A COMPREHENSIVE REVIEW OF ELECTRONICALLY CONTROLLED IMPLEMENT ARCHITECTURES FOR MOBILE MACHINERY USING SECONDARY CONTROL

Edwin Heemskerk[1]*, Michael Brand[2]

[1] *Bosch Rexroth AG, Partensteinerstraße 23, 97276 Lohr am Main, Deutschland*
[2] *Bosch Rexroth AG, Glockeraustraße 4, 89275 Elchingen, Deutschland*

* Corresponding author: Tel.: +49 9352 183127; E-mail address: edwin.heemskerk@boschrexroth.de

ABSTRACT

Transmission architectures for drive and implement functions in mobile machinery are currently diverting. On the one hand new market requirements, as alternative energy sources, impact the system design, and so do direct or indirect market drivers as efficiency, controllability, predictability, and driver comfort. On the other hand, the ability to electronically control components in alternative ways enable new architectures as well.

The persons in charge of the machine design must find the balance between considering the new demands and relying on known building blocks to reduce risks and safeguard valuable resources. To help the decision making, an overview of new and promising architectures is presented, utilizing secondary control approaches for drive and work functions. These architectures target to recover kinetic energy, reduce throttling losses, and operate components in their sweet spot.

Decisive criteria for the shown architectures are their maturity, degree of fulfilment of the market demands, minimized risk criteria via proven sub-components and feasibility of handling the transmission variants for varying market demands.

Keywords: Electro-hydraulics, secondary control, mobile machinery, energy recovery

1. INTRODUCTION

Our increasing demands to protect our environment in a sustainable way, to optimize material resources like energy, to reduce CO_2 and to ensure human well-being are well known. This results in more diverse machine architectures for segmented market demands e.g., with various power sources like battery driven machines, e-fuel base driven machines and conventional *ICE*s and well adapted transmission architectures depending on load cycles and machine usage. At the same time machine manufacturers must consider decreasing engineering resources out of cost and availability reasons. This rising gap in increasing demands versus available resources needs to be solved via standardization and usage of overarching building block technologies in general and also for transmissions architectures and their required components.

Beneficially, technological improvements allow new approaches in mechatronic optimizations of components. Sensors get more cost effective, smaller, and more reliable. In the field of hydraulic transmissions, this allows to transit from hydromechanics actuation and controls to more precise and more adjustable electronic controls.

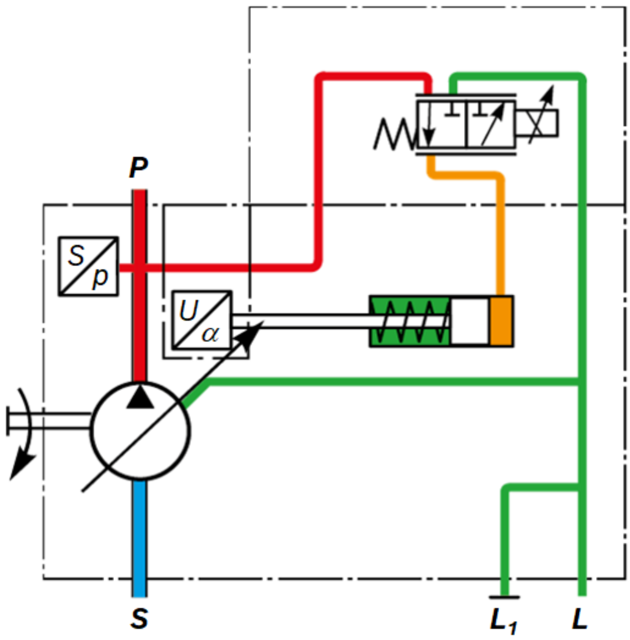

Figure 1: Electrohydraulic control schematic of an electronified open circuit pump

A good example for this transition is the electronified open circuit (*eOC*) pump control for open circuit hydraulic pumps. Its control concept is shown in **Figure 1**. An electro-proportional valve controls the swivel speed of the pump. The pump is equipped with a pressure and a displacement sensor. The valve is controlled via software. Available commands are pressure control, displacement control, torque control and the gradient of these command values as seen in **Figure 2**. Gradients of actual values can be limited.

The concept allows to operate the pump much closer to the physical limits since tolerances are compensated and static or dynamic critical working points can be avoided. Load cycles can be respected. With this mechatronic optimization, the least hydro-mechanic effort reaches the maximum performance.

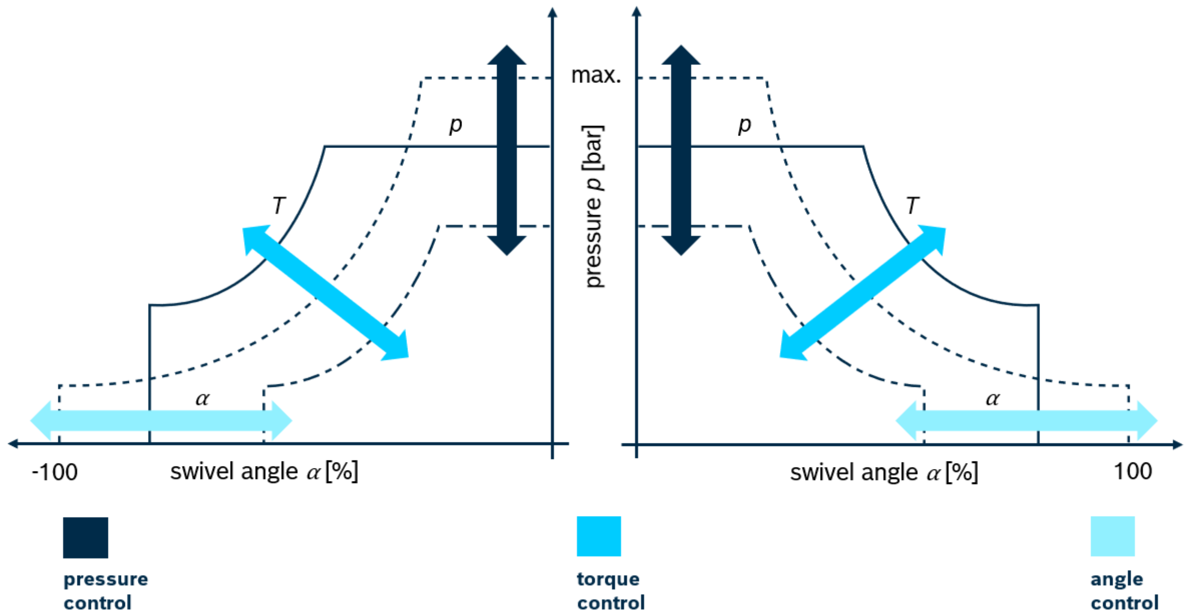

Figure 2: Control options for electronified open circuit pumps

This control approach allows open circuit pumps to be operated in two quadrants as shown in **Figure 2**. This means that without relevant additional hardware effort the pump can supply oil in pumping mode and can receive oil as a hydro motor and transfer this hydraulic energy into mechanical energy at the input shaft of the pump [1].

A second technology trend fosters this mechatronic approach. It becomes easier, more known and accepted and technology wise supported to allocate the component-based software functionality on central control units in an efficient way. This gives the machine manufacturer a maximal degree of freedom to master and adjust the component function to any needs of the transmission architecture with maximum efficiency and in a cost attractive way.

The mechatronic optimization principle is valid also for closed circuit pumps and valves. As important is that the best technology is used for a respective component feature and to follow a pragmatic and not a dogmatic approach. Engineering disciplines for developing components get more heterogenous and competitiveness will be strongly influenced by the ability to adapt to these opportunities.

On a component function level for open or closed circuit hydraulic pumps the potential can be summarized in the following way:

- Pressure, displacement and torque control and limitations
- Dynamic and gradient control for command and disturbance values
- Component protection
- Adjustability on various functional demands resulting on low variance and stock demands
- Self-calibration to reduce or avoid EOL or service efforts
- Speaking failures
- Reduced function ability in failure situations

Focus of the paper are in the following new transmission architectures that are now possible based on this new component control approach.

2. NEW POSSIBILITIES WHEN USING A MECHATRONICALLY OPTIMISED PUMP

As explained in the introduction, a mechatronically optimised pump has benefits in dynamics, flexibility, efficiency, and performance. Depending on the application different aspects can be interesting. In this paper the excavator is used as an example to showcase different possibilities.

2.1. Power Control

In many mobile machines the hydraulic power needs to be limited, as the hydraulic system can take more power than the primary drive train (i.e., a diesel engine or an electric motor) is able to supply. Typically, this is done be a two-spring regulator. These springs as chosen in such a way, that the deviation from the hyperbolic power curve is minimized in the main operation points of the machine. Unfortunately, the maximum power of an engine is afflicted with tolerances. These are caused i.e., by the manufacturing, the fuel used or the operating altitude of the machine and the actual operating speed. To prevent the engine from stalling under all conditions, the hydraulic power limitation is set lower than the lowest expected engine power, as shown in **Figure 3**, while also considering the spring tolerances.
As the electronified open circuit pump has a pressure and swivel angle sensor (see **Figure 1**), the system always knows the load it is putting on the engine. The maximum allowed load can be dynamically communicated to the pump via *CAN* bus message and the electronic pump control ensures that this limit is respected accordingly. In addition, if other power consumers (like the air

conditioning or an auxiliary pump) are switched on, or if the engine speed is operated at other (lower) engine speeds, this can be considered in the pump control.

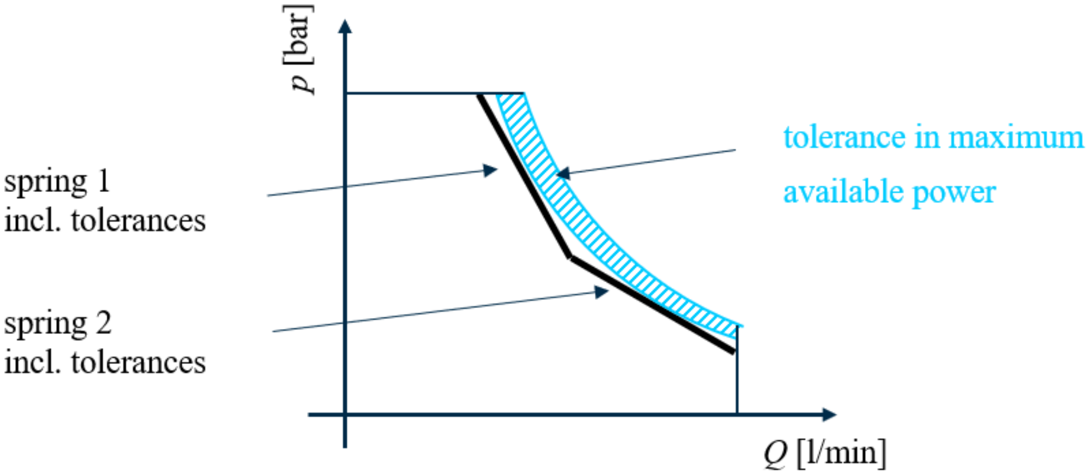

Figure 3: Power control of a hydraulic pump

In case the engine is capable to communicate its rotational speed and remaining torque capacities to the pump controller, the hydraulic output power of the pump can be directly aligned with the load limit of the engine. This integrated load limiting control allows to eliminate any safety margin in the torque setting of the pump and leads to up to 10% increased hydraulic output power. In comparison to conventional load limiting control solutions based on electronic displacement control, there is no negative impact of hysteresis.

2.2. Crawler machines with 1-loop systems

Many mini and midi excavators in the world are equipped with a 1-loop flow sharing system (see **Figure 4** for a crawler excavator setup). This is a well-suited system architecture to achieve a good compromise between performance, controllability, and cost, especially for machines that work with different attachments.

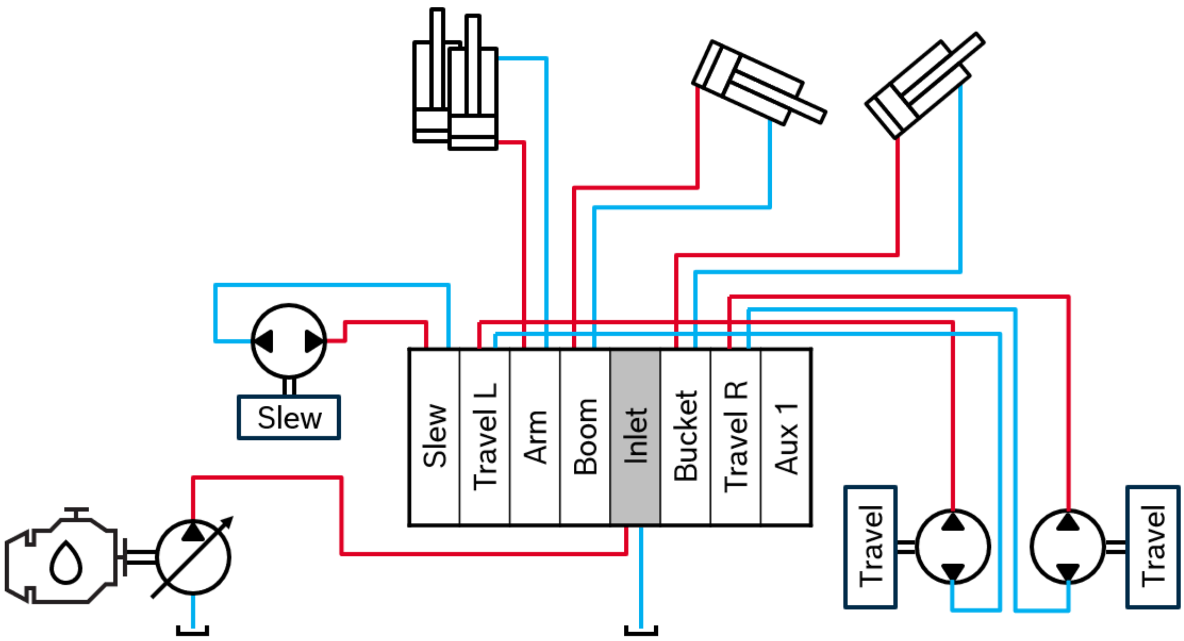

Figure 4: Typical configuration of the hydraulic system in a mini excavator

The biggest challenge for a 1-loop system in a crawler excavator is a light turn while driving at full speed. **Figure 5** shows the transition from driving a straight line to a slow turn.

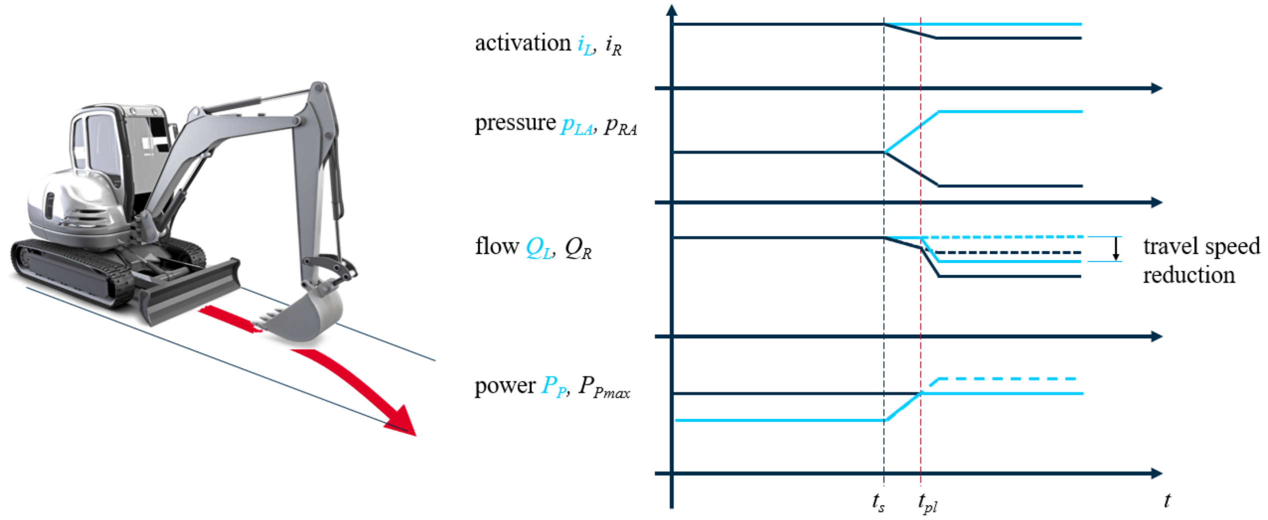

Figure 5: Slow turn with a crawler excavator in a 1-loop hydraulic system

As soon as the right track is slowed down enough for the machine to turn slightly to the right, the left track meter-in pressure rises significantly, while the meter-in pressure of the right track goes down. This is a hydraulic 1-loop system, so also the pump pressure rises accordingly. As it is only a slow turn, the total flow request (the sum of Q_L and Q_R) for the pump is only slightly lower compared to a straight travel. In consequence the hydraulic power is significantly increased. If this increased power need is bigger than the total available power (at t_{pl} in **Figure 5**), the hydraulic power limitation will reduce the total pump flow, slowing down the machine driving speed (the dashed line shows the flows Q_L and Q_R in case of no power limitation).

When replacing the normal fixed displacement travel motors with electronified open circuit pump/motors and operating these secondary controlled, as shown in **Figure 6**, this behaviour can now be significantly improved.

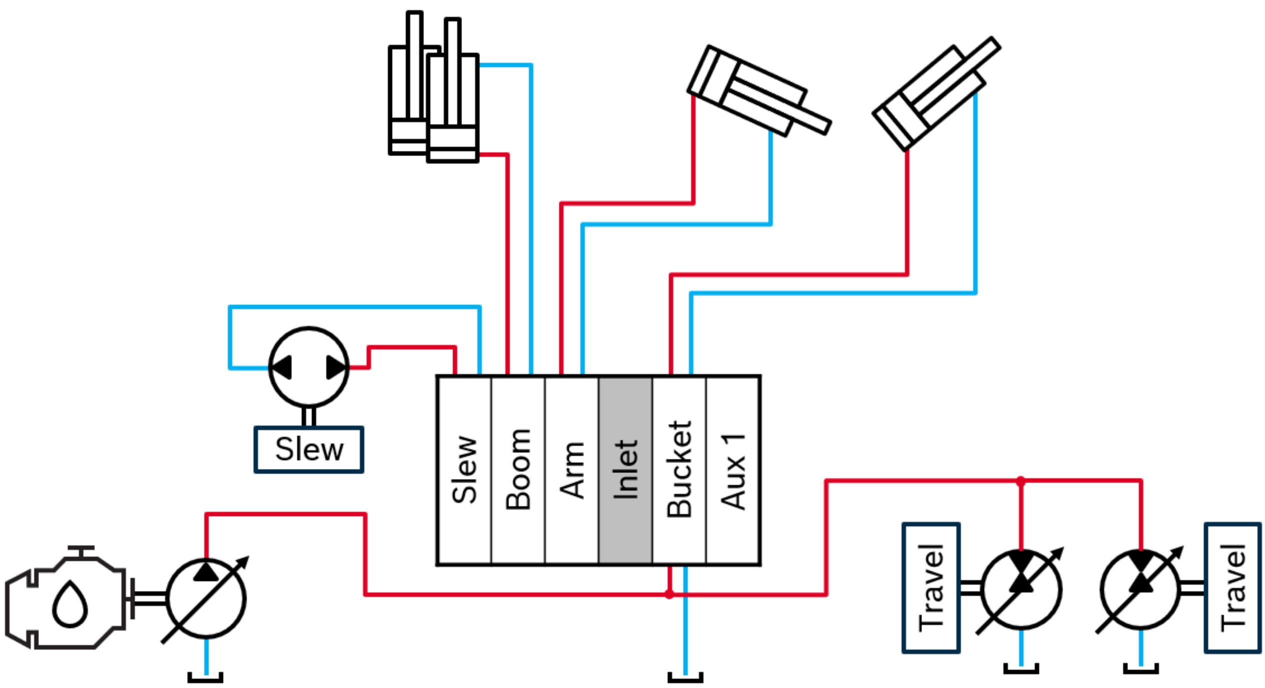

Figure 6: Modified hydraulic system in a mini excavator using secondary controlled travel motors

An operator demand for turning results in different torque demands to both motors. These are realized with an adequate pressure level of the pump together with the calculated displacements on the left and right hydro motor. No throttle losses arise in the main control valve (*MCV*) for both functions and no throttle losses arise for the hydro motor side with the lower torque demand. The flow demand for the same machine speed is lower than compared with the conventional architecture. This way of actuation is only possible based on the pump and hydro motor function described in chapter 1. On machine level it results in faster and more efficient drive manoeuvres.

2.3. Slew control

Like the travel motors, also the slew motor, typically a fixed displacement motor, can be replaced by a secondary controlled pump/motor. Here the target is not an improved machine behaviour, but energy saving.

Also, in this case the electronified open circuit pump/motor is directly connected to the main pump line, with no valve in between, eliminating throttling losses in parallel movement. The swash angle of the slew pump/motor is dependent of the current pump pressure, both when accelerating and de- accelerating. When slowing down the slew, the slew pump/motor operates as a pump, supplying oil to all other functions used in parallel, reducing the energy consumption of the hydraulic system [2]. The degee of freedom of the slew pump/motor displacement allows to adapt the pressure level to other functions and therefore reduces throttle losses.

2.4. Boom energy recovery

Apart from reducing the throttling losses in a system, many machine also have the possibility to recover energy while lowering a load (i.e., reach stackers or industry excavators) or just by lowering its own machine structure. The force needed to lift the empty boom of an excavator is typically about 20 to 50 % of the force needed to lift a full bucket. So just lowering the empty boom already offers potential to recover energy. **Figure 7** shows a hydraulic 2-loop system for a battery driven wheeled excavator that allows for boom energy recovery. The main difference to a normal 2-loop system, that is used in bigger excavators, is the additional power regenerative boom module (*PRB*) and the fact that the left pump is an electronified open circuit pump, as described in chapter one.

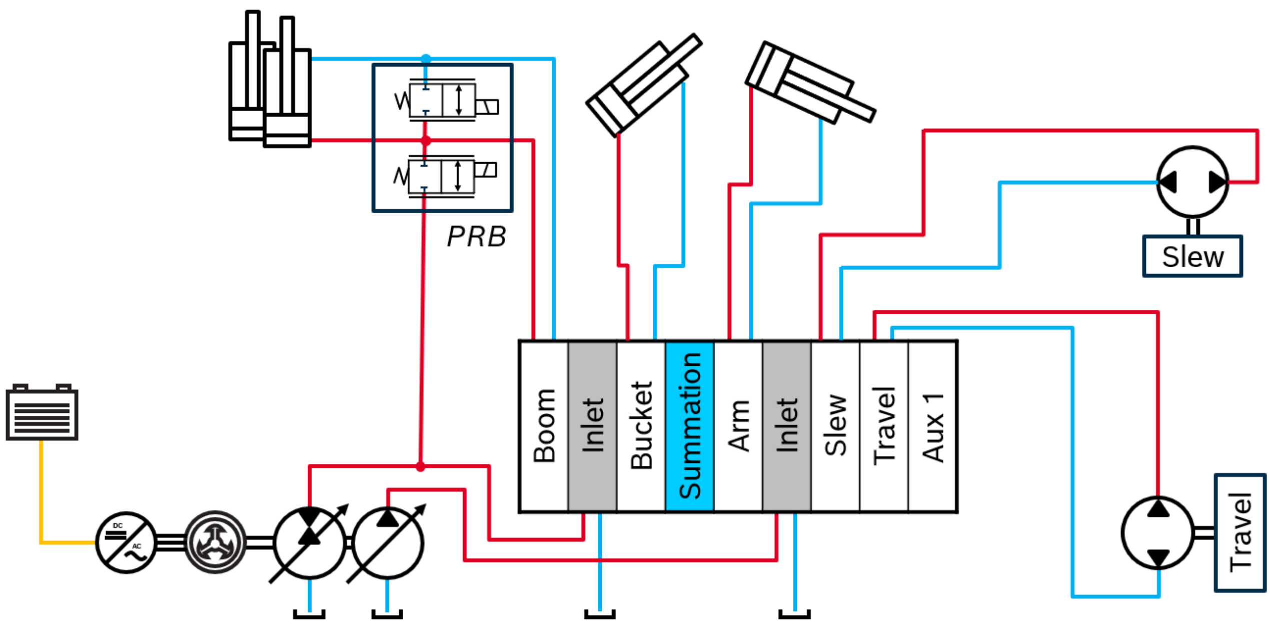

Figure 7: 2-loop hydraulic system with boom energy recovery

With the top valve of the power regenerative boom module, the head and rod side of the boom cylinder is connected. The lower valve connects the boom head side with the electronified open circuit pump/motor. With this hydraulic setup we can increase the pressure and reduce the flow from the boom cylinder to the pump/motor, working as a motor in this condition. So even when lowering the boom at full speed it can recover nearly all the boom down energy, without the need to install a bigger pump, which would reduce the energy efficiency in all operating situations. Also, this function requires the component features introduced in Chapter 1.

2.5. Active ride control

Most mobile machines, like wheeled loaders and wheeled excavators are not equipped with suspensions at the wheel axles. Instead, passive (*PRC*) and active ride control (*ARC*) modules are used [3]. The *PRC* typically use an accumulator and a hydraulic restriction to dampen the oscillation. This lost free solution is optimized for one load conditions and that has reduced functionality in other load conditions. *ARC* systems can adapt to different load conditions, but typically at the cost of energy.

The hydraulic setup shown in **Figure 7** also allows for an *ARC* without additional components. While driving the *PRB* valve connects the boom to the electronified open circuit pump/motor. This pump/motor is operated in pressure control, either taking out oil of the boom or adding oil, to keep the load pressure constant [4]. When working as a pump, it uses energy from the drive train, when working as a motor, it recovers energy, resulting in a near loss free active ride control (*ARC*).

3. CONCLUSION AND OUTLOOK

The mobile machinery market demands for variable architectures to support the different needs of the customers, as alternative energy sources, efficiency, controllability, predictability, and driver comfort. The machine *OEM*s must find the balance between considering the new demands and relying on known building blocks to reduce risks and safeguard valuable resources. New electronified components offer possibilities to handle the transmission variants for the different market demands.

This paper presents different examples of hydraulic architectures, that utilize the dynamics and the control flexibility of an electronified open circuit pump/motor, that improve the performance and/or the energy efficiency of an excavator. These architectures are examples to stimulate machine *OEM*s to find new individual solutions to improve their specific machines based on enhanced component functionalities.

NOMENCLATURE

α	Swivel angle percentage of the max. pump swivel angle	%
A	Area	m^2
ARC	Active ride control	
CAN	Controller area network	
CO_2	Carbon dioxide	
eOC	Electronified open circuit	
EOL	End of line	
ICE	Internal combustion engine	
i_L, i_R	Joystick activation of the left and right track	%
L, L1	Leakage port on the pump	
MCV	Main control valve	
OEM	Original equipment manufacturer	
p	Pressure	bar

P	Main port of the pump	
p_{LA}, p_{RA}	Motor inlet pressure of left and right travel motor	bar
P_P	Hydraulic power at the pump	kW
P_{Pmax}	Maximum available power at the pump	kW
PRB	Power regenerative boom	
PRC	Passive ride control	
Q	Flow	l/min
Q_L, Q_R	Flow to the left and right travel motor	l/min
S	Suction port on the pump	
S	Sent interface (electronic protocol)	
t	Time	s
t_s	Starting time of the steering movement	s
t_{pl}	Time the power limitation limits the flow	s
T	Torque	Nm
U	Voltage	V

REFERENCES

[1] Tetik S (2022) Secondary Control Based Hydraulic Architectures For Mobile Applications. The 13th International Fluid Power Conference, 13.IFK, March 21-23, 2022, Aachen, Germany

[2] Pettersson K (2009) Secondary control in construction machinery – design and evaulation of an excavator swing drive. 11th Scandinavian International Conference on Fluid Power, SICFP'09, June 2-4, 2009, Linköping, Sweden

[3] Madau R (2019) Active Ride Control for Construction Machines Based on Pressure Feedback. ASME/BATH 2019 Symposium on Fluid Power and Motion Control, October 7–9, 2019, Longboat Key, USA

[4] Cardoso R (2022) Active Ride Control Based on an Over-Center Pump. 2022 Maha Fluid Power Conference, May 17-19, 2022, Purdue, USA