Linköping Studies in Science and Technology
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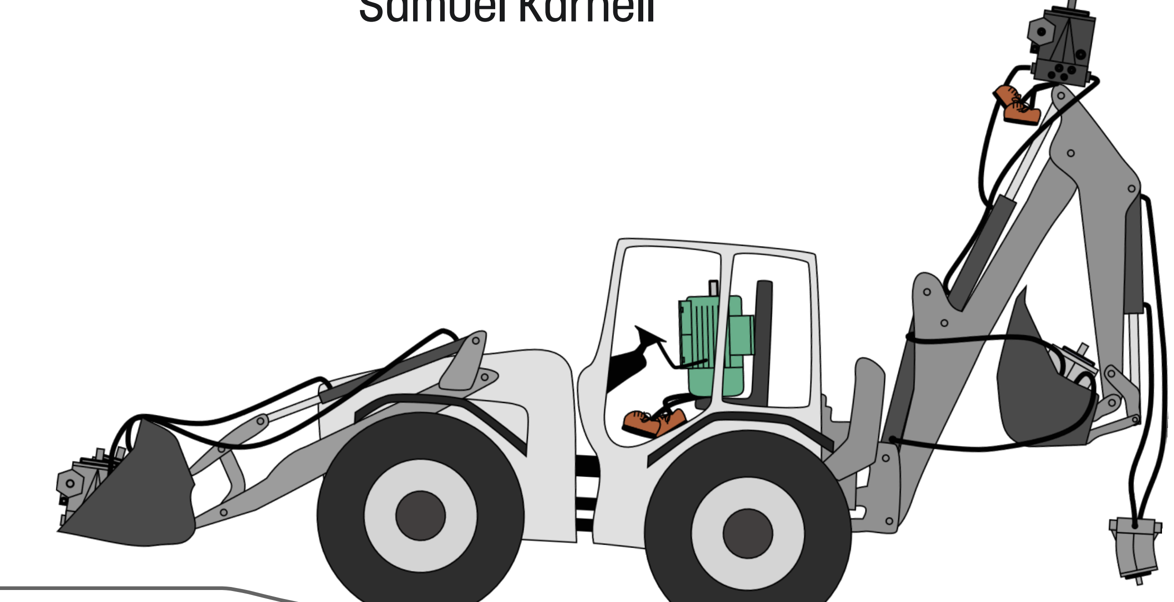
On Electrified Fluid Power Systems in Mobile Machinery

Samuel Kärnell



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Abstract

High power density in combination with flexible power distribution possibilities and extreme robustness are reasons why fluid power has been the preferred technology in mobile machinery, such as excavators and cranes, since the mid-20th century. In principle, the machines have been powered by a combustion engine which powers a pump, with the output from the pump being distributed to different functions via valves. However, a transformation is currently underway. Combustion engines are being replaced by electric motors, and batteries able to store energy corresponding to several hours of operation are often desired. Since batteries tend to be heavy and expensive, reducing the energy consumption is getting higher priority than ever before. There are applications where electrification means that hydraulic components are replaced by electric counterparts, but fluid power has characteristics that are highly desirable in mobile machinery. Therefore, many hydraulic actuators will remain. Conventional hydraulic systems, which are known for their inefficiency, should, however, be adapted to the new conditions brought about by electrification. The question, and the overall subject of this thesis, is: how? The research has focused on two main topics: pump-controlled systems, which are systems where each actuator has its own supply unit, and the use of variable displacement pumps in electrified systems.

A large proportion of the losses in many conventional hydraulic systems is due to the simultaneous operation of functions that require different pressure levels. One way to avoid these losses is to use pump-controlled systems. How these systems should be designed is, however, far from obvious. In this thesis, different types of pump-controlled systems are compared, both statically and dynamically.

Regarding variable displacement pumps, they have had a natural place in many conventional systems, but electrification may change this, since speed-control can now also be used for flow- and pressure control. However, there are still aspects relating to energy consumption and component dimensioning, among other things, that makes variable pumps relevant. These aspects are investigated here, and different types of variable pumps are reviewed.

Populärvetenskaplig sammanfattning

Elektrifiering av hydraulsystem i mobila arbetsmaskiner

Hög effekttäthet i kombination med möjlighet till flexibel effektdistribution och hög robusthet har gjort att hydraulsystemen fått en central roll i mobila arbetsmaskiner, såsom grävmaskiner och lastbilskranar, sedan 1900-talets mitt. Maskinerna har i regel varit utrustade med en förbränningsmotor som drivit en pump och effekten från pumpen har distribuerats till olika funktioner via ventiler. I skrivande stund pågår dock en transformation av maskinerna i fråga. Förbränningsmotorer byts ut mot elmotorer och i många fall önskas energin komma från ett batteri. Då batterier är förhållandevis tunga och dyra blir energiförbrukningen av hög prioritet. I vissa tillämpningar förespråkas också total eliminering av hydrauliken. Där ersätts hydraulcylindrar med kulskruvar och hydraulmotorer med elmotorer. Hydrauliken har dock många egenskaper som uppskattas i mobila arbetsmaskiner och den önskas därför till stor del vara kvar. Konventionella hydraulsystem, som har ett rykte av låga verkningsgrader, bör dock anpassas till de nya förutsättningarna som elektrifieringen medför. Frågan är hur systemen ska anpassas. Det är grundproblemet som denna avhandling kretsar runt. Fokus ligger på två huvudspår: pumpstyrda system, vilket är system där man i princip har ett hydraulsystem per aktuator, samt nyttan med variabla pumpar i elektrifierade system.

En stor del av förlusterna i dagens hydraulsystem är så kallade samkörningsförluster, vilka uppstår då flera funktioner som kräver olika trycknivåer körs samtidigt. Ett sätt att undgå dessa förluster är att nyttja pumpstyrda system. Hur dessa system ska utformas har dock visat sig vara långt ifrån självklart. I denna avhandling beaktas olika typer av pumpstyrda system både statiskt och dynamiskt. Fördelar och nackdelar med olika system presenteras.

Vad det beträffar variabla pumpar så har de haft en självklar roll i många konventionella hydraulsystem, men detta förändras när förbränningsmotorer byts ut mot elmotorer eftersom varvtalsstyrning helt plötsligt blir relevant för flödes- eller tryckreglering. Det finns dock aspekter relaterade till bland annat energiförbrukning och komponentdimensionering som gör att det kan vara intressant att kombinera en varvtalsstyrd elmotor och en variabel pump. Dessa aspekter behandlas, och även olika typer av variabla pumpar beaktas här.

Acknowledgements

On this page I would like to take the opportunity to thank the people from the companies in Hudiksvalls Hydraulikkluster who were involved in my work. I would also like to thank my current and former colleagues at the Division of Fluid and Mechatronic Systems, especially my supervisor Liselott Ericson. It was fun.

Linköping, August 2022
Samuel Kärnell

Papers

The following publications are included in the thesis and can be regarded as its foundation. They will be referred to by their Roman numerals. Apart from formatting changes, they are reproduced in their original form. Notice that they are not appended in chronological order. Instead, they are sorted based on the topics; the first three focus on displacement control and the last two on pump-controlled systems.

[I] S. Kärnell and L. Ericson, "Classification and review of variable displacement fluid power pumps and motors," *International Journal of Fluid Power (submitted)*, 2022.

[II] S. Kärnell, A. Rankka, A. Dell'Amico, and L. Ericson, "Digital pumps in speed-controlled systems - an energy study for a loader crane application," in *Proceedings of the 12th International Fluid Power Conference (12th IFK), 9-11 March, Dresden, Germany*, 2020. DOI: `10.25368/2020.71`.

[III] S. Kärnell and L. Ericson, "Analysis of a digital pump with variable speed drive," in *ASME/BATH 2022 Symposium on Fluid Power and Motion Control (accepted)*, ser. Fluid Power Systems Technology, 2022.

[IV] S. Kärnell, E. Fernlund, F. Lagerstedt, and L. Ericson, "Pump-controlled actuators with dump valves," in *Proceedings of the 17:th Scandinavian International Conference on Fluid Power, Linköping, Sweden, 1–2 June*, ser. Linköping Electronic Conference Proceedings, 2021, ISBN: 978-91-7929-013-9. DOI: `10.3384/ecp182`.

[V] S. Kärnell and L. Ericson, "Hysteresis control in pump-controlled systems - a way to reduce mode-switch oscillations in closed and open circuits," *Energies*, vol. 15, no. 2, 2022, ISSN: 1996-1073. DOI: `10.3390/en15020424`.

The author of this thesis is the main author of all appended papers and was responsible for areas such as idea formulation, conceptualisation, modelling, writing and visualisation. The co-authors have had a supervisory role except for in [IV], where the industrial co-authors were responsible for implementation and measurements.

Additional Publications

The author of this thesis has also written and/or contributed to the publications below. They are not appended in this thesis, but relevant to the topic.

[VI] L. Ericson, S. Kärnell, and M. Hochwallner, "Experimental investigation of a displacement-controlled hydrostatic pump/motor by means of rotating valve plate," in *Proceedings of the 15th Scandinavian International Conference on Fluid Power (SICFP17), June 7-9, Linköping, Sweden*, Linköping University Electronic Press, 2017, pp. 19–27. DOI: 10.3384/ecp1714419.

[VII] S. Kärnell, A. Dell'Amico, and L. Ericson, "Simulation and validation of a wobble plate pump with a focus on check valve dynamics," in *2018 Global Fluid Power Society PhD Symposium (GFPS)*, IEEE, 2018, pp. 1–8. DOI: 10.1109/gfps.2018.8472400.

[VIII] S. Kärnell and L. Ericson, "As simple as imaginable - an analysis of novel digital pump concepts," in *Proceedings of the 16th Scandinavian International Conference on Fluid Power (SICFP19), 22-24 May, Tampere, Finland*, 2019, ISBN: 978-952-03-1302-9.

[IX] S. Kärnell, *Fluid Power Pumps and the Electrification: With a Focus on Discrete Displacement Control in Load Handling Applications.* Linköping University Electronic Press, 2020, vol. 1882. DOI: 10.3384/lic.diva-165795.

Parts of this thesis are based on the licentiate thesis [IX] from the same author.

Contents

Appended Papers

1
Introduction

More efficient and electrified fluid power systems alone will most likely not save the world, but they may help. When only looking at construction machinery, in which fluid power is very widely used, these machines are responsible for 400 Mt of global CO_2 emissions every year [1]. That corresponds to more than 1 % of the global CO_2 emissions. Electrification is seen as a solution to reduce the emissions from these machines, and electrification is currently underway on different levels. There are examples where hydraulic actuators are being replaced by electric or electro-mechanical counterparts, but most common is to replace internal combustion engines with electric motors and keep the hydraulic systems. However, combustion engines and electric motors are different in many ways. For example, electric motors can easily be speed-controlled within a large speed range. This poses a threat to conventional displacement control of hydraulic machines. Electric machines also tend to be simpler and more compact than combustion engines, which means that it can be of interest to replace one combustion engine with several electric motors.

With multiple motors available, so-called pump-controlled systems, in which an actuator has its own hydraulic system, can be used. Such systems are mainly relevant since losses due to differences in load pressures for different actuators can then be avoided. These losses often constitute a substantial proportion of the total losses in a hydraulic system, and to reduce the losses is of high priority in mobile machinery. This particularly applies to battery powered machines since batteries tend to be heavy and expensive.

1.1 Contributions and Research Questions

The aim of this thesis is to provide an overview of the impact that the electrification of mobile machinery will have on hydraulic components and systems, with a focus on displacement control and pump-controlled systems. The research questions the thesis is based on are:

- **RQ1:** When is the use of variable displacement of interest in electrified mobile machinery?
- **RQ2:** When is the use of digital pumps of interest in electrified mobile machinery?
- **RQ3:** How can pump-controlled systems in electrified mobile machinery be implemented as a practical solution?

These questions cover the overall themes of the appended papers, but the contributions from each paper are more specific, and they are generally more focused on the performance of certain solutions. However, the results from the papers are used to provide information to answer the questions stated above. The first three papers focus on pumps, and digital pumps (i.e. pumps with discrete displacement settings) in particular. The last two papers focus on pump-controlled systems. The analysed use cases range from a loader crane, to a backhoe loader, to general load cases. The main contributions from the individual papers can be summarised as follows:

- **Paper** [**I**] provides a classification and overview of methods for achieving variable displacement.
- **Paper** [**II**] provides a comparison between pumps with discrete and fixed displacement. A case study for a loader crane cycle is presented.
- **Paper** [**III**] provides concepts for different switching strategies in pumps with discrete displacement. Simulation results for the switching performance is presented.
- **Paper** [**IV**] provides concepts of pump-controlled systems that does not require a pressurised reservoir. Simulation results of the energy consumption for different concepts are presented. The simulations are based on measurements made on a backhoe loader.
- **Paper** [**V**] provides a control strategy that can eliminate problems with mode-switching oscillations in pump-controlled systems. Both open and closed circuits are addressed, and the importance of the placing the pressure sensing components is highlighted.

Table 1.1 shows how the papers relate to the research questions.

Table 1.1 *Papers vs research questions.*

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
RQ1	x	x	x		
RQ2	x	x	x		
RQ3			x	x	x

1.2 Methodology

This is applied research that is based on industrial needs. The aim is to increase knowledge in society. A general overview of the research methodology is shown in Fig. 1.1. In summary, established theories and concepts are combined in new ways and new knowledge and insights emerge. And this happens in several loops, as can be seen in the figure. The research is heavily based on virtual modelling and simulation. The models are often based on measurements from existing components/machines, and sometimes validated by measurements. Note that the measurement results alone can also contribute to increased knowledge. Another part of this research to involves structuring pre-existing concepts and ideas.

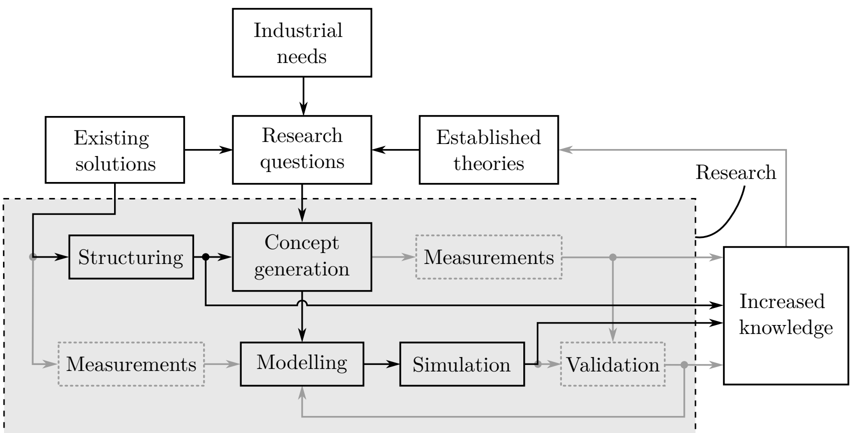


Figure 1.1 *Block diagram of the general methodology for this research. The grey lines and blocks are often desirable but not required.*

1.3 Thesis Outline

This is a compilation thesis that is based on appended papers. It comprises this introduction chapter, followed by chapters that describe the electrification of fluid power systems, hydraulic machines, displacement control, and pump-controlled systems in general. The intention is to put the appended papers in to context. Findings from the papers are also briefly mentioned when relevant. A discussion follows in chapter 6. Thereafter, the research questions are answered in the conclusions, chapter 7. The appended papers are then summarised in chapter 8. Lastly, the papers appear in their full versions.

2

Fluid Power Systems and Electrification

The heart of a full-grown giraffe weighs 12 kg. It pumps 60 l/min at a pressure of 0.04 MPa. This can be compared to a common hydraulic pump of similar weight, from which you can get 180 l/min at 40 MPa. This equates to a specific power that is 3,000 times higher. Although, the comparison may be a somewhat unfair, partly since the heart is of a much older design, and neither has there been any reason to increase the pressure levels inside giraffes. However, the comparison does serve to exemplify the high specific power that man-made fluid power systems offer, and the specific power (or the strongly related power density) is one of the reasons why fluid power has been the preferred technology in mobile machinery in the last century.

2.1 Historical Overview

It rarely makes sense to pressurise fluids just for fun. Fluid power is a transmission technology (with energy storage capabilities). In principle, mechanical power goes in, and mechanical power comes out. The neat thing is that it is easy to obtain very high transmission ratios and that the power can be distributed easily with good controllability.

It is often stated that fluid power engineering dates back to the year 1795, which was when Joseph Bramah patented the hydraulic press [2]; the first machine that really made use of the high transmission ratios offered by fluid power. In the following years, he built numerous machines that demonstrated the potential of his invention. For example, he built simple cranes and machines that could be used to remove trees along with their roots. In 1812, he also registered a patent concerning the use of large-scale fluid power systems for distribution of power to different machines within cities [3]. This idea became reality in several cities around the United Kingdom during the second half of the 19th century, and many of the power networks were in operation until the mid-20th century. One of the most famous hydraulic power networks was located in London, and around 1930 it powered 8,000 machines via a 300 km pipe network [4], but the last pumping station in London was shut down in 1977. In fact, the interest in large-scale fluid power networks started to diminish already when the electric grid became popular in the beginning of the 20th century. That can be considered as the first wave of electrification. Nevertheless, the principle of hydraulic power distribution was still of large interest, and it remains so, but on a much smaller scale. Instead of having centralised power sources for whole cities, there are centralised power sources for individual machines. However, what we are witnessing now is the second wave of electrification. Internal combustion engines are being replaced by electric motors. This allows for electric power distribution within the machines. But this electrification wave does not necessarily mean that electric and electro-mechanical components will replace all hydraulic components. Fluid power systems possess some highly desirable characteristics, especially for heavy-duty applications.

2.2 Characteristics of Fluid Power Systems

There are always losses when energy is transformed between different domains. It can therefore be preferrable to keep the number of transformations low. However, different domains have different properties, and some of those offered by fluid power are highly desirable in many applications. For this reason, the use of fluid power in electrified mobile machinery can be beneficial. Some notable properties of fluid power systems relate to:

- **Power density and specific power**
  Fluid power components can offer very high power density and specific power. The high specific power is exemplified in Fig. 2.1, where hydraulic motors are compared to electric motors.

- **Transmission ratio**
  Very high transmission ratios can be achieved, and the ratio can easily be continuously variable for rotary motions.

- **Heat transfer**
  The energy losses that are turned into heat are transported via the fluid. All cooling can therefore take place at one central location.

- **Shock absorption and overload properties**
  Oil is about 100 times more elastic than steel. The fluid itself can handle shock loads and mechanical parts can thereby be spared from damage. Overload can simply be avoided by means of pressure relief valves.

- **Load holding properties**
  A load can be held simply by keeping a valve closed. No power or additional mechanical brake needs to be applied to the system to keep it in place. If the valve is opened, the load can be lowered, and the potential energy can be recuperated. A load can also easily be lowered in event of of a failure.

- **Power distribution**
  Power can easily be distributed via hoses and pipes. Distribution can be controlled centrally or locally, conventionally by means of valves.

- **Material requirements**
  Even though electronics are increasingly being integrated into hydraulic systems, the systems are essentially just based on well-designed compositions of common metals and alloys. And a fluid.

- **Drivability**
  Hydraulic systems have been developed over many decades and today offer drivability that is highly appreciated by operators.

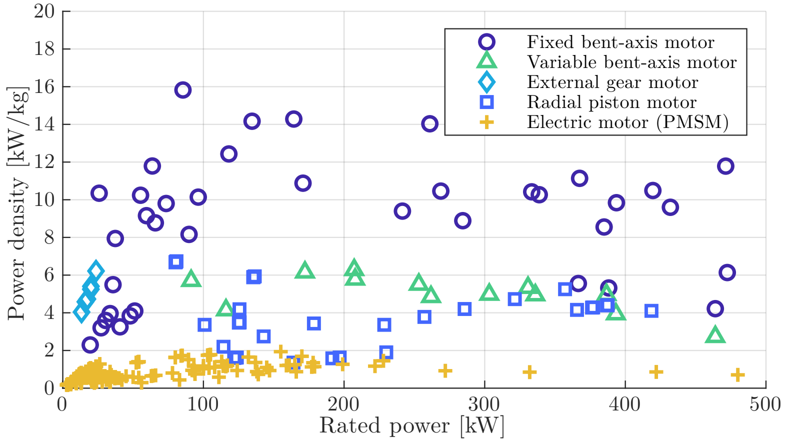


Figure 2.1 *Specific power for a selection of different commercial hydraulic and electric motors. The specific power is based on the continuous power that can be transmitted. The electric motors are liquid cooled and designed for mobile machinery applications.*

If only the points above were to be mentioned, it might seem that there is no reason to even consider anything other than fluid power. However, there are naturally also disadvantages with fluid power systems. The major ones are related to:

- **External leakage**
  External leakage due to damaged hoses and seals is the most common problem in fluid power systems. Apart from causing machine downtime, oil leakage can have a negative environmental impact, and a jet of oil can also harm people nearby.

- **Maintenance**
  The oil must be clean to prevent component damage. Filtering is therefore required, which in turn means regular maintenance. Also, hydraulic oil contains additives that improve performance, but they degrade with time and usage. This means that the oil should be changed regularly.

- **Contamination between machines**
  External tools and attachments are often hydraulically powered, and they can be shared by many machines. This also means that oil is exchanged between the machines, which potentially can cause issues. However, the fact that many tools are hydraulically powered means that there is resistance to switch to machines without hydraulic systems, since that would mean tools must also be changed.

- **Cost**
  Fluid power components tend to be expensive. In [5], a mechanical gear transmission and a pump was compared in terms of manufacturing cost perspective. The mechanical transmission costed 13 €/kg and the pump more than 40 €/kg even though they required somewhat similar machining. One explanation for the difference is that the pump production volume is smaller.

- **Efficiency**
  Hydraulic systems are often claimed to be inefficient, but most of the losses in hydraulic systems can be avoided by changing the system design. There are hydraulic machines with up to 96 % efficiency [6]. Still, one of the reasons why the electric grid outcompeted the hydraulic networks was the pressure losses that were evident in long distance transmission pipes. However, hydraulic lines are most often not that long today.

- **Nonlinearity**
  Fluid power systems are highly non-linear, which can make automatic control challenging.

- **Temperature-dependency**
  The viscosity of the oil has a large impact on the performance of the hydraulic system, and the viscosity is highly dependent on the temperature.

- **Noise**
  Hydraulic systems can be noisy. The noise usually comes from the pump, but flow pulsations from the pump can be transferred throughout the

whole system, which in turn can cause noise and vibrations at various locations.

2.3 System Design

Most mobile machinery has several actuators. If we look at a typical excavator, we will at least find one cylinder for the boom, one for the stick, and one for the bucket. Then there is the swing, the travel function, maybe features such as a backfill blade, and additional outlets. All these functions are traditionally powered by a combustion engine and the power is hydraulically distributed, but there are many ways of distributing the power to the different functions. And these ways can also be combined. A brief summary of hydraulic, mechanic and electric power distribution is presented below. The basic principles are also shown in Fig. 2.2.

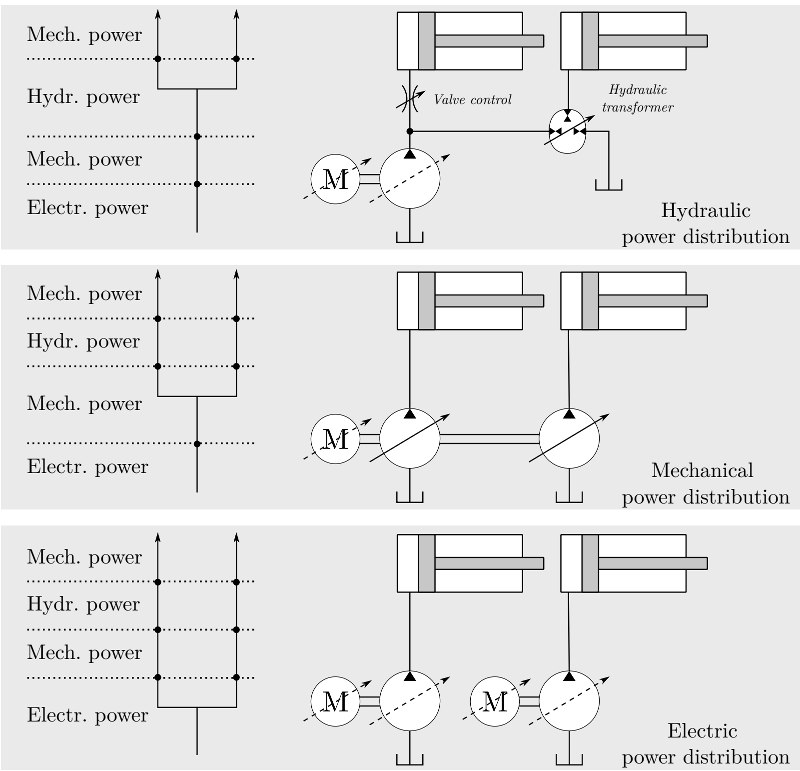


Figure 2.2 *Different ways of power distribution to multiple actuators. Electric input power is here assumed. Dashed arrows mean optional variability.*

2.3.1 Hydraulic Power Distribution

Hydraulic power distribution means that one or more pressure lines are used to power several functions. The conventional method of controlling the movement of different functions is to use one pressure line combined with valve control. There are, however, alternatives based on displacement control and/or so-called digital hydraulics.

Valve Control

In a valve-controlled system, multiple functions are powered by the same pump. The distribution of pump flow to the different functions is controlled by valves. This is also referred to as throttle control. On a high level, conventional valve-controlled hydraulic systems can be separated into systems with fixed and variable flows. In turn, these systems can either work at a constant pressure level or adapt the pressure level to the load. This classification is illustrated in Fig. 2.3. There are plenty of possible solutions within the presented system classes, shown in the figure. An overview of common system architectures can be found in [7].

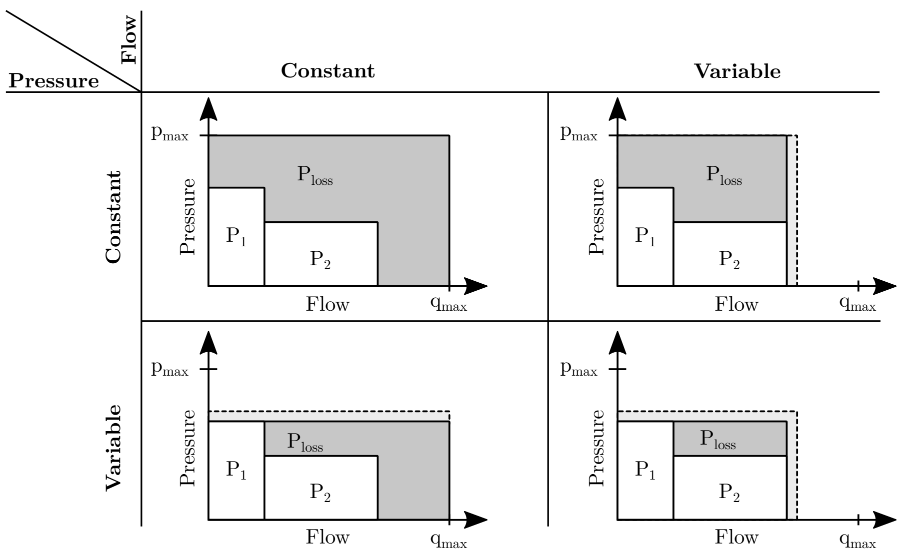


Figure 2.3 *High level classification of hydraulic systems based on how the pump power adapts to the load condition. In the figure, P_1 and P_2 represent the required load power and P_{loss} is the additional power delivered by the pump. Some control types with variable pressure and/or flow requires slightly more than the load. Thereby the dashed lines.*

As seen in Fig. 2.3, it is beneficial from an energy perspective to work with both variable flow and variable pressure levels. However, losses can still be substantial when there are large differences in load pressures. These losses will hereinafter be referred to as pressure-compensation losses. Pure valve-controlled systems will always have some problems with pressure-compensation losses, but there are different approaches that can be applied to avoid them. Solutions based on hydraulic power distribution are described below.

Displacement Control and Digital Hydraulics

The concepts presented in this section can often be found together with the term "common pressure rail", and they are considerably more energy efficient compared to valve-controlled systems. Primarily because they are not based on throttling, but there are other advantages too. In common pressure rail systems, there is one or more pressure lines, usually with somewhat constant pressure. Each pressure line can then utilise an accumulator. The accumulators can take care of the power peaks, which means that the prime mover only needs to be dimensioned for the average power. In battery-powered machines, this is also advantageous since large power out-takes from the battery can be avoided, which can in turn increase the service life. The accumulators also allow for energy recovery. This is advantageous compared to electric energy recovery since the number of energy transformations is smaller, and entails less cycling of the battery.

Several different approaches for controlling the power flow between the pressure lines and the actuators have been studied over the years. The most straightforward example is when rotational actuators are used (i.e. hydraulic motors). In such cases, variable displacement units can be used. The displacement is then used to control the torque. This is often referred to as secondary control.

For linear actuators, things are more complicated. The problem is that linear actuators are not continuously variable; the cylinder areas cannot not be continuously varied. The force therefore cannot be controlled with high precision. However, the number of available forces increases if multi-chamber cylinders are used and/or if more pressure lines are added. Such systems represent a branch within the field of digital hydraulics, and they have been studied by plenty of researchers. A review from 2020 by Donkov et al. summarises the state of the art of such systems [8]. Nevertheless, the control is still discrete, but digital systems can be combined with valve throttling to achieve continuous control. The throttling losses are then small compared to purely valve-controlled systems (see e.g. [9]–[11]).

An advantage of digital hydraulics is that it is based on simple on/off-valves. The need for customisation is therefore limited, but the use of multi-chamber cylinders can be considered a drawback in terms of component availability. However, Volvo CE has teamed up with Norrhydro, who manufactures multi-chamber cylinders, and commercial machines are planned to be launched in 2024 at the latest [12].

Another common pressure rail-based approach is to make use of hydraulic transformers. A hydraulic transformer can take in one ratio of pressure and flow and transform it to another. There are several kinds of transformers. Some are based on switching valves and inertial effects (see e.g. [13]), and others are based on rotary machines. A transformer based on rotary machines can essentially be built up from two hydraulic machines connected to the same shaft. The transformer ratio can be controlled by means of the displacement. The company Innas has also presented an innovative transformer concept based on a three-port machine [14]. This principle is used for one of the actuators in Fig. 2.2. An immense drawback with rotary hydraulic transformers, however, is that no efficient concept is commercially viable to date.

2.3.2 Mechanical Power Distribution

Mechanical power distribution simply means that shafts, levers, and gears are used to transfer power to different functions. If it is assumed that a hydraulic actuator is to be used, mechanical power distribution basically means that multiple pumps share a prime mover, as shown in Fig. 2.2. The actuators have their own dedicated hydraulic system. Pressure-compensation losses are thereby avoided. Systems like this are often referred to as pump-controlled systems and there are many different architectures for such systems, which are described more in detail in chapter 5.

2.3.3 Electric Power Distribution

From a hydraulic system standpoint, mechanical power distribution and electric power distribution are very similar. The difference is that the pumps tend to be displacement-controlled when mechanical power distribution is used since the speeds cannot be individually controlled. In systems with electric power distribution, the actuators have individual prime movers, which are electrically powered. Such systems are also referred to as pump-controlled. The relevance of pump-controlled systems based on electric power distribution is naturally increasing with electrification.

2.4 Electrification

For most vehicles, electrification is mainly driven by environmental arguments and emission regulations. Still, electrification involves more than just the substitution of energy storage and prime mover. It can add new values to the product, and this especially applies to mobile machinery. When a combustion engine is replaced by an electric counterpart, the local emissions from the machine are largely eliminated. This means that the machine can work in places where it has not been allowed to before, such as indoor environments and other poorly ventilated areas. Furthermore, an electric drive produces less noise than a combustion engine, which leads to improved comfort, and it can also result in opportunities for extended working hours as well as operation in highly populated areas. To exemplify this, the noise level from a 2.5-tonne electric excavator from Volvo can be compared to the diesel-powered counterpart. It can be noted that the perceived external noise level is almost cut in half [15], [16]. Nevertheless, to gain a better understanding of the benefits provided by electrification, it is useful to take a look at some properties of electric machines and compare them to internal combustion engines.

2.4.1 Electric Machines

Electric machines convert power from the mechanical domain (most often the rotational) to the electric, or vice versa. When power is converted from mechanical to electrical, the machine is working as a generator. When the power flow is in the other direction, the machine is working as a motor. Most electric machines can perform both tasks well.

There are many types of electric machines to choose from. In mobile machinery, Permanent Magnet Synchronous Machines (PMSMs) are popular. Advantages of these machines include high efficiency, comparatively high power density, and low inertia. Several manufacturers have released PMSMs specially built for mobile machinery [17]–[19].

Characteristics of Permanent Magnet Synchronous Machines

The regions of operation for electric machines are usually divided into a constant torque and a constant power region. The latter is entered when the speed exceeds the rated speed. This is illustrated in Fig. 2.4. There is also an intermittent region, in which the motor can operate for short time periods without becoming overheated. This region is defined by the rated torque, which in turn depends on the cooling of the machine. As a rule of thumb, the point that corresponds to the root mean square torque and root mean square speed of the drive cycle should be within the continuous region [17]. This applies if the overload time is considerably shorter than the thermal time constant of the copper in the motor. The thermal time constant for the motors examined here is around 20-70 s.

Electric Motors vs Combustion Engines

Essentially, all of today's electrified mobile machinery still has hydraulic systems that are very similar to the combustion-powered counterparts. However, there are multiple reasons why it is not ideal to keep it that way, such as the fact that combustion engines and electric motors are fundamentally different. Literally, there are not many similarities except that both make shafts rotate. Important differences between PMSMs and diesel engines, which are most commonly used in mobile machinery, are stated below:

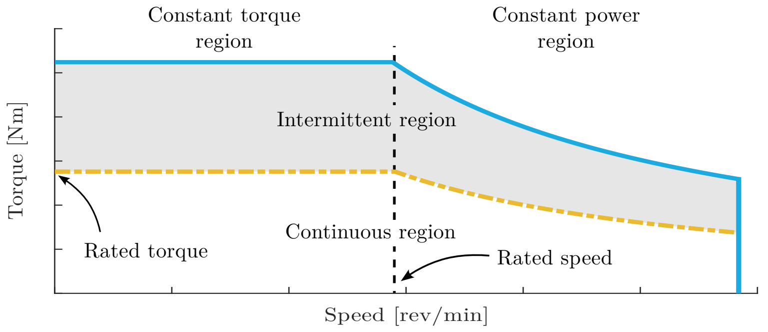


Figure 2.4 *Operating regions for an electric motor.*

- **Multi-mode operation**
  An electric motor can run in both directions and can run as a generator, whilst a diesel engine is not designed for bi-directional operation. The diesel engine would also have a hard time reproducing diesel from mechanical input power.

- **Minimum speed**
  The diesel engine has a minimum speed which must be exceeded, whilst the PMSM can go all the way to zero speed (and below as stated above). This means that it only needs to run when power is required, and this is one of the reasons why electric systems are considered quiet.

- **Efficiency**
  The efficiency of a diesel engine generally peaks around 40 %, whilst synchronous motors together with inverters cover large operating areas with 90-95 % efficiency. This means that less heat is generated.

- **Efficiency map**
  Regarding efficiency, PMSMs tend to perform best at medium/high speeds and low/medium torques, whilst diesel engines are most efficient at medium speeds and medium/high torques.

- **Dynamics**
  The PMSM has a faster response than a diesel engine.

- **Torque curve**
  Unlike a diesel engine, a synchronous motor can provide constant torque, independent of the speed (if the speed is below the rated speed). The rated torque can also be exceeded for short time periods, as illustrated in Fig. 2.4.

- **Complexity**
  An electric motor consists of considerably fewer moving parts and requires less maintenance, which reduces the cost of operation substantially.

- **Size and volume**
  Electric motors are generally smaller and lighter compared to conventional diesel engines. They also offers a greater installation freedom.

- **Air pollution**
  There is no local pollution from electric machines.

- **Noise**
  Combustion engines are based on explosions. It is therefore not surprising that they tend to be noisier than electric machines. The frequency spectrum is also quite different, with electric machines being more focused on higher frequencies.

With these aspects in mind, it is clear that systems powered by PMSMs have advantages over the diesel-powered systems. The benefits allow for new system architectures and improved performance. However, the obvious disadvantage with electrification is the energy storage/supply. Batteries are more expensive and bulkier than a fuel tank with similar energy content, and solutions based on grid connections are usually not practical. An alternative is to use fuel cells, but such solutions are also costly, and the infrastructure for hydrogen is limited.

2.4.2 Commercial Trends for Mobile Machines

Different combinations of the words "first" and "electric" have regularly appeared in press releases from manufacturers and trade magazines in recent years. There are hybrid solutions and battery-powered, fully electric alternatives as well as cable-powered solutions.

Mini excavators in sizes below 5 tonnes account for a large proportion of the fully battery-powered machines, but wheel loaders and backhoe loaders are also included. The machines are typically rebuilt versions of combustion-powered counterparts, and there are in general not many changes made to the hydraulic system. The acquisition costs of the battery-powered machines can typically be about 30-100 % higher compared to the conventional machines. For larger machines, it can be even more. However, the reduced operating costs can be substantial. Case claims that operating costs have been reduced by 90 % with its 580 EV backhoe [20]. This is due to reduced energy consumption and reduced maintenance. The trend indicates an optimistic view of electrification for smaller machines, and Volvo CE has stated that it will phase out combustion-powered machines in sizes for which it offers electric alternatives [21].

There are also examples of full-electric alternatives for mid-size and large machines. One example is the 11-tonne wheeled excavator from Mecalac, who also have developed a wheel loader and a dumper in this segment [22]. Doosan offers a 16-tonne wheeled excavator and a 30-tonne crawler excavator, both fully electric [23]. These are rebuilt versions of the combustion-powered counterparts. In addition, Caterpillar has built an all-electric excavator in that size range, which also is a modified combustion-powered machine [24]. The list of excavators in that size continues. An example is LiuGong, who also has a wheel loader of similar weight [25].

Larger battery-powered machinery is available from Epiroc, which is offering battery-driven underground loaders and mining trucks [26]. The loaders can carry the weight of the Mecalac excavator in their buckets. There are also fully electric solutions for surface-mining. One example is the 210-tonne excavator from Liebherr [27]. This is, however, powered by cable. And in fact, cable-powered hydraulic excavators for mining have been around since the late '70s [28]. Nevertheless, cable-powered solutions are also of interest for construction [29].

Among mid-size and large-size construction machines, hybrid solutions are also popular. Komatsu released a mid-size excavator with electric swing as early as 2008 [30]. This machine used capacitors instead of batteries. Hitachi has also offered a similar concept [31]. Huddig has released their 1370T, which is a large articulated backhoe that can run on diesel, electricity, or both [32]. Volvo CE has been working on the prototype LX1, in which hybrid technology has made downsizing possible and reduced fuel consumption by 50 % [33]. Hybrid solutions can also be found among large machines in the mining sector [27].

These are just a few examples from a long list of electrified mobile machinery that show the general trend.

Electro-Mechanic Actuation

Advantages and disadvantages with hydraulic systems were discussed in section 2.2. It is clearly beneficial for some applications to move away from the hydraulic domain. This especially applies to rotary motions. However, there are also examples where it can be of interest to use electro-mechanical actuators instead of hydraulic cylinders. In a study from 2020 by Hagen et al. [34], a self-contained electro-hydraulic actuator was compared with an electro-mechanical off-the-shelf actuator. The conclusions were that the electro-hydraulic solution is preferable when there are high impact forces, when the continuous power demand is above 2 kW (due to component availability), or when space, weight, or cost is critical. On the other hand, the electro-mechanical actuator does offer better controllability, higher efficiency, and lower complexity. Earlier, Michel and Weber came to similar conclusions [35].

There are examples where electro-mechanical actuators have been implemented in more demanding tasks in mobile machinery. Bobcat has presented an all-electric skid-steer loader called T7X, with ball-screw actuators instead of hydraulic cylinders, which is about to be commercialised [36]. The machine is supposed to have a faster response than the hydraulic counterpart since no pressure build-up is required. Volvo has also investigated replacing the hydraulic actuators with electro-mechanical. A proof-of-concept excavator was presented in 2017. At the time, there were, however, no plans for productisation [37]. Hydraulic machines are therefore still highly relevant. And that sentence provides a good transition to the next chapter, which happens to be focused on hydraulic machines.

3
Hydraulic Machines

A hydraulic machine refers to either a pump or a motor. A pump transforms mechanical power into hydraulic, and a motor does the opposite. The mechanical motion can be linear or rotary. Here, only rotary machines are considered. Many machines are capable of both pumping and motoring operation. But as for electric machines, they may be optimised for one or the other. There are different kinds of hydraulic machines, but in fluid power – where high pressures are desired – it is almost exclusively positive displacement machines that are used, and not rotodynamic machines such as centrifugal pumps. Therefore, the focus here is exclusively on positive displacement machines.

An ideal positive displacement machine provides constant flow independent on the pressure level. The oldest known positive displacement machine is the Archimedean screw. This machine dates back to Ancient Egypt and was used to transport water from the river Nile [38]. The pump was built up from a single screw contained in a cylinder. However, about 2,300 years ago, Ctesibius came up with a different type of positive displacement pump, which is more like the ones that are commonly used in fluid power today. This was the force pump, which was based on pistons sliding in cylinders. It made use of check valves to direct the flow. This pump was powered by a lever, but variants with rotational inputs were soon produced. An example is Heron's wind-powered organ [39].

More pumps were developed over the centuries that followed. In 1588, a book by Ramelli describing different machines that could be used for welling applications, for example, was published [40]. It contains illustrations of different screw pump configurations, various piston pump arrangements and as well as vane pumps. Around the year 1600, Johannes Kepler came up with what appears to be the first gear pump [41]. The pump worked, but it did not revolutionise society at the time. Kepler moved on and became famous for other things. However, others continued to develop hydraulic machines and today there are many types to choose from.

Hydraulic machines are often categorised as either rotational pumps or piston pumps. In rotational machines, the volume displacement is achieved by a rotating motion whilst the volumetric displacement comes from a translating motion (i.e. a moving piston) in a piston machine. Piston machines can generally work with high efficiency at high pressures because of their comparatively small sealing surface. However, different types of gear and vane machines are very common due to their simple construction, compact design, and low flow pulsation properties.

3.1 Operating Modes

From a functional perspective, a conventional hydraulic machine has four operating modes since both the flow direction and the pressure difference over the machine can be varied. Therefore, it is common to divide the operating modes into quadrants, as in Fig. 3.1.

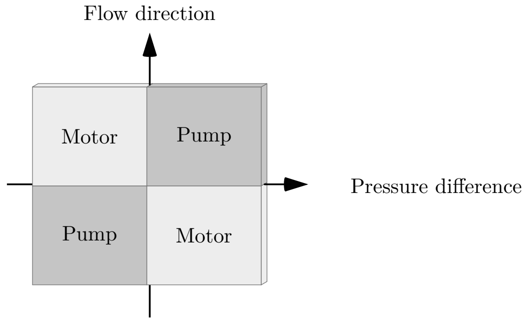


Figure 3.1 *Operating modes in quadrant division.*

The flow direction can be changed by either changing the sign of the displacement setting or the rotational speed. Therefore, there are in fact eight different operating modes, which are graphically represented in Fig. 3.2. However, it is hard to come up with applications where it would make sense to be able to change both the sign of the displacement and the speed since these changes cancel each other out. Therefore, it is usually sufficient to use the quadrant representation with either displacement setting or rotational speed as a replacement for the flow direction. Traditionally, the displacement setting is used to define the flow direction since it has not been relevant to change rotational speed in machines driven by combustion engines, but as pointed out in section 2.4.1, electrification changes the conditions.

With systems that do not rely on valve control, the relevance for machines that can work in both pump and motor modes increases. Depending on the architecture, the machines must be able to work in either two or all four quadrants. This is elaborated on for pump-controlled systems in chapter 5.

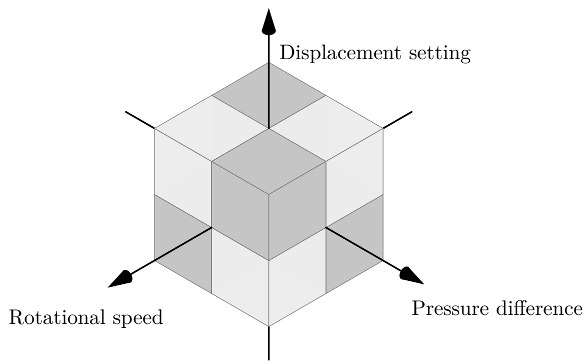


Figure 3.2 *Operating modes in octant division.*

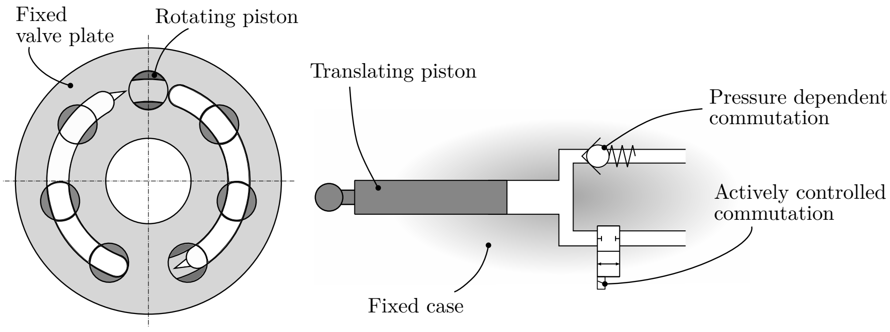
3.2 Commutation

A very important aspect of the hydraulic machine design is the commutation, which somewhat defines the operating modes in which it can work. Commutation refers to switching from high to low pressure or vice versa for an individual displacement element. To achieve operation that is as smooth as possible, the pressure in the displacement element should match the inlet or outlet pressure during commutation. There are principally three types of commutation techniques, which in special cases can also be combined:

- Mechanically forced
- Pressure-dependent
- Actively controlled

Examples of these are shown in Fig. 3.3. Rotation-dependent commutation means that the timing is defined by fixed mechanical connections. An example of this is the valve plate (sometimes called the port plate), which is shown in Fig. 3.3a. This technique is preferably used when displacement elements (e.g. pistons or vanes) are rotating with the shaft. The problem lies in matching the pressure in the cylinder with the system pressure. There are several ways to deal with this problem. The use of pressure-relief grooves is a common solution for achieving smooth commutations for a large pressure range.

Figure 3.3b shows an example of pressure-dependent commutation, where a check valve determines the commutation timing. This means that nearly optimal pressure matching is always achieved. Note, however, that a pump with check valves cannot run as a motor and that the flow direction is independent of the shaft's rotational direction. This commutation technique is mainly relevant for piston pumps where the pistons do not rotate with the drive shaft. However,



(a) *Mechanically forced commutation with a valve plate.*

(b) *Pressure dependent commutation with check valve together with actively controlled commutation.*

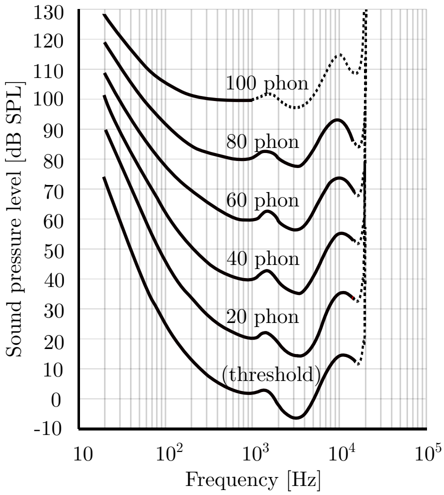
Figure 3.3 *Two possible valve configurations for a digital pump with two pump elements.*

solutions with inbuilt check valves in the valve plate have been investigated [42], and such a design would also be classified as pressure dependent.

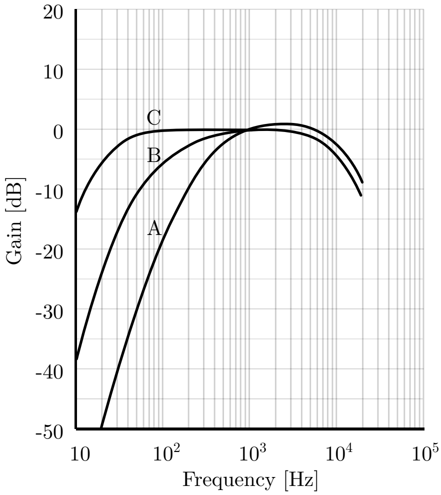
The check valves can be replaced with actively controlled valves, and actively controlled commutation can then be achieved. This is what is done in machines based on Digital Displacement® technology, which will be described further in chapter 4. Another example of active control is use of a rotatable valve plate [VI], [42]. Active control can be used both for displacement control and for noise minimisation.

3.3 Noise

Noise emissions are an important parameter when designing hydraulic systems and – not least – the pump, which in many ways can be considered the source of noise. The perception of noise is subjective, and noise is also perceived differently depending on whether we are prepared or not. Furthermore, the perceived loudness is dependent not only on the sound pressure level but also on the frequency, which can be seen in Fig. 3.4a, where so-called equal-loudness contours are shown. To compensate for this, weighting filters are often used when measuring noise levels. The choice of filter depends on the noise level. The most common filters are shown in Fig. 3.4b. However, there are many other effects that make the analysis of noise perception complex, such as the masking effect, which means that a frequency can suppress other adjacent frequencies, and the dissonance that can be perceived for certain combinations of frequencies.



(a) *Equal-loudness contours according to ISO 226:2003 [43]. This shows that we are most sensitive to frequencies in the region 2-5 kHz, but our hearing range spans between 20 and 20,000 Hz.*



(b) *Weighting filters used to compensate for the equal-loudness curve in measurements. Different filters are used depending on noise level, but A-filters are most commonly used.*

Figure 3.4 *Perceived noise and compensating filters.*

3.3.1 Noise from Hydraulic Machines

It is common to separate the sources of noise into fluid-borne and structure-borne noise. Fluid-borne noise originates from the non-continuous flow delivery from displacement elements. The flow variations cause pressure variations, which make components in the system vibrate. Thus, airborne noise emerges that will reach our eardrums. This means that noise caused by the hydraulic machine can appear in a completely different part of the hydraulic system. It also means that the properties of the system are important for the amplification of the noise. Structure-borne noise comes from variations in forces within the machine. This makes the machine structure and adjacent components vibrate, causing airborne noise. The force variations have their origin in the pressurisation of displacement elements.

Both fluid- and structure-borne noise are important. It is also clear that the system in which the pump is working has a great influence on the amplification of the noise, so it can be hard to state the most important source without having the specific system at hand.

Noise and Variable Speed

In traditional systems where the pump speed is somewhat pre-set, the fundamental frequency from the pulsations is well bounded. The hydraulic system and the mechanical structure can then be designed with this frequency range in mind, and undesired resonance can be avoided. However, the fundamental frequency varies a great deal when a variable-speed drive is used, and there is an increased risk of excitation and undesired modal oscillations.

An additional problem that may need to be addressed if multiple speed-controlled pumps are used relates to dissonance; combinations of certain speeds may be perceived as unpleasant due to poorly matched frequency content. Although, this has not yet been fully investigated. Nevertheless, speed-controlled systems are generally perceived as quiet compared to displacement-controlled systems. A major reason is that the noise from the prime mover is significantly reduced at part load, and completely absent when there is no flow demand.

3.4 Losses in Hydraulic Machines

In simple terms, there are leakage losses and there are frictional losses, and these counteract each other in many ways. Leakage losses come from gaps between sliding surfaces. Large gaps reduce the friction but increase the leakage. Furthermore, the viscosity, which is both pressure and temperature dependent, has a big influence here. This means that the performance of a hydraulic machine will vary during operation. Also, the rotational speed has a high impact on frictional losses as well as on wear. Too low speeds mean that lubrication films cannot be formed properly, and dry or mixed lubrication occurs. To prevent this, many pumps have a specified minimum speed, typically around 500 rpm. This is a huge limitation when variable-speed drives are used. In hydraulic machines there are also losses due to e.g. compression of the oil, churning losses, bearing losses, and internal fluid friction. In variable machines, there are also losses related to the controller for the displacement setting.

3.4.1 Controller Losses

Losses related to the displacement controller are often overlooked and the standards do not describe how the controller should be considered in the measurements. One reason is that the same pump machine often can be used with many different controllers, and the controllers can have different settings. Most conventional controllers require a bypass flow to achieve satisfactory damping performance and for reasons related to cavitation [44]. This introduces losses, and these losses result in poor machine efficiency at low displacement settings. As an example, the required bypass flow can account for as much as 19 % of the total outlet flow at 50 % displacement [44]. Literature on controller losses is limited but Lux and Murrenhoff have also shown that controller losses can account for a considerable share of the total losses, especially in part load conditions [45]. However, it was also stated that an electrically controlled controller can reduce the controller losses by 30-60 % since the damping orifice can be smaller or even removed.

There are also less conventional ways of controlling the displacement, and some have shown promising results in terms of efficiency. Different ways to control the displacement are discussed in the next chapter.

4 Displacement Control

Traditionally, a hydraulic pump generally runs at a predetermined constant speed or at a speed set by a pedal or lever. The flow is then controlled by the displacement setting of the pump, which naturally requires a pump with variable displacement. However, things may be about to change since electrification affords greater opportunities to use speed-control. A relevant question then is whether variable displacement will still be of interest.

4.1 Why Displacement Control?

Displacement control can be used for many different purposes. For example, displacement control of pumps can be used to control the flow rate or the outlet pressure level. For motors, displacement control can instead be used to control the output speed or the torque.

When considering the pump application, there are some arguments that advocate the use of displacement control in combination with a variable speed drive. These are related to downsizing possibilities, energy efficiency improvements, improved response, and system design. These topics are individually described below.

Downsizing

Imagine that the pump/motor combination must be able to deliver power continuously within the marked borders in Fig. 4.1, i.e. maximum 30 kW, with additional limits on 35 MPa and 100 l/min. This is a very simple example that does not consider the time aspect at all. The time aspect is, however, often relevant since both pumps and motors can withstand high loads for short time periods. Still, it exemplifies the downsizing possibilities provided by variable displacement.

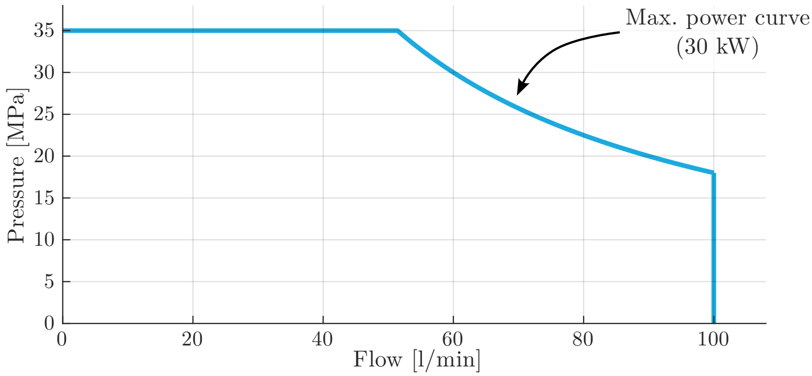
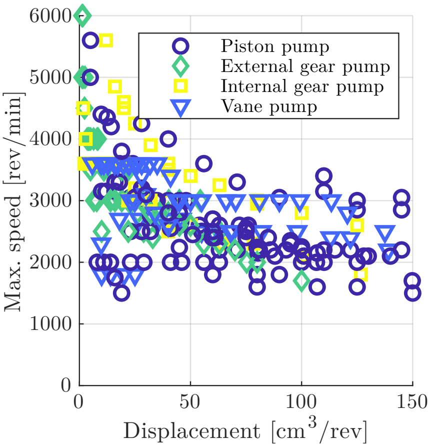


Figure 4.1 *Example of drive cycle requirements.*

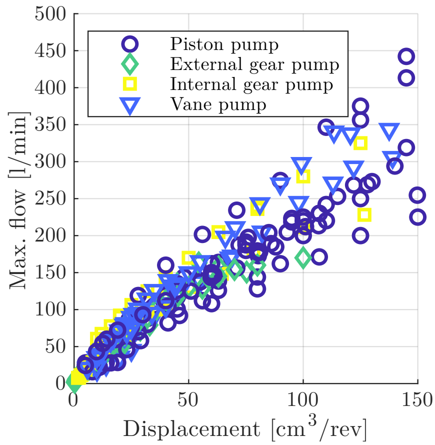
There are several approaches to dimensioning the pump/motor configuration. If it is assumed that the pump speed is the limiting factor, and that the smallest possible displacement is desired, the following approach can be used.

The displacement can be calculated from $q = Dn/60$, where q is the flow in m^3/s, D the displacement in m^3/rev, and n the rotational speed in rpm. The problem is knowing what speed to use. Figure 4.2a shows maximum speeds for different types of commercial pumps for mobile applications (bear in mind that the maximum speed can be somewhat increased with an increased inlet pressure). As can be seen, the maximum speed generally decreases with the displacement. Figure 4.2b is based on the same data, but it shows the flow. From this data, it can be seen that a speed of about 3,000 rpm and a displacement of 35 cm^3/rev is reasonable.

With the displacement known, the required motor torque in Nm can be calculated as $T = \dfrac{\varepsilon D p_{max}}{2\pi}$, where ε is the displacement setting (which can be set between -1 and 1) and p_{max} is the maximum pressure difference over the pump in Pa. If the displacement is fixed, the torque is independent on the flow since $\varepsilon = 1$. For a pump of 35 cm^3/rev and a pressure of 35 MPa, the torque becomes 195 Nm. A motor with a rated speed above 3,000 rpm and with a rated torque above 195 Nm should then be chosen. However, if a variable pump is used, the torque requirement can be substantially reduced since the effective displacement only needs to be about 50 % at 35 MPa in this example. Then, along the constant-power curve, the increase in displacement has no effect on the torque due to the decrease in pressure. This means that the required torque is suddenly only about 100 Nm. This cuts both the weight and volume of the motor almost in half. However, the variable pump is larger compared to a fixed pump of the same size (compare the power densities of fixed and variable hydraulic motors in Fig. 2.1 to get an idea of the ratio).



(a) *Maximum speed as a function of the displacement.*



(b) *Maximum flow as a function of the displacement. Efficiency is neglected.*

Figure 4.2 *Maximum speed and flow as a function of the displacement for a sample of common commercial pumps. The data is for 0.1 MPa in absolute inlet pressure and is based on data sheets of products from several major manufacturers.*

Another approach to component selection is to start from the motor speed and assume that the pump speed is not limiting. A motor with a rated speed of e.g. 3,000 rpm can be chosen. The required pump displacement can be calculated based on the point where the constant-power curve starts, i.e. at around 50 l/min. This gives a displacement of 17 cm^3/rev, which means that the required torque is about 100 Nm. For higher flow rates, the motor can go in to its constant-power mode until 6,000 rpm, when 100 l/min is reached.

As can be seen in the example above, variable displacement is mainly relevant for downsizing when the drive cycle is far away from the corner power (i.e. maximum pressure and maximum flow at the same time) and when the pump speed is limiting, which most often is the case today. However, it is possible to avoid the problem of limited pump speed by introducing a gearbox between the motor and the pump. This has been investigated by e.g. Roth et al. [46]. Their example showed that the power density could be increased by 50 %.

Efficiency

Since both hydraulic and electric machines tend to be inefficient at low speeds, the total power loss can be reduced by changing the displacement setting and thereby moving the operating points, as illustrated in Fig. 4.3, which shows efficiency maps of a typical PMSM and hydraulic pump.

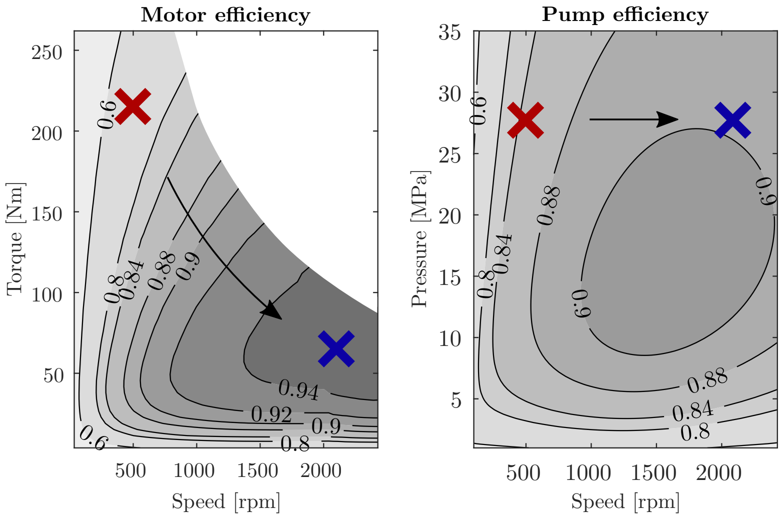


Figure 4.3 *Example of how the operating points can be moved to more efficient regions when displacement control is applied. The decrease in efficiency that usually comes with reduced displacement setting is not shown.*

The figure is somewhat over-optimistic since the pump efficiency tends to decrease with the displacement setting. However, it shows the potential for pumps with high efficiency at low displacement settings. And it shows that the greatest efficiency gains are obtained for operation at high pressures and low flow rates. It should also be stated that efficiency maps are similar for energy flow in the other direction. Furthermore, not only is efficiency poor at low speed, but wear in the hydraulic machines can also increase due to improper lubrication films.

Response

When both the motor speed and the pump displacement can be varied, a faster response can be achieved. The number of studies on this topic is limited, but a control strategy for this has been presented by Willkomm et al. [47].

System Design

There are several energy efficient system architectures based on displacement control. This was described earlier in section 2.3. Since a large proportion of the losses in a conventional hydraulic system often are pressure compensation losses, the efficiency can usually be improved by using multiple pumps, and if they share the same prime mover, the installed power can be reduced as along with the total volume of the required components. However, since the pumps will have the same speed, it is beneficial to have displacement-controlled pumps.

There are also systems based on common pressure rails. These systems should preferably use displacement-controlled motors as rotary actuators, while for linear actuators it is possible to use hydraulic transformers, which can be based on displacement control. However, such hydraulic transformers are not commercially viable today, as stated in section 2.3.

4.2 Types of Displacement Control

Different displacement control methods have been classified and reviewed in paper [I]. The methods are classified based on whether they are on displacement element- or pump level, and whether it is the amount of displaced fluid or the usage of the displaced fluid that is controlled. The classification is shown in Fig. 4.4. The different classes are briefly described below.

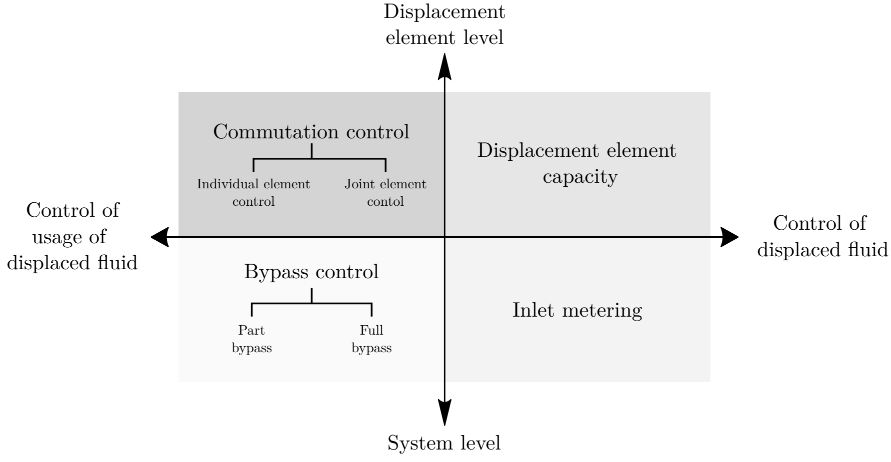


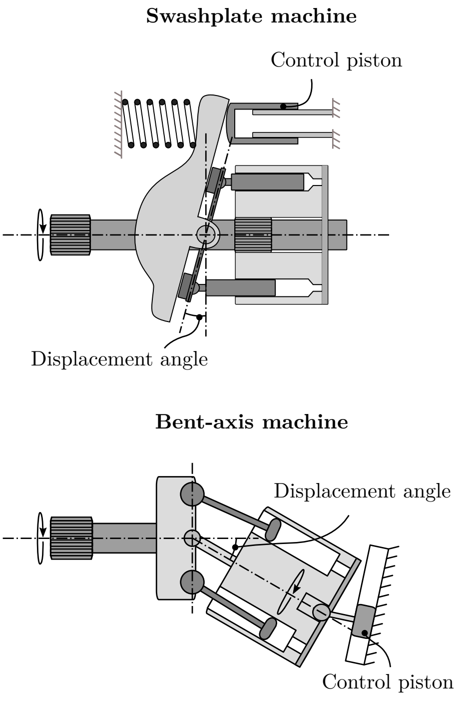
Figure 4.4 *Classification of displacement control methods.*

On displacement element level, control takes place inside the machine, meaning that either the geometry or the commutation is affected. When the geometry is controlled, the capacity of the displacement elements is controlled, i.e. the amount of displaced fluid. When the commutation is controlled, it is instead the usage of the displaced fluid that is controlled.

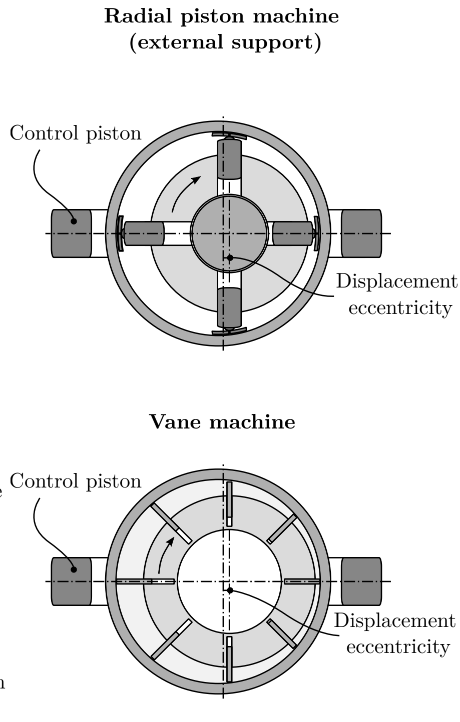
On system level, the control is achieved with valves that are placed up- or downstream of the machine. The control on system level can thereby be seen as a kind of add-on to a conventional fixed pump. The usage of the displaced flow can be controlled by means of by-pass valves. The amount of displaced fluid can be controlled by choking the inlet flow to the machine.

Displacement Element Capacity

In commercial variable displacement machines, the displacement is almost exclusively controlled by means of the displacement element capacity. Figure 4.5a shows how the stroke length can be varied by changing the displacement angle. In some machine types, the stroke length is instead varied by means of the eccentricity. This is illustrated in Fig. 4.5b. There are also less conventional displacement controllers in this class that have not reached commercialisation. At the University of Minnesota, they have worked on an adjustable linkage concept for both pumps and motors that they claim has the potential to be more efficient than conventional control [48], [49]. Another interesting concept is the so-called alternating flow pump, in which two pistons are connected and the phase between them is controlled [50].



(a) *Variable stroke length by means of angular change.*



(b) *Variable stroke length by means of eccentricity change.*

Figure 4.5 *Conventional control of displacement capacity.*

Back to the conventional methods. The different methods are principally very similar, and the control is achieved by controlling the pressure in the control piston. However, there are many ways to control the pressure. Many controllers use the internal pump pressure for control. Therefore, a bias spring is required to ensure that pressure can be built up. This also means that the pump requires a minimum working pressure level, typically around 2-3 MPa. Note, however, that pumps used in closed-circuit applications generally use their charge pressure for displacement control. For this to work, there is typically a minimum speed limit of a few hundred rpm. Also note that the response of hydraulically actuated controllers is limited by the flow provided to the control piston and is therefore pressure dependent. In practice, the bandwidth does usually not exceed 25 Hz for swashplate machines [51].

Hydro-mechanical or electro-hydraulic controllers are generally used to control the pressure. Due to the high internal forces on the control element, pure electric or electro-mechanical actuation is very rare. Hydro-mechanical controllers are useful because they are simple and robust. However, their flexibility is very limited and stability issues are common, but are usually resolved by the introduction of losses, as stated in section 3.4.1. Problems with hydro-mechanical controllers are discussed in e.g. [52], and the main disadvantages can be summarised as follows:

- Limited signal filtering possibilities
- High losses due to damping orifices
- Temperature-dependent characteristics
- Time delays due to pressure build up in hoses
- Difficulties with automating processes
- Bulkiness of signal lines

Electro-hydraulic control can eliminate most of these problems. This was concluded as early as in 1990 when an electronic version of a conversional load sensing system was presented [53]. Electro-hydraulic control also offers new control possibilities such as flow-on-demand systems [54], [55], where the pump displacement is based on the operator command rather than pressure signals. This can increase energy efficiency compared to load sensing systems, since pressure drops are reduced. Furthermore, since the control is carried out via software, parameters can be tuned on-the-fly and the functionality of the controller can be changed without having to change or adjust any physical parts. This means that one electro-hydraulic controller can replace several other hydro-mechanical controllers.

Electro-hydraulic controllers work similarly to hydro-mechanical controllers. The difference is that the control valve is electrically actuated. Naturally, there are also many variations of control valves and circuit layouts. There are simple alternatives with bang-bang control and advanced multi-stage servo controllers. An example of a typical controller is shown in Fig. 4.6. Note that the displacement angle is not measured in most mobile controllers. Instead, mechanical feedback between the control piston and the valve is used to achieve high precision. This also applies to hydro-mechanical actuators.

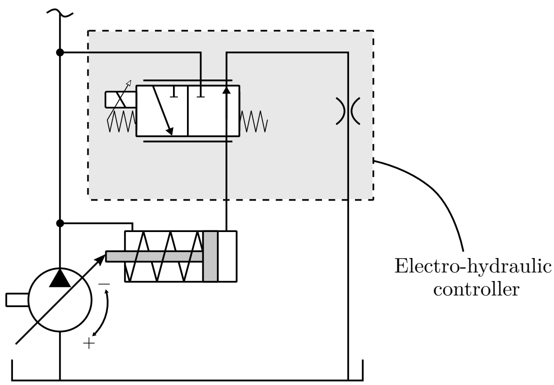


Figure 4.6 *Simplified circuit of an electro-hydraulic controller.*

Commutation Control

Instead of changing the amount of fluid that is displaced in the pump, the amount of displaced fluid that is used for pumping/motoring can be changed. On displacement element level, this can be done by changing the commutation.

The most well-known examples of this are based on the so-called Digital Displacement® technology. A Digital Displacement® machine is a piston machine in which each piston is individually controlled. By using active valves, a piston can be deactivated by simply keeping it connected to the reservoir. If each piston can be controlled for every revolution, the resolution of the discrete control can be very high. In principle, it is also possible to control the displacement by only using parts of the stroke. Different control methods have been heavily investigated over the years in industry (primarily by the company Artemis Intelligent Power, the company that has been developing Digital Displacement® machines since the early 1990s) and academia (primarily at the University of Edinburgh [56], [57], from where Artemis Intelligent Power originates, Purdue University [58]–[60], Aalborg University [61]–[64], and Tampere University [65]–[67]).

Digital Displacement® pumps are now commercialised by Danfoss Power Solutions [68], who acquired Artemis Intelligent Power some years ago, and motors are coming soon. The main selling points for the pump are:

- **High efficiency at part displacement**
  The conventional controller losses are eliminated.
- **Pressure independent control**
  In conventional controllers, the displacement is dependent on the pressure

since the pressure determines the flow rate to the control piston. This dependency is eliminated. The requirement for a minimum pressure level for control is also eliminated.

- **Fast response**
  The displacement can be changed within tens of milliseconds (depending on the rotational speed) [68].

- **No hysteresis**
  Conventional controllers often suffer from hysteresis, which the Digital Displacement® pump does not.

Furthermore, the advantages of electro-hydraulic control described above also apply to this control method. An additional benefit is that the pump offers multiple isolated outlets. This means that pressure-compensation losses can be minimised. The main disadvantage is the high degree of complexity.

Apart from Digital Displacement®, there are several other approaches that can be used to control the displacement by means of commutation, but these generally do not control all displacement elements individually. One example is valve plate control, where the valve plate is rotated [VI], [42], [69]. Another is the use of slider mechanisms in gear pumps [70].

Bypass Control

The usage of the displaced flow can also be controlled on system level. This means that the commutation of the pump is not controlled. Instead, an additional valve that allows fluid to be bypassed is added. Either all the fluid can be bypassed, or only parts of it (if the pump design allows for this).

Full bypass is based on fast switching valves. This is often referred to as virtually variable displacement. In recent decades, different concepts and valve designs have been investigated. See e.g. [71]–[74]. Examples of possible implementations are shown in Fig. 4.7. A problem with this kind of control is poor efficiency due to throttling losses during the switches and compression losses.

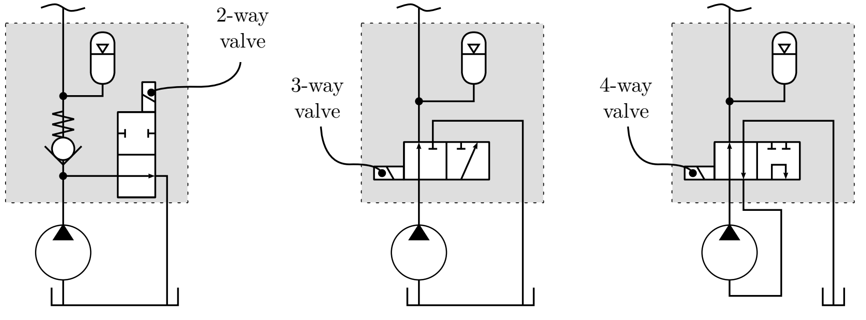


Figure 4.7 *Different architectures for virtually variable displacement pumps.*

Pumps that utilise part bypass are often referred to as digital pumps (which should not be confused with Digital Displacement® pumps). They are built up from several smaller pumps that can be deactivated individually and they only offer a discrete number of displacement settings. The implementation is similar to virtually variable displacement pumps. However, each pump element needs a valve, but the requirement for fast switching is not as critical, and the control can be passive (i.e. based on hydraulically transmitted pressure signals). The use of such pumps in combination with variable speed control is investigated in papers [II] and [III]. Paper [II] focused on the power losses. Different numbers of displacement settings were analysed. The analysis was based on a drive cycle for a loader crane. The results showed that a major part of the benefits with variable displacement could be achieved with just a few displacement settings. In fact, the difference in using 3 or 7 settings was small. It was also clear that reduced energy losses can primarily be achieved at low flow rates and high pressure levels. The energy losses were also analysed in paper [III], but this was done for another type of pump. Still, the results were similar. However, the focus on that paper was the control. Shunt based solutions for managing additional flow provided during switchings, shown in Fig. 4.8, were proposed to smoothen the switches between different displacement settings. The shunts can improve the switching performance, but seamless switches should not be expected.

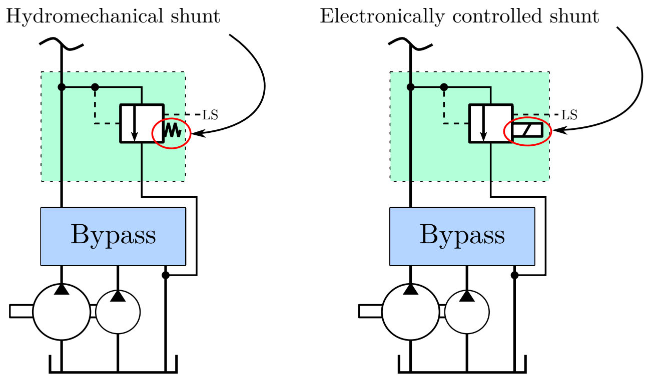


Figure 4.8 *Suggested shunt layouts for a digital pump.*

Inlet Metering

The last class is inlet metering. It is only applicable to pumps and is based on cavitation. By placing a valve at the inlet of the pump, the flow that enters the pump can be restricted and partial filling of the displacement element can thereby be achieved. The flow can be controlled by changing the opening of the valve. The principle is shown in Fig. 4.9.

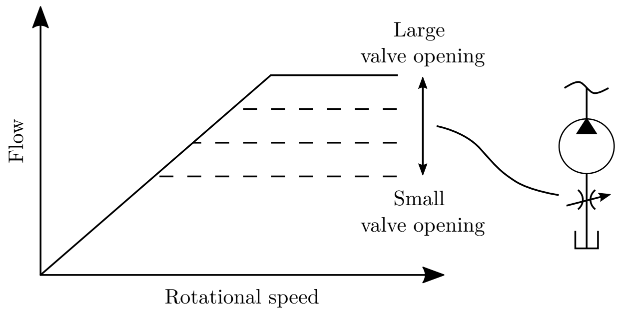


Figure 4.9 *Working principle for inlet metering.*

This type of control has been used extensively for fuel pumps in e.g. automotive applications. There are also examples from the automotive industry where it has been used in hydraulic systems, but then as a flow limiter rather than for active displacement control [75].

An issue with inlet metering is noise. This was researched in the '90s [75], [76]. There have also been some more recent studies, which focused on the dynamics and efficiency [77], [78], and it was observed that the dynamic behaviour was satisfactory, but the efficiency was worse than for a conventional pump.

5
Pump-Controlled Systems

In a pump-controlled system, an actuator has its own drive unit/units, and the pump flow determines the speed of the actuator. Other names for such systems include throttle-less hydraulics, valve-less hydraulics, and direct-drive hydraulics. However, the terms pump-controlled actuators and pump-controlled systems are used here.

There are plenty of different possible architectures for pump-controlled systems, and yet, they have not converged. A reasonable question to ask is: why? Fluid power systems have been around for more than 200 years, so one could assume that we would know how to control a single cylinder properly by now. There is, however, one issue, and it relates to energy efficiency. A cylinder has four operating modes, which can be visualised as quadrants (similarly to the hydraulic machine in Fig. 3.1). The cylinder works in motor operation when it converts hydraulic power into mechanical power, and it works a pump when it does the opposite. Both modes of operation can occur in both directions of movement. The mode of operation depends on the external force. In the modes when the cylinder works as a pump, there is a possibility to recover energy. In traditional hydraulic systems, this energy is simply wasted through the valves. This essentially means that the pump does not have to switch mode, but in practice, it also means that energy must be put into a system from which it would have been possible to extract energy. The energy efficiency is therefore poor. However, the mode switches tend to cause issues. Another thing that must be considered, especially when asymmetric cylinders are used (which usually is the case in mobile machinery), is flow compensation. The flow that enters the cylinder is different from the flow that leaves. Some kind of reservoir and flow compensation are therefore needed.

Figure 5.1 shows one of the most commonly researched architectures, which is based on a single pump working in closed circuit, and it shows how it operates in different modes. In the figure, valves used for flow compensation are shown as variable orifices. Their function is usually passively controlled with some kind of hydraulic logic elements, such as pilot-operated check valves or inverse shuttle valves, but actively controlled concepts have also been presented.

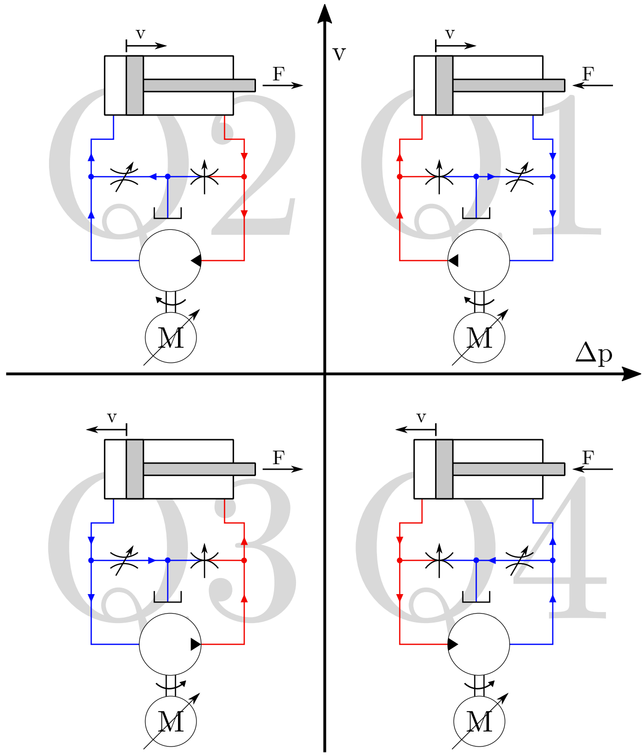


Figure 5.1 *Closed circuit single pump architecture in different modes of operation.*

5.1 System Architectures

When looking at a displacement controlled closed-circuit single-pump system, it can be noted that the working principle is very similar to rotary hydrostatic transmissions that are used extensively in mobile machinery (primarily for propulsion), which has been around for more than 100 years [79]. Similar systems are also applied in aircraft for flight control, where symmetric cylinders are used [80]. Still, there are problems with asymmetric cylinders that are supposed to work in four quadrants, but many concepts have been presented.

In a review from 2019, Ketelsen et al. presented and classified the work on pump-controlled systems that had been conducted so far [81]. The reference list contains 129 items. The works are classified based on whether they rely on speed control or displacement control, the number of prime movers, the number of pumps, and whether they are based on closed or open circuits. It is recommended to read that article to obtain a detailed view. In the following sections, general concepts are only briefly described.

5.1.1 Flow Control Element

Pump-controlled systems are often considered to be controlled by means of the flow through the hydraulic machines, which can be controlled by the speed, the displacement setting, or both. However, pressure control is also possible to implement.

Concepts that use displacement control and speed control can, in many ways, be very similar. The main difference is that displacement-controlled circuits tend to have a charge pump that is required for the conventional displacement control. This pump is sometimes used to supply the low-pressure side. With electrification, focus has shifted from displacement control to speed control. However, as described in the previous chapter, there are still reasons why displacement control, or a combination of displacement and speed-control can be of interest. But the literature on the subject is very limited.

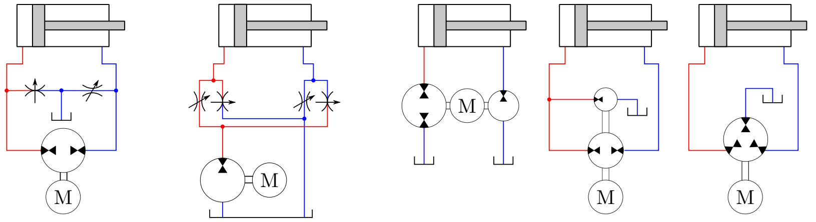
5.1.2 Flow Compensation

On a high level, the flow compensation methods that have been presented in literature can be split into two categories:

- **Valve compensation**
  Some kind of valve arrangement is used to make sure that the low-pressure side of the cylinder is connected to the reservoir. Naturally, there are many ways of implementing this, and both closed and open circuits can be used as shown in Fig. 5.2a. However, closed circuits are most common.

- **Pump compensation**
  In systems with pump compensation, at least one additional hydraulic machine is added to manage the difference in flow. The pumps can share a prime mover. Both pumps can work in an open circuit, but one of them can also work in a closed circuit. A special case only requiring one pump is when an asymmetrical pump is used (similar to the three-port transformer described in section 2.3.1). Different concepts are shown in Fig. 5.2b.

The main advantage with valve compensation is that the use of one conventional hydraulic machine is sufficient. Another advantage is that there are no problems with flow matching, i.e. mismatch between pump and cylinder flows. Flow matching can be a problem for the concepts based on pump compensation. For example, it can be hard to find hydraulic machines that exactly



(a) *Valve-based flow compensation concepts.*

(b) *Pump-based flow compensation concepts.*

Figure 5.2 *Principal schematics for different flow compensation concepts.*

match the area ratio of the cylinder. Furthermore, even if the sizes theoretically match well, problems can occur due to internal leakages and oil compression. However, a difference of about 5% has been stated to work well [82].

5.1.3 Reservoir

When looking modes Q1 and Q2 in Fig. 5.1, it can be seen that fluid must be suctioned from the reservoir. If the pressure drop is too high, there is a risk for cavitation, which, among other things, can result in lost controllability. To overcome this problem, low-pressure accumulators are typically suggested as a solution. A similar solution is so-called bootstrap reservoirs [83]. Such systems can be more compact compared to accumulator-based systems [84].

Other solutions are presented in paper [IV], in which so-called dump valves together with different pressure sources are considered, such as the charge pump in a conventional variable closed-circuit pump and a pressure reducing valve connected to a pump that supplies functions that are not pump-controlled. The latter is illustrated in Fig. 5.3. These concepts are desirable from a maintenance perspective since they do not require any pre-charge pressure. Their volume is also appealing. However, this is paid for in energy losses in the supply and when the cylinder is retracted. But the analysis in the paper, which is based on a backhoe loader, showed that the losses can be comparatively small.

5.1.4 Auxiliary Functions

Auxiliary functions ordinarily included in hydraulic systems are filtering and cooling. This must also be considered in pump-controlled systems. The problems are well summarised by Fassbender et al. in their article about the electrification of hydraulic systems in mobile machinery [85].

Filtering is required even in closed systems since hydraulic components tend to wear, and thereby contaminate the oil. Ideally, the filter should be placed at the low-pressure side and all oil should pass through it, but this is hard to

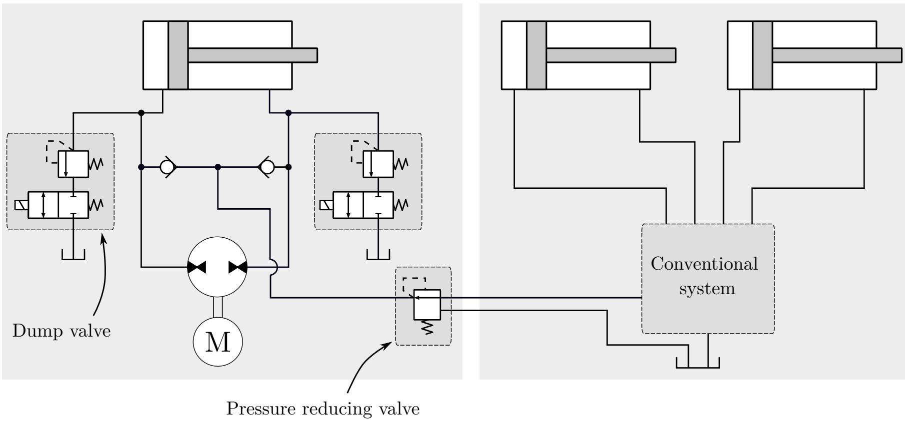


Figure 5.3 *Concept for a pump-controlled system based on dump valves.*

achieve in many pump-controlled architectures. Solutions with several check valves may be required.

When it comes to cooling, the power required for the application has a high influence on the degree of cooling required. Since throttling losses are supposed to be small in pump-controlled systems, the need for cooling is much smaller compared to conventional valve-controlled systems, but it may still be required. Ketelsen et al. has analysed the thermal properties and concluded that passive cooling may be sufficient for a power range of 5-10 kW [86].

In section 2.2, it was stated that the heat transfer properties of hydraulic systems were an advantage. However, if hydraulic actuators are isolated from each other, all actuators also need their own auxiliary functions. It should be stated, however, that pump-controlled systems do not have to be isolated, they can share a reservoir in which auxiliary functions can take place.

5.2 Mode Switches

The first record of problems with mode-switches in pump-controlled systems is from 2008 by Williamson and Ivantysinova [87]. Since then, numerous researchers have addressed the problem in different ways.

Mode-switch oscillations occur due to pressure oscillations that emerge from excitation of the hydraulic system. When the pressure oscillates close to the switching condition, there is a risk of mode-switch oscillations. And the mode switches can in turn amplify these oscillations. Mode-switch oscillations have primarily been studied for architectures based on a single pump. An effective approach for reducing the risk of mode-switch oscillations is to increase the damping of the system, either by introducing leakage [88], [89], throttling [90], or by controlling the pump [91], [92].

Another approach has been presented by Costa and Sepehri [93]. Their strategy is to perform the mode switch when $p_a A_a = p_b A_b$ instead of when $p_a = p_b$, which ordinarily is the case. Index a and b denotes the different cylinder chambers. A is the area and p is the pressure. They claim that their strategy is superior [94], but it has been shown that their strategy also is prone to oscillations [95].

In paper [V], the mode switching behaviour for different single pump architectures was investigated. It was found that it is important to consider where in the systems the pressures were sensed, especially when there are considerable pressure drops in the system. The pressure sensing components should be placed so the static pressure level is not changed if a mode-switch takes place. This minimises the induced pressure oscillations, which in turn can cause mode-switch oscillations. It was also found that a control based on hysteresis switching could be used to minimise the risk for mode-switch oscillations. The more hysteresis, the less risk of mode-switch oscillations. However, a large hysteresis width also requires a high pressure on the low-pressure side. The principle of hysteresis switching is illustrated in Fig. 5.4.

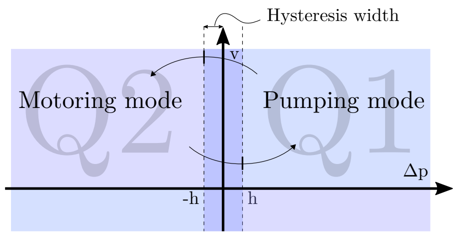


Figure 5.4 *Hysteresis control applied in a pump-controlled system. The switch is defined by the pressure difference* Δp *and the hysteresis width* h*.*

Another finding in paper [V] was that single-pump-architectures based on closed circuits were less prone to mode-switch oscillations compared to single-pump-architectures based on open circuits. The motivation is that the flow through the hydraulic machine must change direction in an open circuit, which is not the case in a closed circuit.

Nevertheless, when it comes to mode switch oscillations, architectures based on two pumps are less prone to oscillations than concepts based on one pump [96]. An explanation is that a mode switch causes a change in speed of the actuator in a single-pump configuration, which must be compensated for. However, this excites the system. The two-pump configuration does not suffer from this.

6 Discussion

In principle, there are two things that must be addressed in conventional hydraulic systems; the pressure-compensation losses must be reduced, and they should allow energy recovery.

One way to reduce pressure-compensation losses is to isolate loads from one another by using pump-controlled systems for important functions. Such systems can also allow electric energy recovery. In most cases, it is not reasonable to make all actuators pump controlled. More conventional systems are therefore likely to continue to be used for some functions. A major disadvantage with pump-controlled systems is that they tend to be bulky, and that each system must be dimensioned for its required peak power. The installed power will therefore be considerably higher than for systems with hydraulic power distribution since most actuators are not used at peak power at the same time. However, there are ways to address the bulkiness of pump-controlled systems. One way is to get rid of the accumulators, which was suggested in Paper [IV]. Another way is to reduce the size of the electric machine by reducing the torque requirement. One option for achieving this is to use variable displacement. For functions and applications where the positioning of the actuator is less critical, digital pumps can be of interest. Another option is to use pumps that can run at higher speeds. The pumps available for the mobile market today are, however, not designed for the higher speeds. Either a gearbox must be included in the assembly or the high-speed performance of pumps must be improved. Another thing that should be improved is the low-speed performance. There are pumps that perform really well at low speed rates, e.g. pumps based on the floating cup-principle [6]. Still, most pumps are not built for speeds under a few hundred rpm. This must be addressed if pure speed-control should be relevant. Pumps should also be optimised for multi-quadrant operation, which may be trickier than it sounds due to the desired pressure-matching during commutation. Many of the most promising pump-controlled architectures are based on closed-circuit pumps, which means that the pump should be able to perform well in all four quadrants. The results from Paper [V] also show that a high pressure on the low-pressure side can be used to lower the risk of mode-switch oscillations, and it is known that a higher pressure also makes the system stiffer. Pumps should therefore be able to handle higher pressures on their low-pressure side than they do today, which typically is around a few bars.

Another way to address the pressure-compensation losses is to opt for systems with hydraulic power distribution that are not based on throttling control. For rotary actuators, this means displacement-controlled concepts. Energy recovery can be achieved by using a common pressure rail system with accumulators. This implies that over-centre control of the displacement is of high relevance. When it comes to linear actuators, there are digital solutions that do not rely on any displacement control, but there are also concepts with hydraulic transformers, in which the ratio is controlled by means of the displacement. Such transformers are, however, not commercially available today, but there is potential for development. Systems based on hydraulic power distribution systems have a main advantage over pump-controlled systems regarding the sizing of the electric motor and pump, since they can be dimensioned for the average power of all consumers, if accumulators are used for energy management. High power out-take from batteries can also be avoided, which is good for the service life of the batteries. The possibility for a high degree of modularity of pump-controlled systems is, however, an advantage for pump-control. Either way, displacement control is highly relevant for both options.

Keeping the problems described above in mind, it is not surprising that the electrified mobile machinery that has been commercialised so far is equipped with conventional hydraulic systems. There are many things to solve. Concepts that can form part of the solution have been presented in the appended papers, but there is generally still a need for experimental validation.

7
Conclusions

The research questions focused on in this thesis were stated in the introduction. The questions have been investigated throughout the text, and the answers are summarised here.

RQ1: When is the use of variable displacement of interest in electrified mobile machinery?

Efficiency is key in electrified mobile machinery. It is therefore important to be able to control the flow rate. This can be achieved by means of speed control, displacement control, or a combination of both. It is reasonable to assume that speed control will prevail in electrified mobile machinery. However, there are several arguments for using speed control in combination with displacement control:

- **Optimised operating points**
  The losses can be reduced if speed control is combined with displacement control since the operating points for the hydraulic and electric machines can be moved to more efficient regions. The potential loss reduction is highest at high pressure levels and low flow rates. This has been shown in papers [II] and [III]. Furthermore, the fact that most hydraulic machines are not suitable for very low speed rates means pure speed control is not ideal.

- **Downsizing of the electric motor**
  With variable displacement, the required torque can be reduced since the displacement setting can be reduced when high pressure levels are required. Consequently, the size of the electric machine can be reduced. This was exemplified in paper [II].

- **Dynamic performance**
  Higher control bandwidth can be achieved when speed-control is com-

bined with displacement control. This has, however, not been investigated by the author.

Furthermore, displacement control can also play a central role in system designs based on common pressure rails, which likely will become more common in the coming years. However, to be able to fully utilise the advantages, electronic control is required. There are also many different types of displacement control methods, which can be relevant for different applications, as described in paper [I].

RQ2: When is the use of digital pumps of interest in electrified mobile machinery?

Since a digital pump is a type of variable displacement pump, the answer relates to the one above. The advantages that come with continuously variable pumps are also applicable to digital pumps. The advantages with digital pumps in particular are that they easily can be electronically controlled, and that the control can be simple. However, the discrete nature of the pump reduces the resolution of the control, which can be problematic in some applications. Furthermore, seamless mode-switches cannot be achieved, even though shunts can improve the performance. High-precision applications are therefore not appropriate. The dynamics have been investigated in paper [III].

RQ3: How can pump-controlled systems in electrified mobile machinery be implemented as a practical solution?

The fact that pressure-compensation losses do not exist in pump-controlled systems makes pump-controlled systems highly relevant for electrified mobile machinery. However, pump-controlled systems are known for being bulky and prone to mode-switch oscillations, which often makes them non-practical.

One of the components that generally takes up a considerable amount of space is the low-pressure accumulator. Concepts based on dump valves that do not utilize accumulators have been presented in paper [IV]. An additional advantage with these concepts is that they are easier to install since they do not need any pre-charge pressure. They are not as efficient as concepts with accumulators, but the losses are small in relation to the pressure-compensation losses, for example. Another way to address the bulkiness is to downsize the electric motor. This can be done by using a variable pump, which has been discussed above.

Regarding the mode-switch oscillations, it has been shown that they can be avoided by using hysteresis control. This was analysed in paper [V]. The larger the hysteresis width, the smaller the risk of oscillations. However, the pressure on the low-pressure side must be increased with the hysteresis width to ensure controllability of the motion. Hysteresis control with actively controlled valves has been investigated, but it is possible to achieve hysteresis with passive valves too.

8
Review of Papers

Paper I

Classification and Review of Variable Displacement Fluid Power Pumps and Motors

This paper is a literature review of the displacement control of positive displacement pumps and motors. Different methods for displacement control that have been proposed in research or that are commercially available are classified and reviewed. The classification is based on whether the method controls the amount of circulated flow or the usage of the circulated flow, and if the control is on system level or displacement element level. This results in four main classes, which to some extent can describe the characteristics of the control.

Paper II

Digital Pumps in Speed-controlled Systems – An Energy Study for a Loader Crane Application

This paper focuses on the potential benefits that come from a discrete number of displacement settings compared to a fixed displacement. In the analysis, a drive cycle for a loader crane is used. The results show that the potential energy savings are relatively small, but the downsizing possibilities for the electric motor are substantial. Furthermore, the energy savings will be much greater for a drive cycle that operates extensively at low flow rates and high pressures. A further conclusion is that a small number of discrete displacement settings (e.g. two or three) can be enough to achieve significant improvements regarding energy savings and downsizing possibilities.

Paper III

Analysis of a Digital Pump with Variable Speed Drive

This paper focuses on the performance of a digital pump, i.e. a pump with discrete displacement settings. Efficiency and switching performance are considered. Different shunt-based concepts and switching strategies that can improve the dynamics during switching are proposed. The results show that a digital pump is most relevant in applications that frequently work at high pressures and low flow rates. Furthermore, it shows that shunt-based control can improve the switching performance, but at the cost of either more complex control or lower efficiency.

Paper IV

Pump-Controlled Actuators with Dump Valves

In this paper, pump-controlled cylinder concepts that do not rely on accumulators, which most concepts do, are presented and analysed. In these concepts, the required differential flow when the cylinder is extended is provided by an external or internal source. Excess flow during retraction is released via so-called dump valves. The energy consumption of these concepts is expected to be higher than accumulator-based concepts, but the question is: by how much? An energy analysis, where the boom cylinder on a backhoe loader is controlled by different pump-controlled architectures, is presented. The results show that the presented concepts can reduce the power consumption by 50-60 %, which should be compared to 55-65 % for an accumulator-based pump-controlled system.

Paper V

Hysteresis Control in Pump-Controlled Systems - A Way to Reduce Mode-Switch Oscillations in Closed and Open Circuits

Mode-switch oscillations in pump-controlled systems are a known issue. In this paper, the problem with so-called hysteresis control is addressed. Different implementations of hysteresis control are presented and the performance is analysed. Generalised models of closed and open pump-controlled circuits are presented and compared. The impact of where the pressure is sensed in pump-controlled systems is investigated, and it shows that the placement can have a great impact on the switching behaviour. It also shows that active hysteresis control can reduce the oscillations significantly – the wider hysteresis the better. However, to be able to maintain controllability, the reservoir pressure must increase with the hysteresis width.

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Papers

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> A man without a moustache is a man without a soul.
>
> Confucius?

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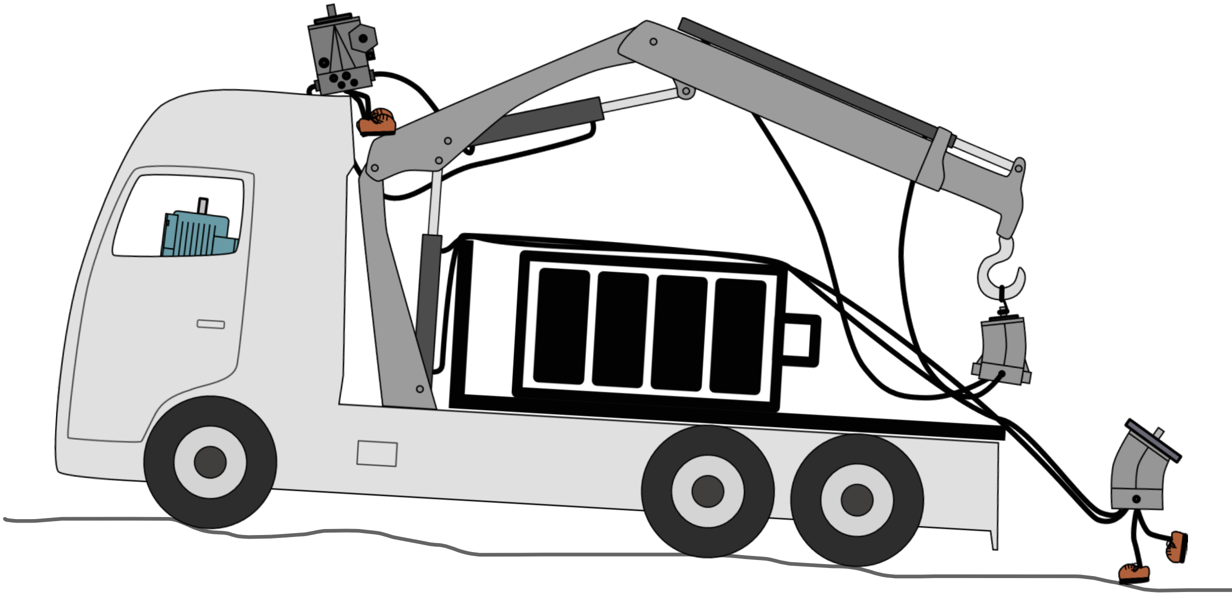

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