increasing its efficiency. Other transformer concepts or configurations should also be considered if this path is chosen.

![Figure 12 - Left: Schematic of a hydraulic ERS system (transformer). Right: Recuperation efficiency including machine efficiency and conceptual limitations](image2)

In Figure 13 the principle of an electrical solution is illustrated. In this case, the system boundary of the ERS is somewhat less clear compared to the two other solutions. From a holistic point of view, the efficiency in recuperation should include how energy stored in the electrical energy buffer is used over time. For the sake of simplicity in this example, the system boundary ends at the energy buffer, leaving out all losses related to the actual use of stored energy. It is also assumed that the energy buffer’s state of charge is within appropriate limits so that the charging efficiency may be approximated by a function that only varies with the power generated by the motor. In reality, the additional losses related to discharging and transformation to other power domains are also of importance. In Figure 13 (right) the recuperation efficiency is plotted as a function of electrical motor power rating and hydraulic motor displacement.

![Figure 13 - Left: Schematic of an electrical ERS system. Right: Recuperation efficiency including machine efficiency and conceptual limitations](image3)
4 CONCLUSIONS

One advantage of valve controlled systems in general is that pumps may be shared by multiple drives, resulting in a high degree of utilization of the installed hydraulic machine displacement. However, from the point of view of energy efficiency, this advantage is also a disadvantage due to the resulting losses in parallel operation. In many applications, the losses in overrunning load conditions are also an issue.

In this study, the advantages of a valve controlled system based on individual metering is exploited. If such a system is complemented with a device for energy recuperation, the losses in parallel operation and overrunning load cases may be reduced. Also, a high degree of utilization installed hydraulic displacement can be maintained as the ERS can be shared by several actuators on the return side. Furthermore, the solution has benefits in system modularity since different levels of energy efficiency may be achieved without the need for a range of completely different system architectures.

Crucial to the whole concept is how the ERS unit is controlled in order to maximize efficiency without sacrificing the dynamic characteristics of the baseline load-sensing system. The general problem is that the easiest way to stabilize a load-sensing system is to introduce a pressure drop over the metering orifices, while the principles of energy efficient ERS control suggests the opposite. The measure put forward in this study is to employ active damping of the load in order to preserve energy efficiency.

A method for dimensioning an ERS unit is also presented, where the key elements are the selection of dimensioning parameters and determining the system boundary conditions, which becomes especially interesting when the ERS interacts with an energy buffer.

5 FUTURE WORK

As described in previous studies, and confirmed by simulations in this study, an ERS unit attached to an individual metering system can be used to advantage to reduce throttling losses. However, the degree of loss reduction depends on many factors, for example; the application at hand, operating conditions, the type of ERS unit/units, control aspects of the ERS, and the physical limitation imposed by the size of the ERS. Further investigation must therefore focus on one selected concept in order to gain a deeper understanding of the real system potential given a specific application.
Of interest is how different types of ERS influence the dynamic properties of a load-sensing system and with which result the ERS unit may be used to actively damp the load in cases of poor amplitude margin. Further studies are required to find robust control strategies allowing the ERS unit to be controlled without introducing disturbances in the actuation of loads, especially during parallel operation.

If one ERS unit is shared by multiple drives, the selection of which drive to connect to the ERS unit is crucial to the recuperation efficiency. Due to the dynamics in pressure control of the ERS, the frequency in switching between different drives will also affect recuperation efficiency. In applications where repetitive operations occur, predictive control could potentially be used to avoid excessive switching.

Furthermore, when the individual metering valve technology is combined with ERS, opportunities exist to actuate the load in a differential state of operation, which is of interest for further investigation considering downsizing of the ERS.

If the ERS includes an energy buffer, additional control is required to achieve high efficiency in charging and discharging. The addition of other energy consumers or providers makes this control even more interesting.

6 REFERENCES


