COMPACT FLUID POWER CONTROL UNIT WITH INDEPENDENT METERING

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ABSTRACT

safety and installation space restrictions, require new customized technological solutions on a system level. Independent meter-in and meter-out control edge arrangements with aligned electronic network and software solutions provide the freedom for the design of intelligent overall fluid control systems. The focus of the paper presented is the development of a new fluid control unit, that meets the following requirements: high power based on a maximum pressure level > 500 bar and a flow rate of up to 200 l/min, an appropriate valve stroke, valve speed, and installation space according to the specification. The fluid control unit presented has independent control edges actuated by a step motor, and a compact pilot control solution. On system level the modelling and simulation of an excavator implement drive has been carried out by means of a typical operating cycle. Firstly for a throttle system with conventional linked control edges and already with a customized load sensing pump control. Secondly for an optimized throttle system with independent metering, hydromechanical flow sharing, a customized load sensing pump control, and with an electronic control of the regeneration circuit. The comparison of the simulation results of both system variants shows already an excellent reduction of the energy consumption of 20% for the optimized implement drive system .

Keywords: Fluid power control unit, Independent metering, System simulaton

1. INTRODUCTION

Tighter guidelines on mobile machine implement drive systems in terms of power requirements, emission standards, energy efficiency, system safety, and installation space restrictions lead to new customized technological solutions on system level. To meet the increasing requirements, various drive and control technologies have been discussed since the turn of the century (e.g. [1], [2]). With focus on valve control, particularly independent metering has been the base of various developments [3], [4], [5], [6], [7], [8], [9]. Goal of the project presented is the implementation of engineering research findings in an intelligent fluid power control unit that enables advanced functionalities of high power implement drives.

The focus of the paper presented comprises the conception (section 2) and the design (section 3) of a hydraulic control unit to meet the following specification:

- significant reduction of energy consumption
- high fluid power with maximum pressure > 500 bar and a flow rate of 200 l/min
- valve spool adjustment key data: travel +/- 8 mm, speed 100 mm/s, and force 5000 N in case of direct control
- limited installation space (power density)
- intelligent control by integration of electronic hardware and software

- fail safe functionality
- acceptable investment cost (Return on Invest).

The focus in section 4 is the simulation and assessment of excavator implement drive systems with regard to their energy efficiency. The energy consumption of a conventional hydro-mechanical control system with connected control edges has been compared with the consumption of an electrohydraulic control system with independent metering.

2. CONCEPTION OF THE VALVE CONTROL SYSTEM

Within the valve control system the actuation system is of particular significance, due to its function between the Electronic Control Unit (ECU) and the hydraulic power section. Adjustment limits of various actuation systems in terms of force, travel and speed, are compared in **Figure 1** based on [10]. It becomes clear, due to restricted space requirements, that high pressure and consequently high adjustment forces in a dimension of 5000 N exclude a direct control concept. By means of a pilot control concept the adjustment limits of the actuation system as well as the space restrictions are accessible. Various actuation principles for the pilot control stage have been discussed. The preferred solution consists of a step motor with spindle, due to the sufficient travel, speed, and force for the adjustment, high position accuracy, stability, and the fail safe usability.

With respect to **Figure 1** the design of a pilot control actuator with a combination of a step motor and a spindle comply with the given adjustment limits. High power requirements in combination with limited installation space of the fluid control unit need an extremely compact pilot control valve stage. Therefore, the pilot piston is arranged concentrically inside the power stage (control chamber, control sleeve, main piston) according to **Figure 2**. By means of the actuator the axial position of the pilot piston is changed.

The central control edge of the pilot piston opens and enables a volume flow in the control chamber. Increasing pressure in the control chamber move the control sleeve together with the attached main piston as far the central control edge of the pilot piston is closed again. So the high pressure and flow rate levels of the power stage are manageable.

The forces at the actuator (spindle, step motor) for moving the pilot piston are controllable small, due to the pressure compensated pilot piston [11].

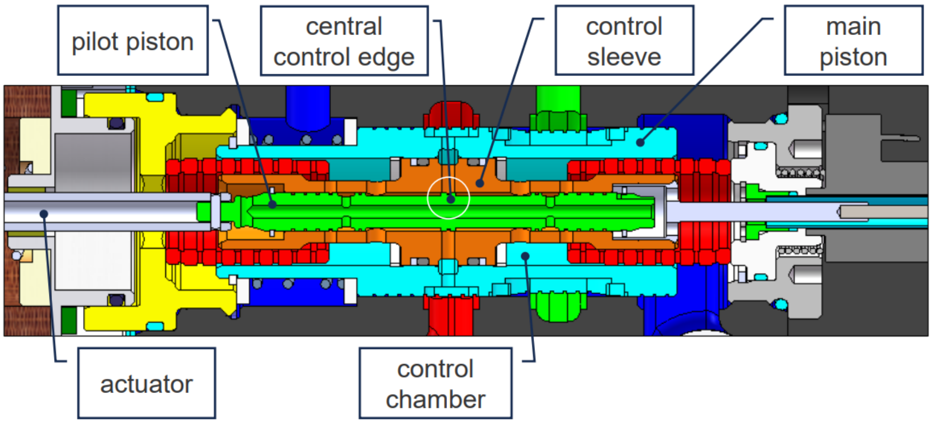

Figure 2: Compact pilot control valve concept [11]

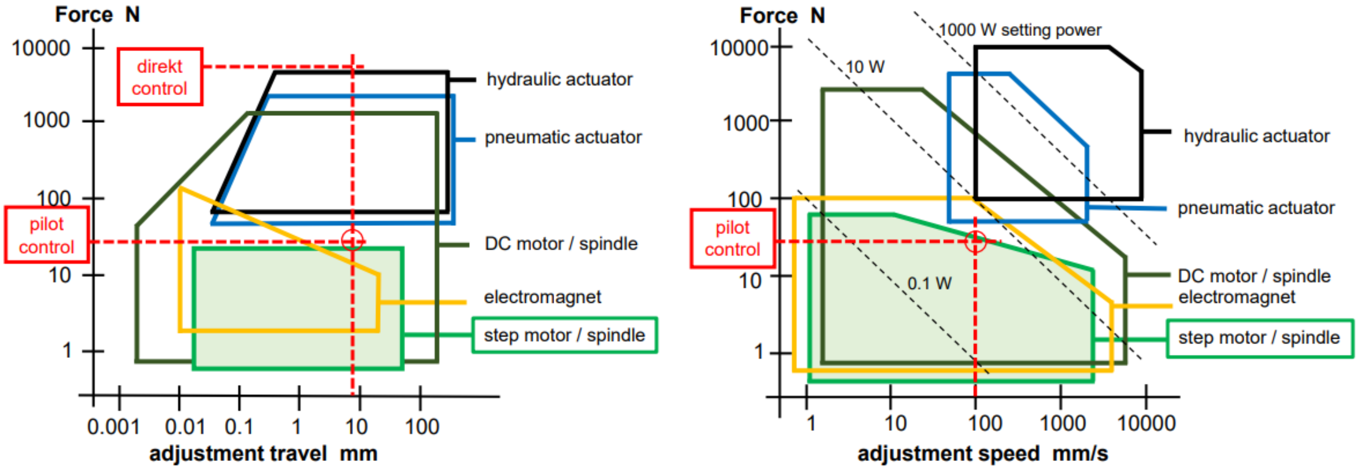

Figure 3: Comparison of relevant actuation principles (data based on [10])

To meet the specification the hydraulic control unit consist of a compact hydro-mechanical pilot valve spool arrangement (**Figure 2**), actuated by a step motor with very high power density and with a low friction spindle (compare **Figure 3**). The functional integration contains, if appropriate, additionally mechanical pressure relief valves with anti-cavitation function and a position sensor, a mechanical fail safe mechanism, an electronic control unit, and aligned software. To overcome the restrictions of conventional valve control systems with mechanically linked orifices, an independent meter-in and meter-out control edge concept with two 3/3 way proportional valves has been preferred. Separate valve control edges enable freedom for the versatile configuration of an intelligent fluid control system.

The actuation concept of pilot control has been built as a test set up (compare **Figure 4**). The actuation of the pilot valve is carried out by a step motor (1) with a smooth-running ball bearing spindle (2). Precondition for fail safe is a spindle carried out as double-threaded ball bearing screw with insignificant self-locking. In case of electric current disconnection (fail safe) the screw nut (3) (including connecting element (4) and connected pilot valve) is enabled to move back to its initial position due to the return spring mechanism (5). For the measurement of the position of the movable parts (4, 3) with reference to a fixed object (6) a laser position sensor (7) is attached.

By means of the test setup, investigations of the actuator requirements in terms of adjustment travel +/- 8 mm, adjustment speed 100 mm/s, pilot valve adjustment force (ca. 30 N), and the fail safe functionality have been carried out. Due to the pressure compensated pilot valve only the spring force is dominant and has to be overcome. In general the additional impact of flow forces results in an accelerate closing of the control edges of the pilot spool valve. This effect is useful in case of fail safe in particular.

The dynamic behaviour of the pilot control mechanism by means of the step motor with spindle is shown in Figure 4 for a current step signal of 2 A.

The measured adjustment travel of the valve spool is in the required range of ±8 mm and the moving time of ca. 0.04 s (compare **Figure 5** below) correspond to a speed level of 200 mm/s (requirement 100 mm/s).

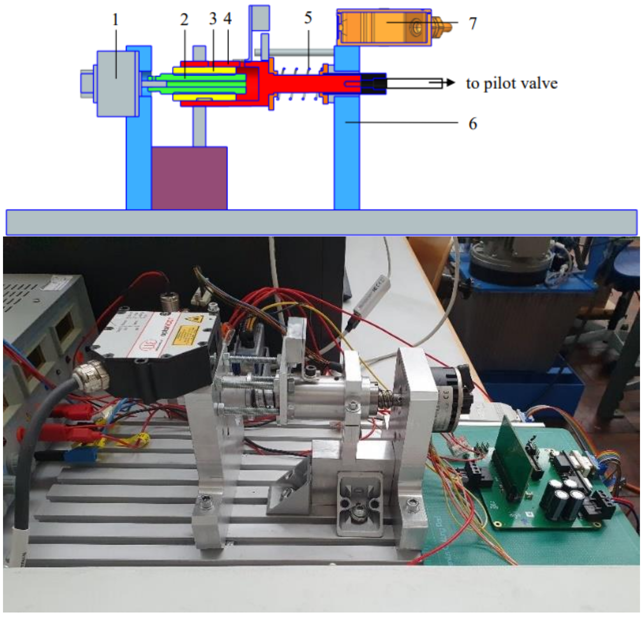

Figure 4: Schema of the actuation concept (top) and test setup (bottom)

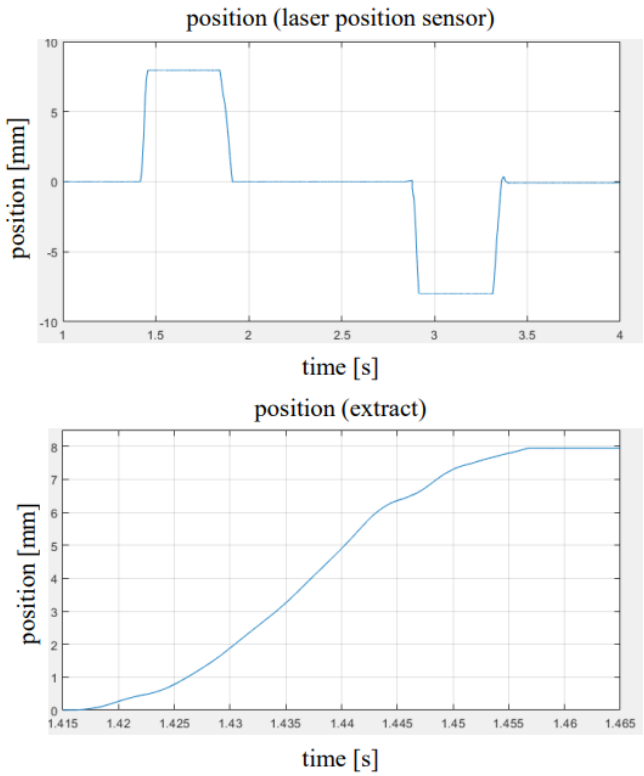

Figure 5: Measured adjustment travel of the pilot control actuator

3. FLUID POWER CONTROL UNIT

The fluid power control unit has been designed with respect to the various functional requirements and the limited installation space. The compact design of a block of several fluid power control units is illustrated in **Figure 6.** The sectional drawing of a single fluid power control unit is shown in **Figure 7**.

A single fluid power control unit contains of the following functional modules (**Figure 6**):

a) actuator module with step motor (4), electronic board (6), ball bearing screw with minimal self-locking (double thread) (2), and a fail safe mechanism (3)

b) main module with two independent stacked pilot-operated 3/3 way proportional valves (1) including centric integrated pressure compensated pilot valve spools, as well as a pressure sensor (8), and a position encoder (7)

c) outlet plates with pressure relieve and anti-cavitation valves (5)

d) connector module as electric interface (9)

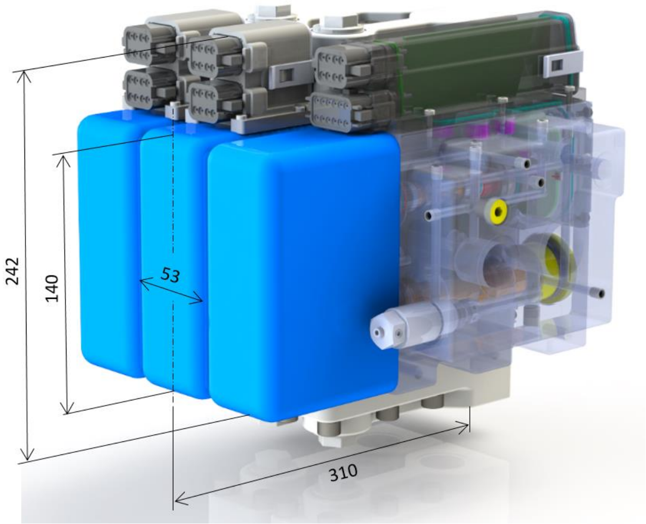

Figure 6: Valve block design of fluid power control units with independent metering (source TRIES GmbH & Co. KG)

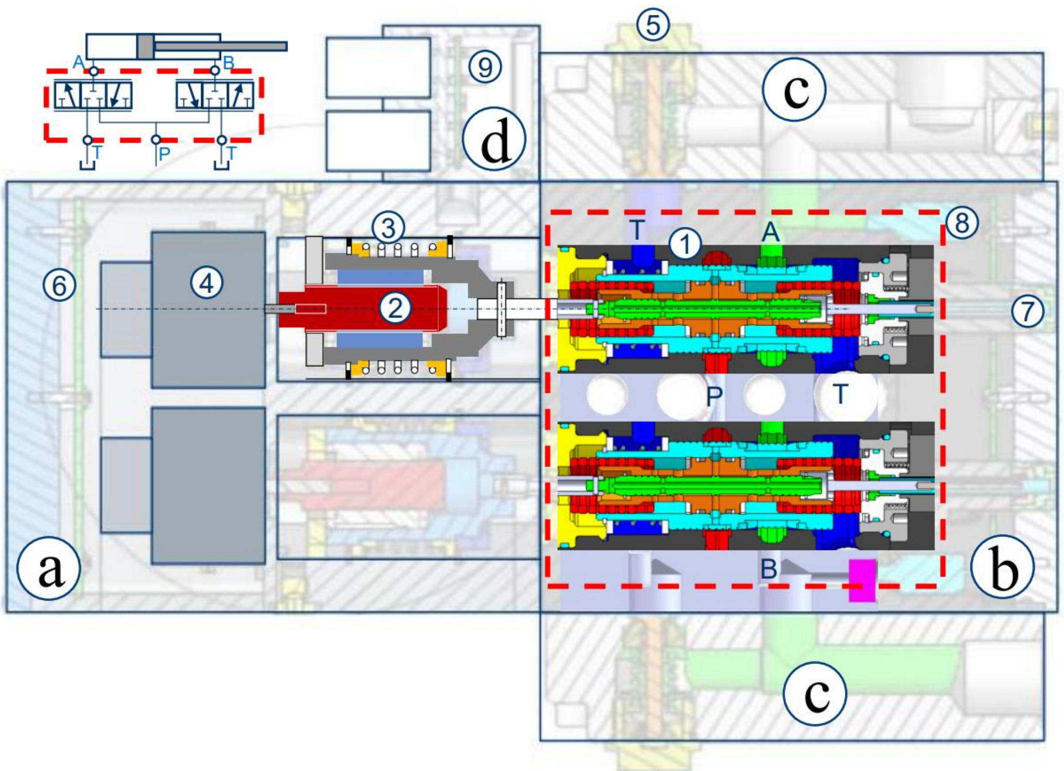

Figure 7: Overall view of the fluid power control unit with independent metering

The potential of the fluid power control unit presented in section 3 for the use in a hydraulic excavator drive have been investigated using system simulation. The fluid power control unit with separate control edges was compared in contrast to a classic hydro-mechanical throttle system with conventionally linked control edges. The fluid power control unit considered, consist of separate control edges, and electronically controlled regeneration modes. Both systems (the conventional system as well) are already equipped with demand-responsive load sensing pumps. The assessment of the system performance is carried out by means of the simulation of excavator implement drive systems. The modelling of the implement drive and the working cycle have been adapted to the practical work and usual requirements with the wheel excavator shown in **Figure 8**. The arrangement of the adjustable boom is fully extended and assumed to be rigid in the simulation. So, the simulation model contains two boom cylinders, an arm cylinder, a bucket cylinder, and a slew drive. All relevant inertia (and gravity) parameters have been determined and an additional bucket load of 800 kg has taken into account. A PI controller represents the operator of the excavator to drive a common working cycle shown in **Figure 9**.

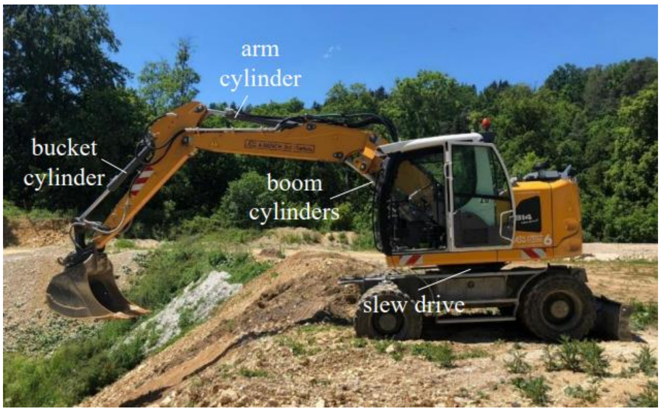

Figure 8: Excavator (Liebherr A 914 Compact Litronic) considered in the modelling

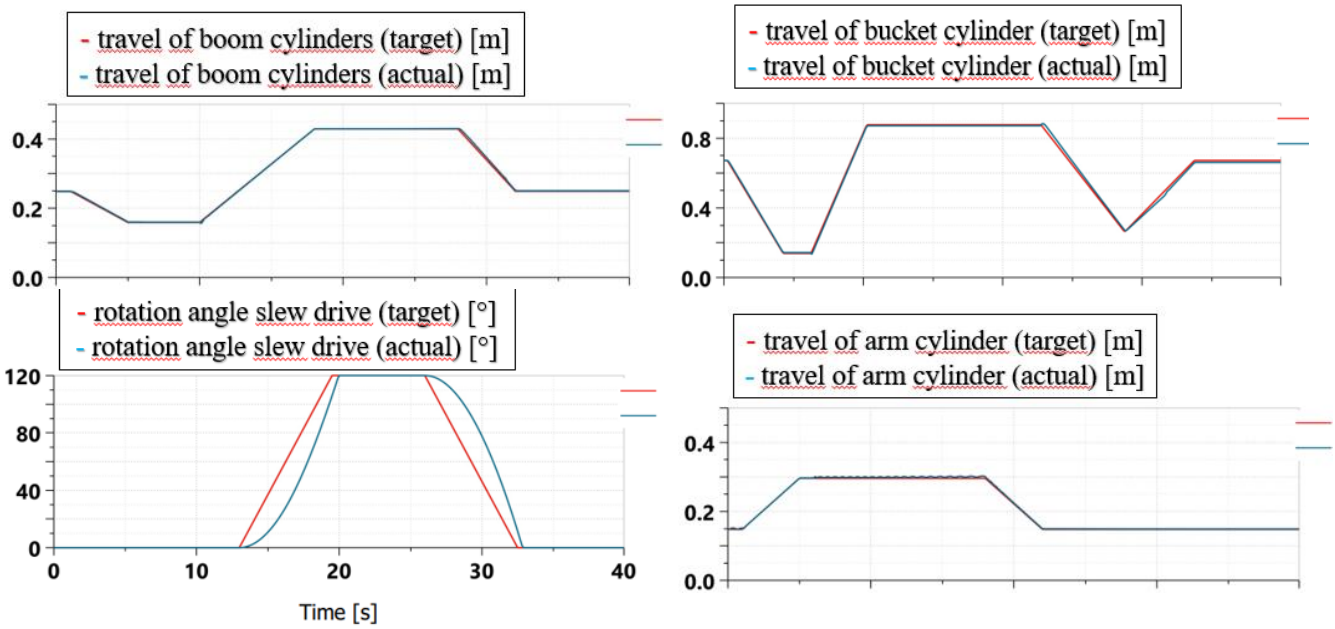

Figure 9: Working cycle of the implement drive used in the simulation

The following two system variants have been investigated by means of simulation:

1. Conventional excavator throttle system, and

2. Optimized excavator throttle system.

The conventional excavator throttle system shown in **Figure 10** consists of

- four 5/3 way proportional directional valves with linked control edges
- a customized load sensing pump with a combined pressure and flow compensator (the highest load pressure is transmitted via shuttle valves to the pump)
- a pressure relief valve to protect the hydraulic system from overload.

2. The optimized excavator throttle system shown in **Figure 11** consists of

- eight 3/3 way proportional directional valves with separate control edges
- eight flow sharing pressure compensators each with bypass and check valve
- three short-circuit valves for an energy-efficient lowering of the loads
- a customized load sensing pump with a combined pressure and flow compensator
- a pressure relief valve to protect the hydraulic system from overload
- pressure sensors for the measurement of the load pressures in the cylinder chambers as well as the pump pressure
- an Electronic Control Unit (ECU) here exemplary used for the control of the regeneration mode.

The energy consumption for the 40 s working cycle has been calculated in time steps of 0.1 s considering the simulation results of pump pressure and flow rate. The calculated energy consumption is for the conventional implement drive system 535 kWs and for the optimized implement drive system 429 kWs. **Figure 11** shows the comparison of the simulation results for both systems.

The decrease in energy consumption has dominant reasons in the general reduction of throttling losses, due to the independent control edges, and in high-pressure regeneration. Low-pressure regeneration using the short circuit valves has an additional effect.

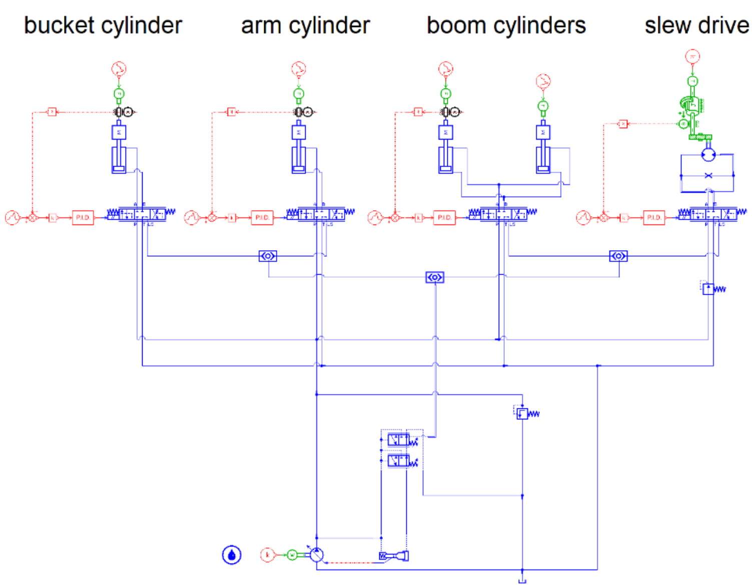

Figure 10: Conventional excavator throttle system with linked control edges (Simcenter Amesim)

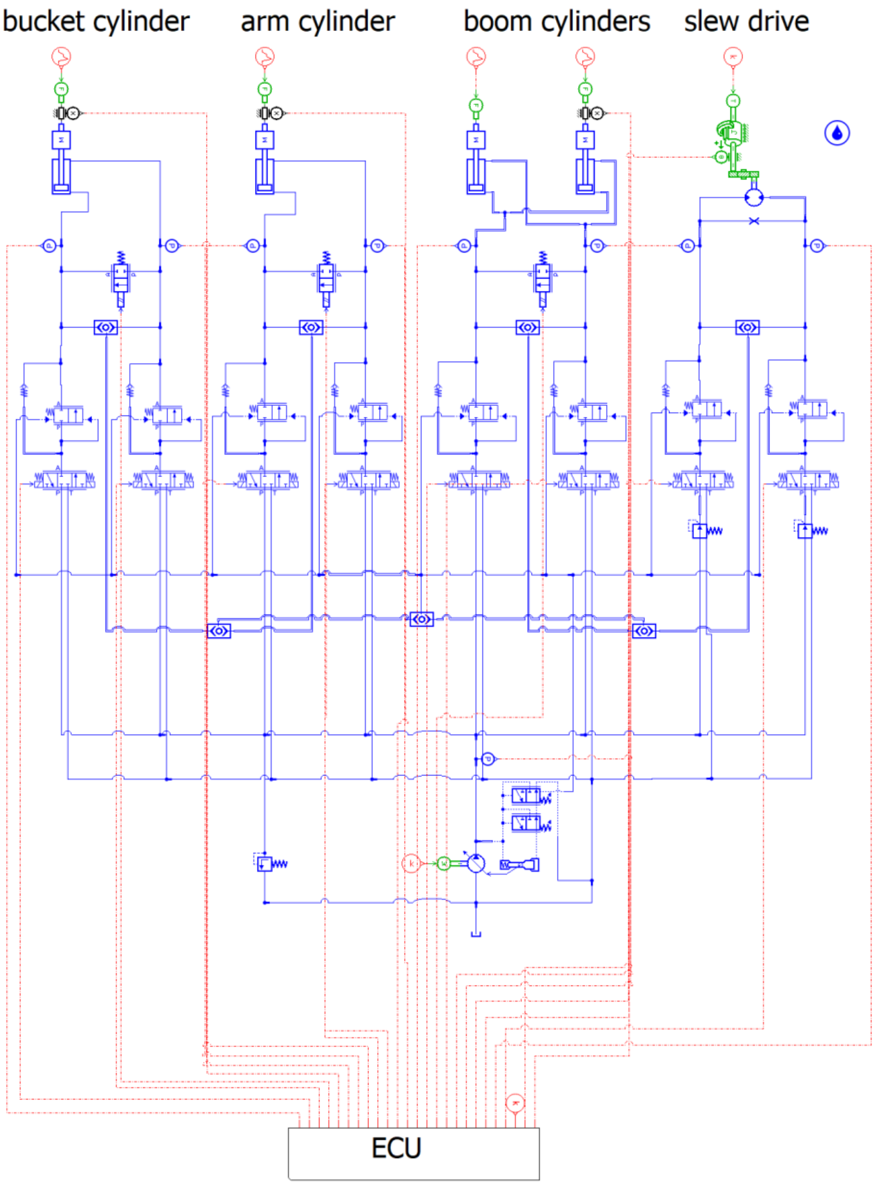

Figure 11: Optimized throttle system with independent metering combined with ECU controlled regeneration (Simcenter Amesim)

The optimized excavator implement drive system with separate control edges shows for the usual working cycle shown in **Figure 9** a good reduction of the energy consumption of 20% towards the conventional excavator hydro-mechanical implement drive system with linked control edges.

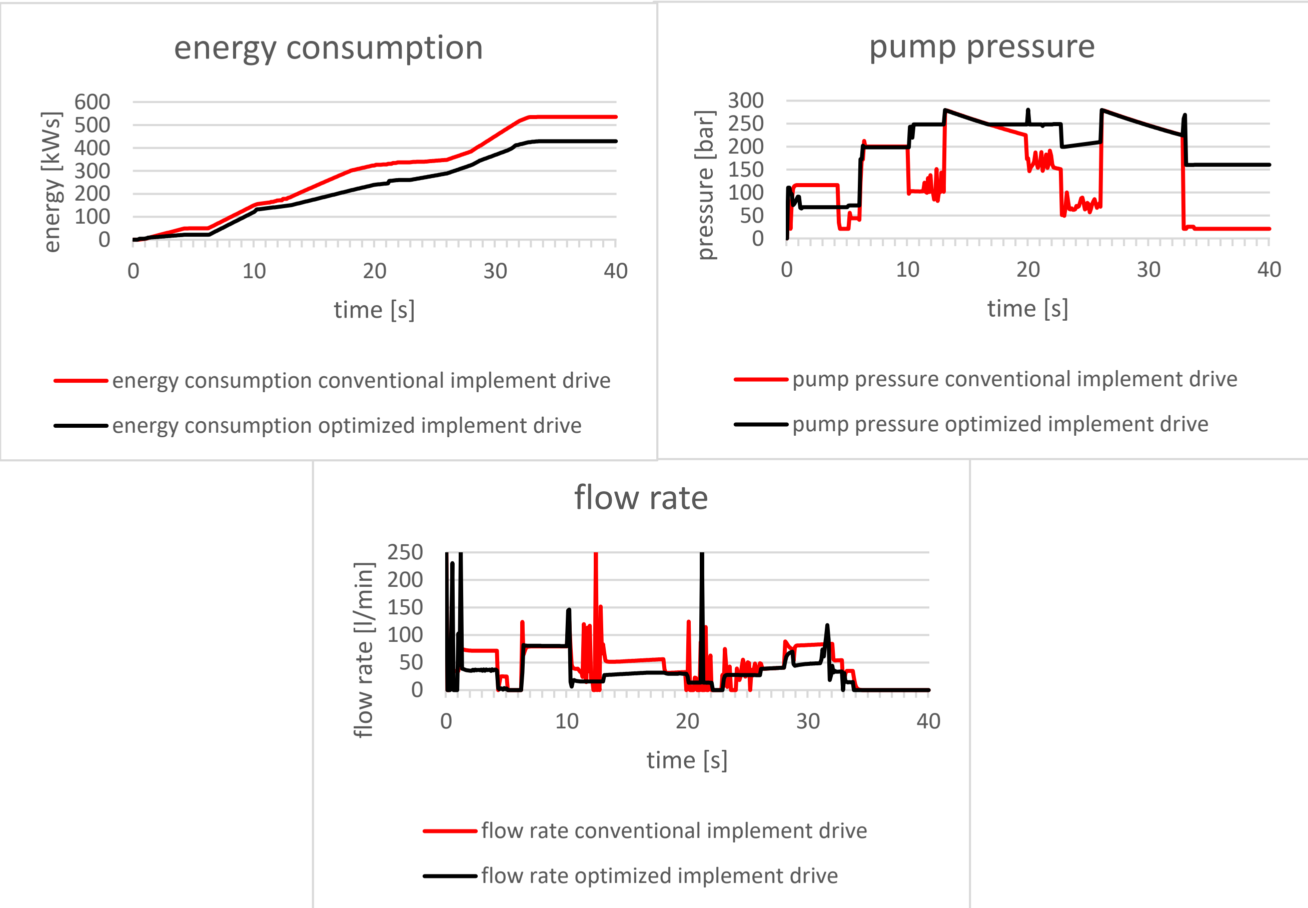

Figure 11: Simulation results of the conventional and the optimized implement drive

4. SUMMARY

The fluid control unit concept presented, has a compact pilot stage, with separate control edges, an actuator, consisting of a step motor with a ball bearing screw with minimal self-locking, pressure sensors and an ECU. The fluid power control unit is designed for high power requirements (maximum pressure >500 bar, flow rate 200 l/min), small installation space, well-defined position accuracy, stability and fail safe functionality (sections 2 and 3). By means of simulation the energy consumption of a conventional hydro-mechanic excavator implement drive system with connected control edges has been compared with an electrohydraulic excavator implement drive system with independent control edges. The comparison of the calculated results shows a good reduction of the energy consumption of 20% for the electrohydraulic solution with independent metering.

Nevertheless, higher system complexity induces higher downtime risks as well as higher investment costs. Rising fuel prices and further intensified emission standards will in future support efficient displacement control solutions. In case of resistance control solutions, separate control edges together with, sensors, electronic control and digitalization are attractive options.

On a higher system level, including implement and travel drive as well as combustion or electric engine, further digital optimization capability can be achieved, in terms of productivity, energy efficiency and emission reduction. Despite the higher investment cost and the remaining engineering challenges, further investigations are worthwhile to be considered.

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