Efficiency Optimization of a Hydrostatic System using an Intermediate Pressure Line

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Abstract

The paper introduces a new hydraulic system based on a constant pressure system with the aim to increase the efficiency of actuation of hydraulic cylinders in mobile machines. Using a third pressure level located between high pressure and tank pressure called intermediate pressure the system enables additional pressure potentials from high pressure to intermediate pressure and from intermediate pressure to tank pressure. This reduces throttle losses at hydraulic cylinders when driven at low or medium loads. An accumulator connected to the intermediate pressure line is being charged or discharged in function of which pressure potential is currently used. Using the example of a typical duty cycle of a wheel loader the paper describes how the accumulator can be applied in order to reach best efficiency results for the new system. A simulation shows that the demand of hydraulic energy of the new system is 13% lower than of a conventional Load Sensing system.

KEYWORDS: hybrid, intermediate pressure, control strategy, accumulator

1. Introduction

Load Sensing (LS) systems are considered today as one of the most efficient drive systems for linear actuators in mobile machines. The pump only generates the flow, which is really needed at a pressure which is adapted to the highest load pressure. This generally leads to low throttle losses and therefore to a low energy demand. A disadvantage of LS systems is their incapacity to recover potential or braking energy which makes them to unfavorable drive systems for hybrid drive concepts.

A hydraulic system that is well suited for hybrid applications is a constant pressure (CP) system with a pressure controlled pump and a hydraulic accumulator connected to the main pressure line. In these "Advanced Constant Pressure Systems" /1/ four quadrant secondary controlled hydraulic rotary drives can be operated as a motor or as a pump without system-related losses /2/. The accumulator allows recovery of braking energy for later use so the system can be considered as a hydraulic hybrid drive system. These systems already exist at the market /3/ even though not in mobile applications yet. A disadvantage of this system is its incompatibility with linear actuators as the high pressure still needed to be throttled to adapt it to the actual load pressure. In order to create an integral hybrid drive system including driving and working hydraulics there are concepts to change the design of hydraulic cylinders /4/ or to adapt the pressure with a secondary controlled pump-motor couple /5/.

Another approach for the efficient integration of linear actuators in a CP hybrid system with the use of simple state-of-the-art components is the creation of multiple discrete pressure levels allowing to reduce pressure losses at proportional valves when actuating the piston at partial loads. An introduction of a supplementary pressure line with a pressure level located between high pressure (HP) and tank pressure (TP) is called "intermediate pressure (IP) line" creating a constant cressure cystem with intermediate pressure line (CPIP) /6/ as illustrated in **Figure 1**. Two switching valves can change the pressure on the inlet and the outlet port of the proportional valve between high, intermediate- and tank pressure enabling four different pressure potentials. A hydraulic accumulator is connected to the IP line allowing recovery of potential energy. A second accumulator is connected to the HP line to buffer pressure oscillations. Due to energetic reasons the IP line can furthermore be connected to the suction side of the pump resulting in lower energy demand of the system when using the pump.

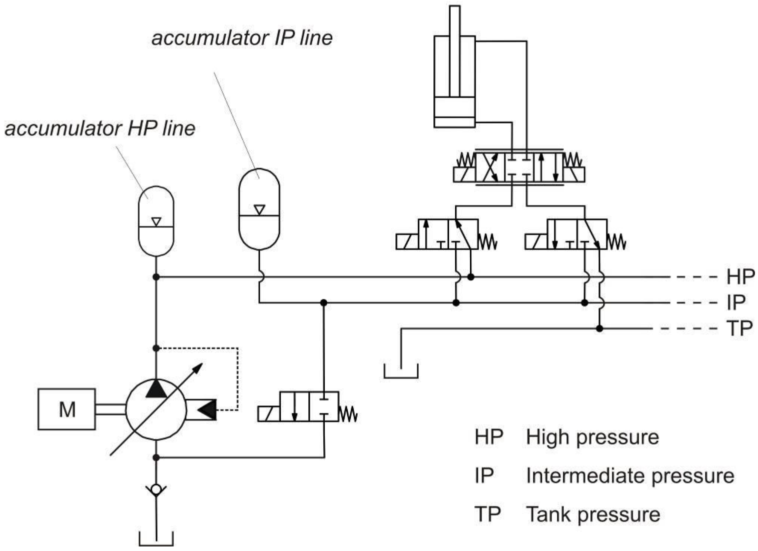

Figure 1: Constant pressure system with intermediate pressure line

The strength of the pressure potential applied at the proportional valve depends on which pressures are connected to inlet and outlet port so each pressure potential can be considered as a maximum reachable force of the respective switching state (**Figure 2**). This force can be calculated with the piston areas and the pressures of the connected pressure lines. Assuming a switching state connecting HP to the piston-side and IP to the rod-side of the cylinder the maximum force at this switching state when stroking out is determined as (pressure drop at the proportional valve is neglected):

$$F_{\max,\,HP/IP} = A_{piston} \cdot p_{HP} - A_{rod} \cdot p_{IP} \tag{1}$$

Besides the hydraulic components the CPIP system needs a control algorithm to be operated. This control algorithm is programmed into a programmable logic controller (PLC) and determines the actual load at the cylinders according to equation (1) by monitoring the pressures in the cylinder chambers. It chooses a switching state satisfying the condition

$$F_{\max,\,HP/IP} \geq F_{Load} \tag{2}$$

Once the switching state is set, the fine control of the piston is enabled by controlling the proportional valve according to the needed flow demanded by the operator. Furthermore, the algorithm contains the switching strategy which performs actuation of the switching valves not only in terms of having enough force to move the piston but also in terms of global efficiency of the system. The algorithm therefore allows switching states that may cause high throttle losses in a short term but it enables to charge or to discharge the accumulator in order to reach a more advantageous state of charge for future energy demands. Charging strategies are subject of intensive research in the field of hybrid drivetrains /7/ as they influence essentially the overall efficiency of the system and represent also in this system the most important part of the control architecture.

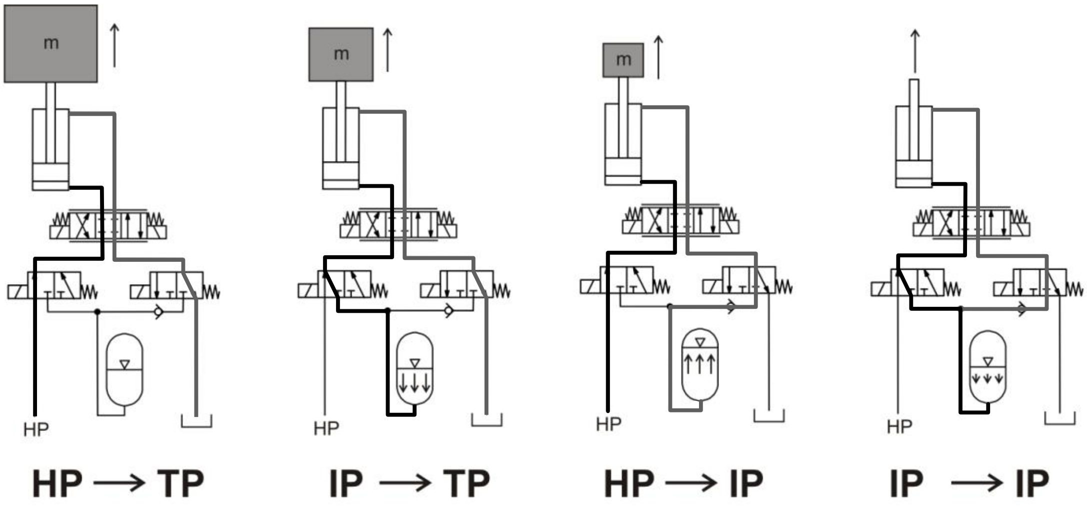

Figure 2: Possible switching states and corresponding forces

2. Optimization Potential of a Wheel Loader using Typical Duty Cycles

As reference system a wheel loader was used, which was originally equipped with a LS system. To the shaft of the diesel engine two (isolated) hydraulic circuits are mounted: a closed circuit for driving and an open circuit LS system supplying lifting cylinder, tilting cylinder and steering cylinder. Further supplementary working functions can be connected to this second circuit. To identify the energy saving potential of a CPIP system the loads on the cylinders and the piston strokes were determined during typical duty cycles of the wheel loader. This data allows developing a switching strategy for an efficient use of the new system.

A wheel loader is mostly used for two purposes: loading of pallets and digging/loading. In **Figure 3** the so called “Load and Carry” cycle is shown, which can be composed in different stages as described in /8/:

1. The wheel loader drives from the starting position (A) to the material (B). The bucket is lowered and aligned to the ground.

2. The machine drives into the material and loads the bucket. In the following the wheel loader transports the material to the transport vehicle at (C).

3. The machine drives to the transport vehicle and lifts the bucket when arriving.

4. As the bucket is above the bed of the transport vehicle the tilt cylinder is actuated and the bucket is dumped.

5. The loader backs off and the operator brings the bucket back into the starting position.

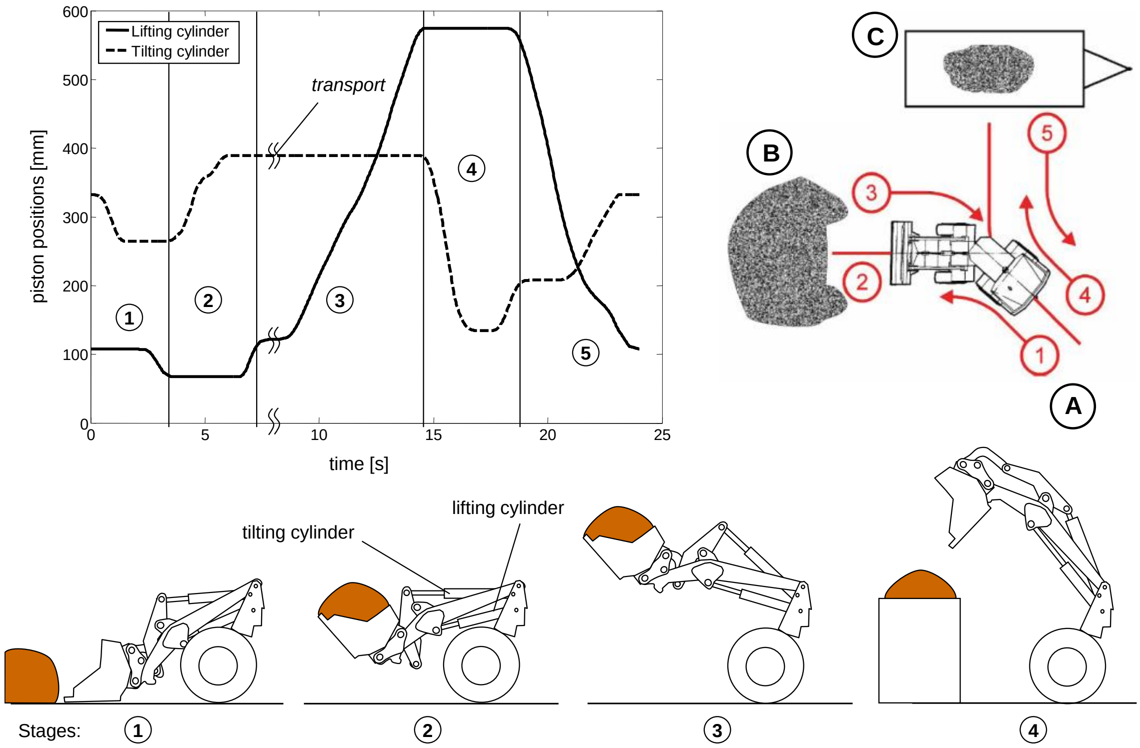

Figure 3: "Load and Carry" duty cycle according to /8/

The described movement was repeated during tests about 90 times at realistic digging conditions. For an energetic analysis one representative duty cycle was chosen and the load pressures were transformed into forces acting on the pistons of the cylinders. This allowed identifying the needed forces and calculating the needed energies in the different stages.

With the measured duty cycle an optimum switching sequence was determined using a multi-objective (Pareto-) optimization algorithm. Assuming equivalent values attributed to invested pump energy (first criteria) or used accumulator energy (second criteria) the Pareto-optimum switching state at each time step is the one that can not make better off one criteria without making worse off the other one. That consequently means that at a temporary higher pump energy "invest" may be more favorable in some situations in order to keep the accumulator charged for later use. This analytic determination of a strategic use of the accumulator is the first step to the development of a switching strategy of the system. The result of the Pareto-optimization with the relevant energy flows can be seen in **Figure 4** (in order to limit the calculation time the cycle was discretized in 0.5 s steps). Above the x-axis all input energies are shown, which can be pump energy, accumulator energy, potential energy or a combination of those. Below the x-axis all output energies are represented. These energies occur in form of accumulator energy (potential energy), throttle losses and used mechanical energy. It can be observed that pump energy is always input energy type as well as throttle losses are always output energy type. Accumulator energy and used energy (mechanical energy) appear both as input and as output energy and show the two major aspects of hybrid drives: at least two different energy sources (here: pump and accumulator) and the capability of recuperation of potential (or braking) energy.

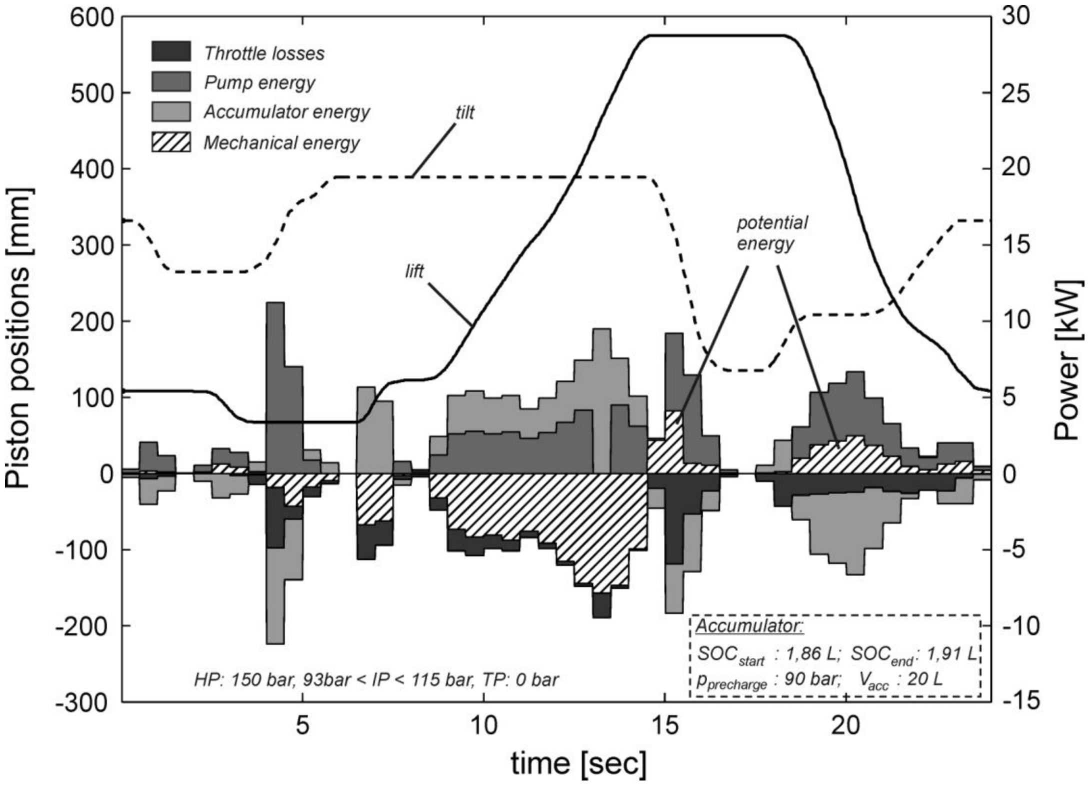

Figure 4: “Load & Carry” cycle with optimum switching sequence

The optimum switching sequence found with the Pareto optimization leads to a reduce of hydraulic energy of 20% compared to a conventional LS system (with a supposed constant control pressure of 20 bar). This high reduce of energy can only be reached because the duty cycle is known and because throttle losses due to friction in pipes and valves are not taken into consideration. For a switching strategy, which can be used online in real application an algorithm must be found that is able to determine an optimum switching sequence without “a priori” knowledge. The most promising results can be obtained using a Model Predictive Control (MPC) /9/. MPC implies a mathematic model of the system and extrapolates the present state of loads for a definite time step into the future, called prediction horizon. Using this model the controller can approximate the future response of the system to interactions of actuators at the present instant of time enabling a positive influence on the system behavior for the prediction horizon.

Due to the mechanics of the wheel loader the load on the lifting cylinder is a linear function of the piston's position. Once the arm is lifted and the present load and the piston's position are known the future evolution of loads is determined no matter which velocity will be chosen or whether the movement will be interrupted or not. Using this information the prediction horizon is not only an approximation of the present load but a precise determination of the actual evolution of loads. As lifting has the highest energy demand the global optimum can be well approached by optimizing it. For this reason a control algorithm was developed, which is capable to minimize the total throttle losses at one cylinder stroke by calculating the (optimum) length of the sections *s* for each switching state. This algorithm was generated using the Dynamic Programming method /10/. It avoids time expensive iterations making it suitable for an online optimization in a real application. **Figure 5** illustrates the described optimization problem as well as the influence of the duration of the sections *s* to the respective maximum forces (note: HP/IP (2) and HP/TP (2) are same as HP/IP and HP/TP but the switching valve at the suction side of the pump is active, see also Figure 1).

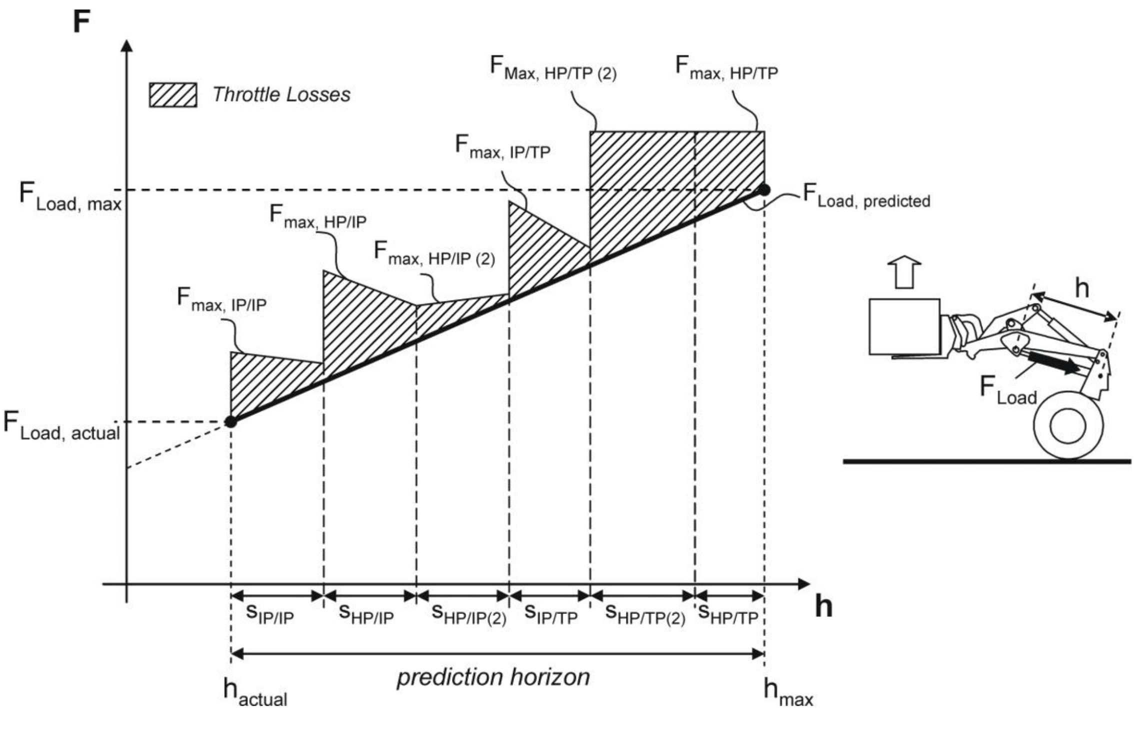

Figure 5: Prediction horizon for lifting

3. Test of Switching Strategy in Virtual Operation

In order to proof the efficiency improvement of the new system and to accelerate development time of the programming of the PLC a virtual operation of the CPIP system was effectuated first as described in /11/. For this reason simulation models of the machine were created whose submodels like machine kinematics, switching and proportional valves, pump behavior etc. were validated with test data. The existing LS system and the new CP system with intermediate pressure line were modeled for direct comparison of energy demand of both systems.

In order to make the virtual test environment as realistic as possible and to have an efficient tool to improve the program code of the PLC the simulation model of the new system was connected directly to the program code via an Object Linking and Embedding for Process Control (OPC) interface. The principle of the virtual operation can be seen in **Figure 6**. Major part of this simulation environment is a virtual PLC, so called SoftPLC representing the real PLC. Just like the real PLC the SoftPLC has an OPC-server, which enables a transfer of data like pressures or valve control signals. In the virtual operation the system response is generated by the simulation model while the control algorithm and its output signals are the same as in real application.

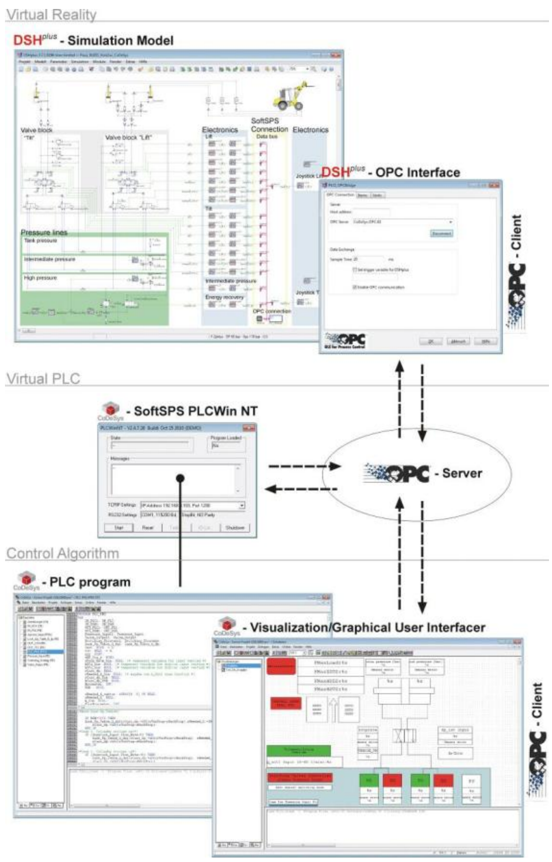

Figure 6: Principle of virtual operation of the system

For a test run, the bucket of the loader was charged with a load of 600 kg, which represents a middle charge and is therefore particularly interesting for a test of the system. A simulation run of a LS system and the new system was effectuated with the same piston loads and the same piston strokes for both systems. **Figure 7** shows the simulation run of four consecutive Load and Carry cycles. Due to losses in pipes and particularly in the valves the efficiency improvement in this simulation is lower than the one determined with a purely static analysis but still very high of about 13% lower demand of hydraulic energy.

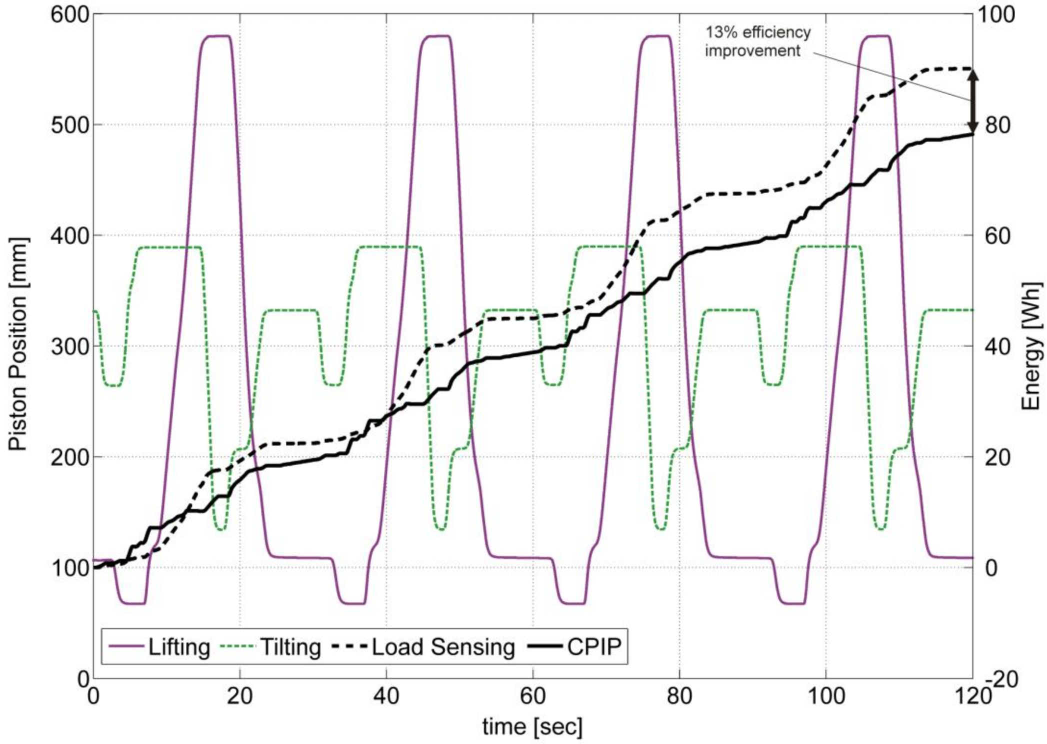

Figure 7: Simulation run with validated simulation model

4. Summary and Outlook

The paper presents the idea of an energy efficient actuation of hydraulic cylinders in a constant pressure system when an additional line with intermediate pressure is used. This allows an integrated hydraulic system with secondary controlled hydraulic rotary drives and standard hydraulic cylinders operated at different pressure potentials between high pressure, intermediate pressure and tank pressure. An optimal sequence for a chosen specific duty cycle is determined by the use of a multi objective optimization. In order to reach best results in real application the switching strategy is developed using the Dynamic Programming method and programmed in a PLC. The control algorithm of the PLC is directly tested in a virtual environment using an OPC interface with a validated simulation model. The results of the simulation run show still a high reduce of hydraulic energy of about 13%.

The tested and improved control algorithm will be used on a wheel loader in a real application. **Figure 8** shows the test machine with the mounted valve blocks and the accumulators for HP line and IP line. Each valve block consists of two switching valves and one proportional valve. The fuel consumption of the new system will be compared to the one of the LS system to prove the overall efficiency improvement.

Figure 8: Test machine with mounted valve blocks and accumulators

5. Acknowledgements

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6. References

/1/ Dreher, T. 2010. *The Capability of Hydraulic Constant Pressure Systems with a Focus on Mobile Machines,* 6th FPNI – PhD Symposium, West Lafayette 2010.

/2/ Haas, H.-J. 1989. Sekundärgeregelte hydrostatische Antriebe im Drehzahl- und Drehwinkelregelkreis, PhD thesis, RWTH Aachen, Germany.

/3/ Fischer, H. Steigerwald, T. & Godzig, M. 2010. Hydraulic Systems for Deep-Sea Applications, 7th International Fluid Power Conference, Aachen, Germany.

/4/ Linjama et. al. 2009. Secondary Controlled Multi Chamber Cylinder, 11th Scandinavian International Conference on Fluid Power, Linköping, Sweden.

/5/ Bishop, E. D. 2009. Digital Hydraulic Transformer – Approaching theoretical Perfection in Hydraulic Drive Efficiency, 11th Scandinavian International Conference on Fluid Power, Linköping, Sweden.

/6/ Dengler P. et. al.: Efficiency Improvement of a Constant Pressure System Using an Intermediate Pressure Line, 8th International Fluid Power Conference, Dresden, Germany.

/7/ Böckl, M. 2008. Adaptives und prädiktives Energiemanagement zur Verbesserung der Effizienz von Hybridfahrzeugen, PhD Thesis, University of Vienna, Austria.

/8/ Kohmäscher, T, Jähne, H., Deiters, H. 2006. Moderne voll- und teilhydrostatische Fahrantriebe – Untersuchung und Weiterentwicklung von Antriebsstrangkonzepten mobiler Arbeitsmaschinen, O+P 5, Germany.

/9/ Back, M. 2005. Prädiktive Antriebsregelung zum energieoptimalen Betrieb von Hybridfahrzeugen, PhD Thesis, University of Stuttgart, Germany.

/10/ Sniedovich, M. 2011. Dynamic Programming: Foundations and Principles, CRC Press.

/11/ von Dombrowski R., Dengler P. 2011. KonZwi – Effizienzsteigerung durch eine Zwischendruckleitung, SIMPEP – Kongress für Simulation im Produktentstehungsprozess, Veitshöchheim, Germany.

7. List of Notations

F	force	N
p	pressure	bar
A	piston area	mm^2
SOC	state of charge	L