EFFICIENT AND LOAD SENSITIVE HYDRAULIC SUPPLY UNIT USING MULTIPLE SWITCHING CONVERTERS

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ABSTRACT

In hydraulic drive systems with multiple actuators connected to one common pressure supply often a load sensing strategy is used to reduce the throttling losses. In particular, in mobile applications such load sensitive supply units are installed to lower the overall energy consumption, which results in a more economical and ecological operation of the machine. However, so far common load sensing systems are not able to recuperate the energy, which is actually released when a dead load is lowered. In this paper a load sensitive pressure supply unit is presented, which is able to harvest energy from the load and also efficiently return the stored energy to a load sensitive common pressure rail. The operating principle is based on a parallel arrangement of multiple hydraulic switching converters representing a digital hydraulic transformer, which allows to store recuperable energy in a gas-loaded accumulator. The resulting hydraulic buffer module can even be added to an existing pressure supply, at least in certain cases. Furthermore, the presented storage module is able to boost the hydraulic power at the output beyond the maximum power of the primary motor. The concept is investigated by simulations, the major benefits and limitations are discussed and an outlook on further steps in development is provided at the end of the contribution.

KEYWORDS: energy, efficient, hydraulics, recuperation, digital, switching, load sensing

1. INTRODUCTION

It is well known that lowering heavy loads, like for instance the boom of an excavator, has a high potential of recuperable energy, which unfortunately cannot be used with conventional hydraulic power supply units. In fact, so-called regenerative methods reduce additional losses in the load

(a) Excavator arm with common rail architecture *(b)* HERCULES actuator

Figure 1: Load sensitive digital hydraulic application presented in [10]

sensing system, but in today's valve controlled machines the potential energy of the dead load is mostly converted into heat during the lowering process by counterbalance valves. Since energy efficiency is going to be more and more important the demand after recuperative supply systems increases (see, for instance, [1, 2]). Of course, with conventional proportional valves this cannot be achieved, but new control concepts with independent metering, like presented in [3, 4, 5] or [6], enable the opportunity of reusing the energy when heavy loads are lowered. However, so far only regenerative flow sharing between certain pressure chambers is possible, which requires a sound control strategy. In a different approach so-called Common Pressure Rail (CPR) architectures according to [7] with a constant pressure supply equipped with accumulators are able to recover energy from different actuators, each controlled with a hydraulic transformer like presented in [8]. So far, on the excavator presented in [9] the mentioned transformers for metering the power are located in the body of the machine and not directly at the actuator. Consequently, each cylinder on the arm of the excavator must be connected via a separate pipe lines with the transformer, which relativizes the basic idea of a common rail architecture, at least with regard to installation costs. In the recent publication [10] an excavator arm equipped with efficient digital hydraulic actuators was investigated by simulations. As depicted in Fig. 1a the smart HERCULES actuators from Fig. 1b are supplied by a real common rail system, which offers the possibility to share displaced oil volume between different consumers and, furthermore, to recuperate energy. It turned out that for this kind of application a load sensitive pressure supply for controlling the required pressure in the common rail system is beneficial for a reduction of the overall energy consumption. However, a specific realization of such a pressure supply with the ability to store energy from the load was not discussed in the contribution. Therefore, based on the results of the previous investigations in the following considerations a concept for a load sensitive pressure supply with energy recuperation in combination with a Load Sensitive Common Pressure Rail (LS-CPR) is presented and discussed.

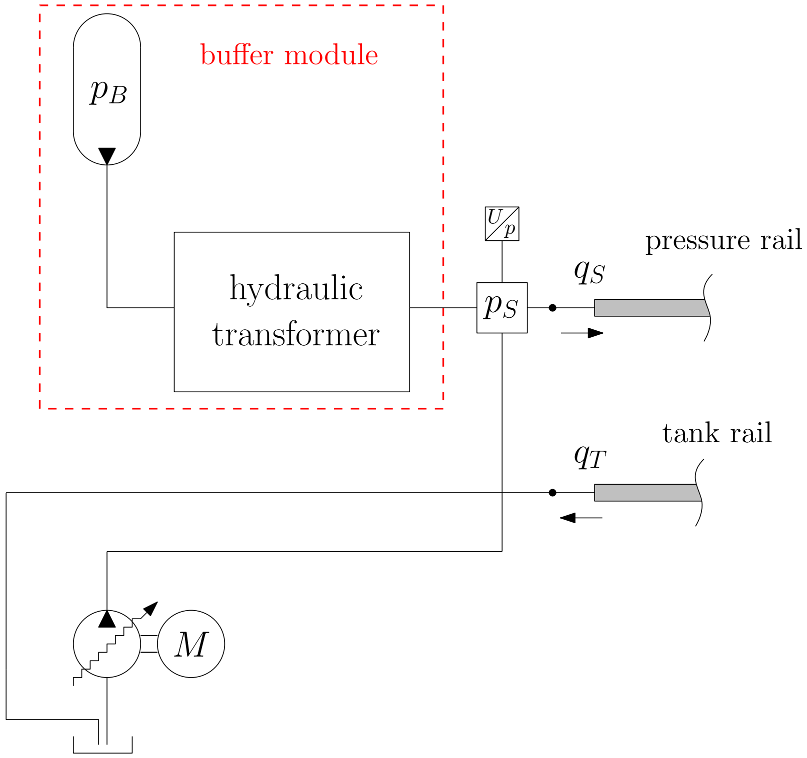


Figure 2: Load sensitive pressure source using a digital displacement pump (DDP)

1.1. Load Sensitive Pump Unit

In the following the conventional standard load sensing (LS) concepts of open, respectively, closed center are completely dropped. It is assumed that the smart actuators request a minimum supply pressure according to their actual state of operation. Thus, the used pump is required to control its output pressure p_S. A convenient and efficient way to realize this goal is the application of a digital displacement pump (DDP, see for instance [11, 12, 13]). For simplicity and, furthermore, for cost reasons it is assumed that the DDP is driven by a motor with constant speed and the pressure at the output p_S is controlled by the quantized flow ratio with regard to the maximum displacement volume according to the number of piston of the DDP. This works perfectly in the delivering flow direction regarding controllability and efficiency. But since the motor and the used pump are not designed to change their direction of rotation, it is not possible to recuperate energy. Thus, a kind of a buffer module is necessary to store the recuperable energy, like illustrated in Fig. 2. Of course, a sufficiently large gas-loaded accumulator must be used in the buffer module in order to store recuperable energy from the pressure rail. But, due to the actual working conditions of all actuators in the LS-CPR system the supply pressure p_S is varying faster than the buffer pressure p_B in the accumulator. Thus, a hydraulic transformer must be used. Furthermore, the desired supply pressure p_S can be either lower or higher as the pressure in the buffer accumulator. Thus, the hydraulic transformer must be able to operate in all four power quadrants.

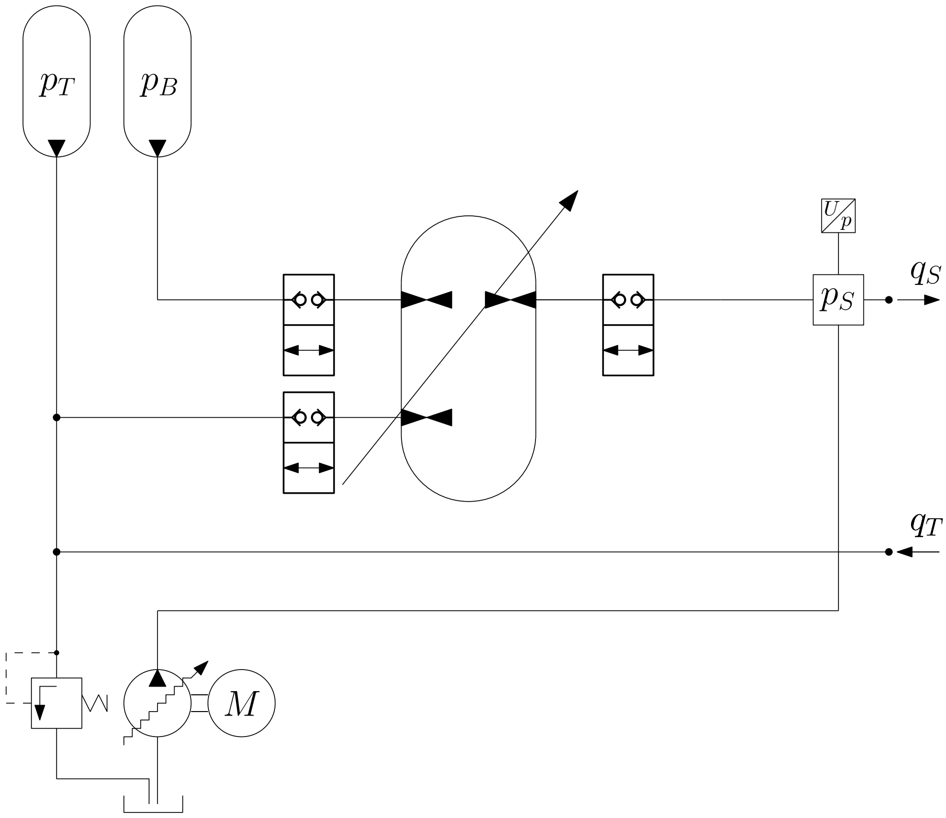


Figure 3: Load sensitive supply unit with buffer module using an INNAS Hydraulic Transformer

1.2. Hydraulic Transformers

As explained in the previous section a hydraulic transformer must be installed between the buffer accumulator and the entry of the LS-CPR. One possibility is given by the well known INNAS Hydraulic Transformer (IHT) according to [14] like illustrated in Fig. 3. Unlike other pump/motor transformers, the IHT is a single rotating machine with a constant displacement and a variable valve plate with three ports; a low pressure port, a high pressure port and a port for the consumer pressure. Depending on the pressure levels at each port of the transformer and on the position of its valve plate hydraulic energy can be either stored in the buffer accumulator or efficiently released to the LS-CPR. Moreover, if necessary the transformer is able to boost the pressure in the LS-CPR up to the double pressure of the buffer accumulator. The IHT seems to be a qualified device for transforming the power in the buffer module, however, there are some drawbacks, which must be reflected critically for some applications. The IHT operates according to an imposed pressure, which means that even a zero flow through the transformer must be actively controlled with the valve plate. Since the position of the valve plate is controlled by a separate electric servo motor a limited response dynamics must be expected, at least to some extent. But, in contrast to the *soft* CPR, which provides an almost constant supply pressure, the LS-CPR represents a considerable *stiff* supply line, which may require a fast variation of the supply pressure in certain operating cases. Moreover, in case of a standstill, i.e. no delivery is intended, additional seat type valves are necessary for load holding.

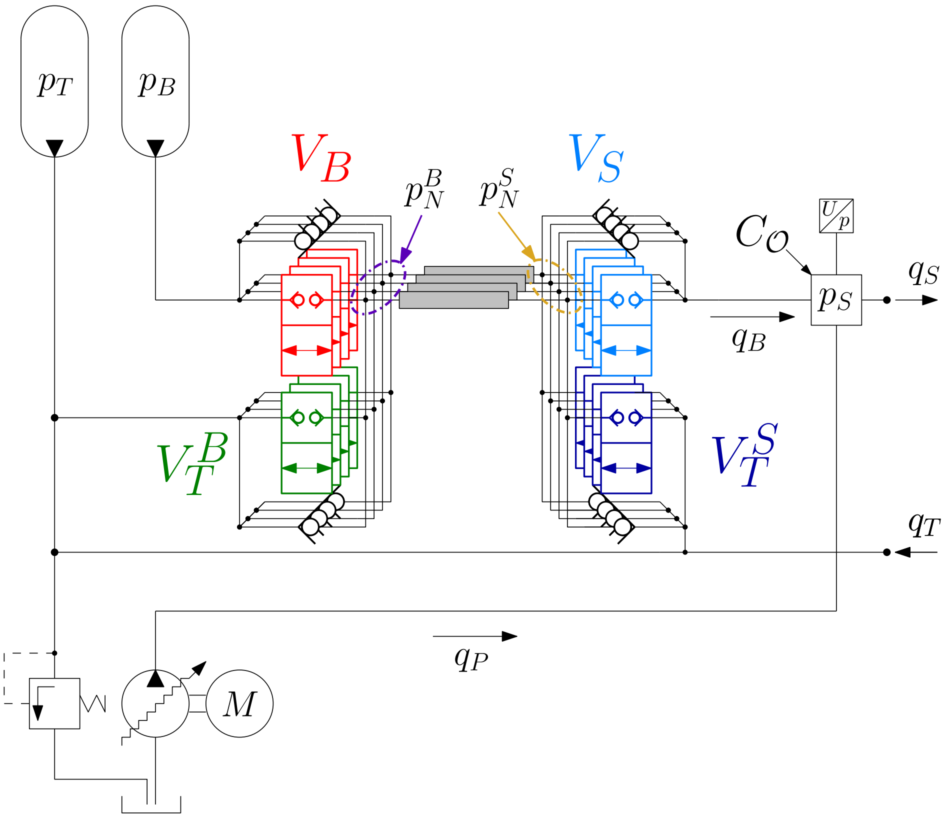
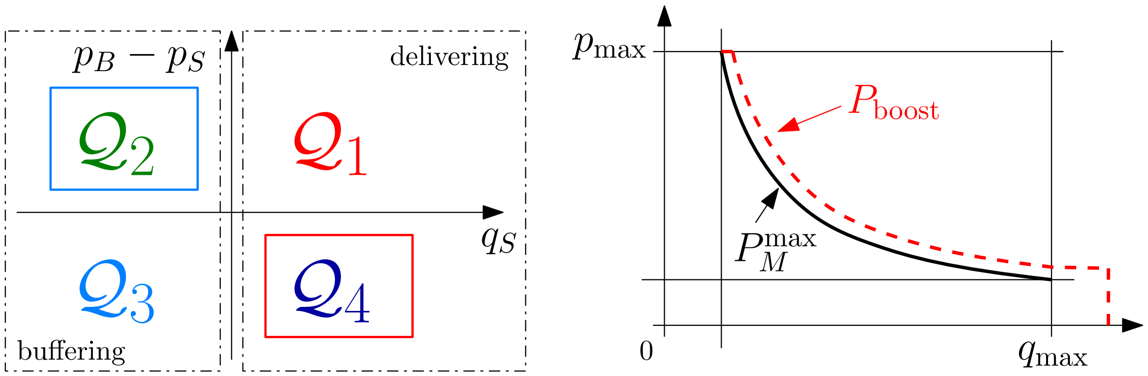


Figure 4: Load sensitive supply unit with buffer module using a Digital Hydraulic Transformer

As an alternative a Digital Hydraulic Transformer (DHT) based on hydraulic switching converters according to Fig. 4 can be used, which is in the focus of this contribution. The DHT represents a parallel arrangement of multiple buck-boost transformer stages, each consisting of 4 switching valves, 4 check valves and one inductance pipe. In case of a stand still, i.e. no flow is desired at the consumers, all valves are shut and therefore no actuation is necessary, which is fulfills the basic requirements for load holding. Depending on the desired transforming direction corresponding valves are switched at a constant frequency in pulse-width mode. In order to keep the pressure ripples due to the switching process in the output cavity C_O sufficiently low, the multiple parallel transformer stages are operated in a phase shifted mode according to [15]. Basically, the higher the number of parallel converter stages, the smaller the output cavity C_O can be. In the presented exemplary case 4 transformer stages are considered, however, the number is basically not restricted and depends on the requirements of the specific application, respectively, on the available components.

The digital transformer is designed for an operation in all four power quadrants regarding Fig. 5a. If the supply pressure p_S is lower than the buffer pressure p_B and flow is delivered to the consumers $(q_S > 0)$, then the pressure is stepped down by actuating the valves V_B, which is defined as power quadrant $\mathcal{Q}_1$. In the reverse flow direction at same pressure conditions and, thus, in power quadrant $\mathcal{Q}_2$ the pressure is boosted to the buffer pressure by switching the valves V_T^B at constantly open valves V_S. When energy is recuperated, the DDP operates in idle mode and, thus, $q_P = 0$. In case of $p_S > p_B$ energy can be recuperated in power quadrant $\mathcal{Q}_3$ by



(a) Power quadrants *(b)* Power range

Figure 5: Operating areas of the DHT

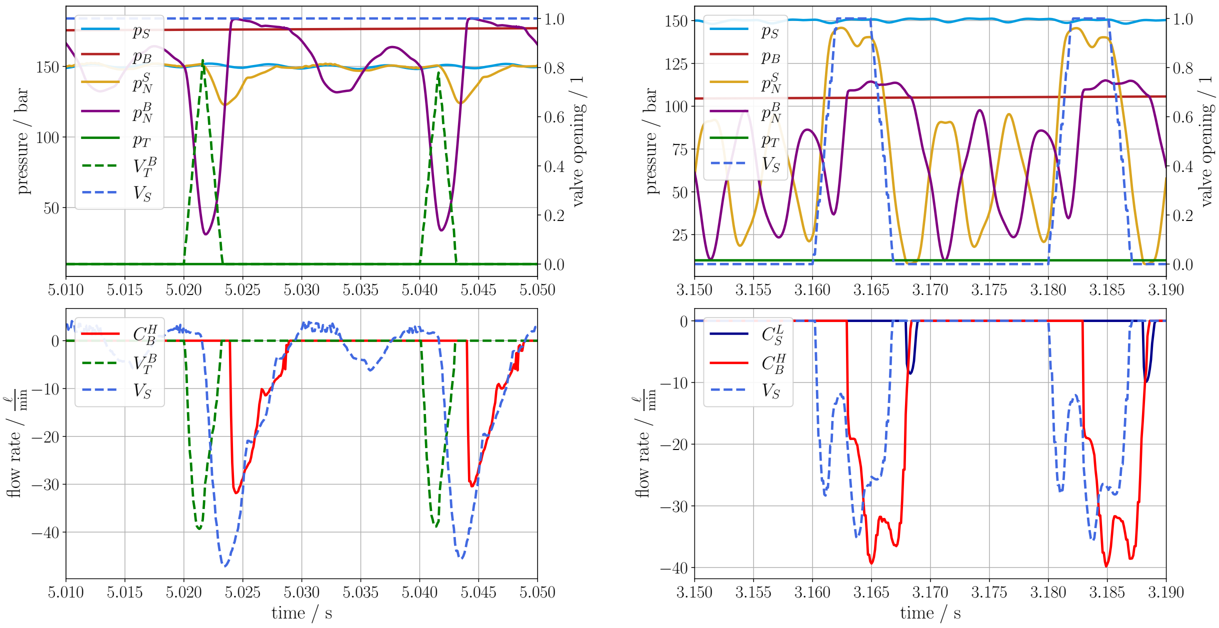
Table 1: Parameters of the DHT buffer module

switching valves	$Q_N = 20\,\ell/\text{min}$@5bar
response time switching valves	$t_S = 2\,\text{ms}$
check valves	$Q_N = 40\,\ell/\text{min}$@5bar
number of parallel switching converters	$n_{SC} = 4$
switching frequency	$f_S = 50\,\text{Hz}$
length of inductance pipe	$l_p = 1.5\,\text{m}$
diameter of inductance pipe	$d_p = 8\,\text{mm}$
cavity at the output port	$C_O = 2\,\ell$
buffer accumulator	$V_A = 5\,\ell$
pre-load pressure	$p_0^G = 40\,\text{bar}$
tank pressure	$p_T = 10\,\text{bar}$

stepping down the pressure to buffer pressure by switching the valves V_S. Finally, in power quadrant $\mathcal{Q}_4$ the pressure is boosted by switching the valves V_T^S at constantly open valves V_B. Since the buffer module is arranged in parallel with the DDP the hydraulic output power can be boosted beyond the maximum motor power in the delivering operating area, at least to some extent, as illustrated in Fig. 5b. Basically, boosting is an expensive operation because the flow through the inductance pipe must be accelerated by being connected to tank for a corresponding amount of time and, thus, additional energy from the buffer must be spent. Furthermore, the boost performance also strongly depends on the size of the installed buffer accumulator.

2. SIMULATION

The intention of this contribution is to present the concept of the buffer module with a DHT and its basic functionality. For this purpose an exemplary parameter set according to Tab. 1 is used, which is not related to a real application. The dynamic model of the DHT is based on ordinary differential equations solved in *Python* using the *scipy* package. In the inductance pipes linear wave propagation is considered according to [16]. In the presented simulation experiments four



(a) Power quadrant $\mathcal{Q}_2$ for $p_S < p_B$

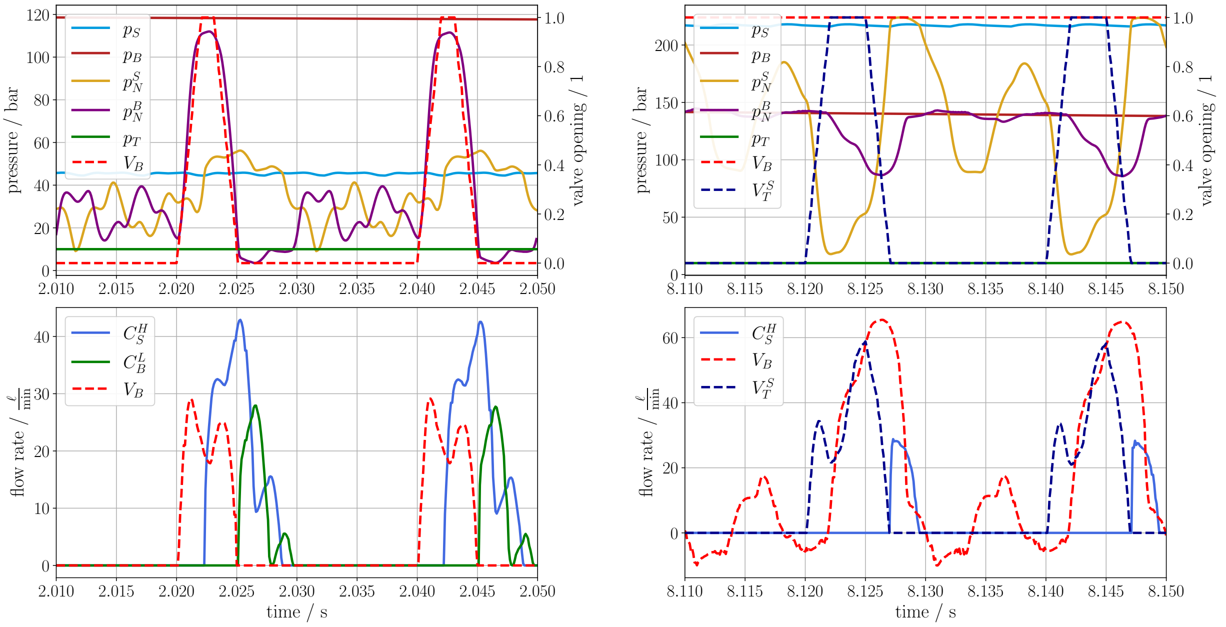
(b) Power quadrant $\mathcal{Q}_3$ for $p_S > p_B$

Figure 6: Energy recuperation ($q_B < 0$)

parallel transformer stages were used, each switching at a frequency of $50\,\mathrm{Hz}$ in a phase shifted pulse-width mode. For the used valve sizes and the inductance pipes an empirically determined output cavity $C_{\mathcal{O}}$ with a volume of $2\,\ell$ results in sufficiently low pressure ripples at the node point C_O. While, the response time of the switching valves was considered with $t_S = 2\,\mathrm{ms}$, the dynamics of the check valves was completely neglected, which can be nearly justified for plate check valves.

2.1. Modes of Operation

The first results show the basic operating areas of the DHT. In fact, the simulations were carried out with 4 parallel digital transformers, however, for clarity in the following the signals denoted with p_N^B and p_N^S according to Fig. 4 represent the node pressures of only one selected transformer stage. In Fig. 6 both power quadrants for energy recuperation ($q_B < 0$) are illustrated. In the upper diagram of Fig. 6a the buffer pressure p_B is higher than the supply pressure p_S, thus, the pressure is boosted as a result of the spill-over of kinetic energy in the inductance pipe. For this purpose the flow through the inductance pipe must be accelerated by pulsing the valve V_T^B while the supply sided valve V_S is constantly open. When the valve V_T^B is shut quickly, then the spill-over of the kinetic energy in the inductance pipe causes the pressure p_N^B to overshoot the buffer pressure p_B resulting in a flow through the buffer sided high pressure check valve C_B^H, which is illustrated in the lower diagram. In the second recuperative case depicted in Fig. 6b, the buffer pressure p_B is lower than the supply pressure p_S and, thus, the pressure is stepped down for energy recuperation by pulsing the valve V_S for an acceleration of the flow through the inductance pipe. In this specific case the actual ratio between p_B and p_S results



(a) Power quadrant $\mathcal{Q}_1$ for $p_S < p_B$

(b) Power quadrant $\mathcal{Q}_4$ for $p_S > p_B$

Figure 7: Releasing energy from the buffer ($q_B > 0$)

in a reduced spill-over effect and, thus, only a smaller amount of fluid is drawn from tank through the supply sided low pressure check valve C_S^L. Therefrom, this example emphasizes that also recuperation of energy is associated with efficiency, which depends always on the actual operating conditions.

In Fig. 7 the power quadrants for releasing the stored energy from the buffer accumulator to the LS-CPR are illustrated. Figure 7a shows an efficient pressure step down operation. In the upper diagram the pressure signals and the valve opening of the actively switched valve V_B for acceleration of the flow in the inductance pipe are illustrated. By shutting the valve V_B quickly the spill-over of kinetic energy forces the pressure p_N^B to fall below the tank pressure and results in a flow rate C_B^L from tank as depicted in the lower diagram. The flow rate C_S^H through the high pressure check valve on the supply side results from the elevated node pressure p_N^S above the supply pressure p_S. Thus, in this case the buffer pressure is stepped down and the flow is boosted. The final operating case shown in Fig. 7b represents a pressure boost to the LS-CPR, which may result in a power boost, if the primary motor operates at its maximum power. In this case the valve V_B is constantly open and the valve V_T^S has to be switched in pulse-width mode.

2.2. Simulation of a Working Cycle

In the following a short exemplary working cycle for the demonstration of all 4 power quadrants is investigated by simulation. For this purpose, a parameter set for the primary hydraulic supply comprising the motor and the digital displacement pump according to Tab. 2 is considered. Since only the energetic performance of the buffer module is in the focus of the investigations the pump and the motor are considered as ideal with regard to efficiency.

Table 2: Parameters of the primary hydraulic supply

Motor		DDP	
maximum power	$P_M^{\max} = 20\,\mathrm{kW}$	number of pistons	12
rotational speed	$n_P = 2000\,\mathrm{rpm}$	total displacement volume	$V_D = 96\,\mathrm{ccm}^3$

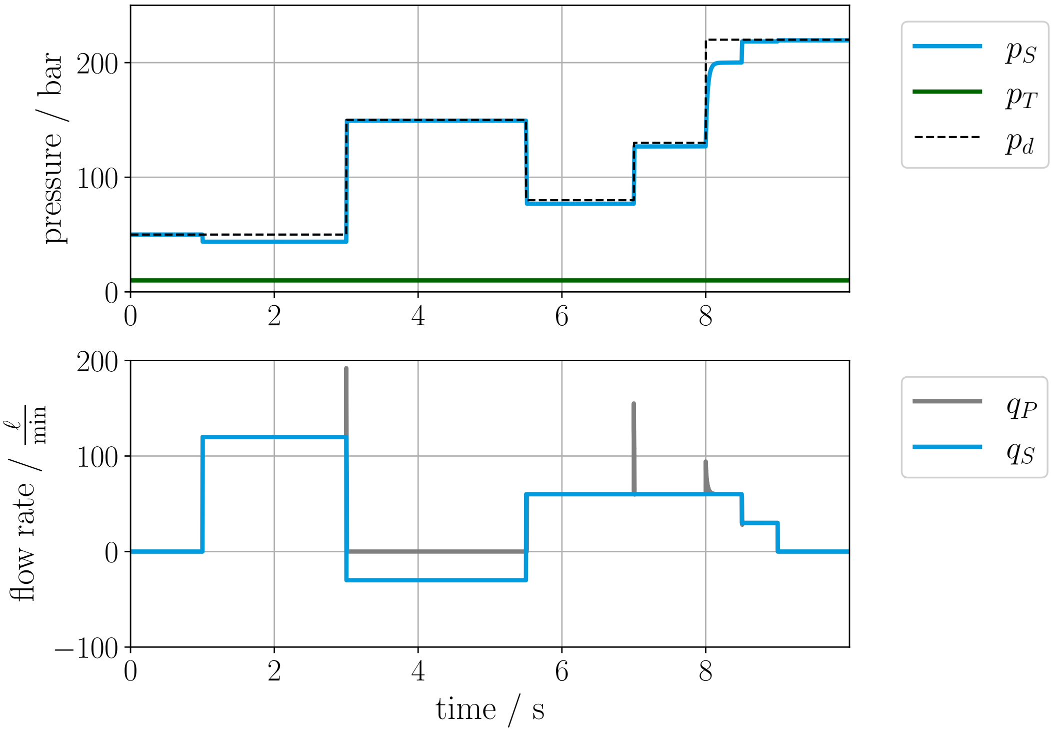


Figure 8: Working Cycle with the motor-DDP configuration

At first, the simulation results for the working cycle only with the motor-DDP combination and without the buffer module is shown in Fig. 8. The upper diagram shows the response of the DDP for a step wise profile of the supply pressure p_S according to the load flow rate q_S depicted in the lower diagram. When the load flow rate $q_S < 0$ then the pump flow rate q_P is truncated to zero and, thus, the DDP is forced to idle-mode, since no energy can be recuperated with the used motor/DDP combination. The peaks in the pump flow rate indicate the additional flow, which is necessary for raising the pressure in the output cavity, i.e. for compression of the fluid. Basically, the remaining control error in the pressure results from using a simple P-controller for tracking. But, at the simulation time $t = 8\,\mathrm{s}$ the power required by the load exceeds the maximum power of the motor and, thus, the desired pressure cannot be realized before the load flow rate is lowered at time $t = 8.5\,\mathrm{s}$.

The simulation results for the same working cycle with the DDP plus the buffer module using a DHT is presented in Fig. 9. Similar as above, in the upper diagram the pressure responses are illustrated. The DHT is controlled with a simple and empirically parameterized PI-controller. At the beginning of the working cycle the initial pressure of the buffer accumulator is $p_B = 150\,\mathrm{bar}$ and the desired supply pressure is $50\,\mathrm{bar}$. When the first step in the load flow rate q_S occurs,

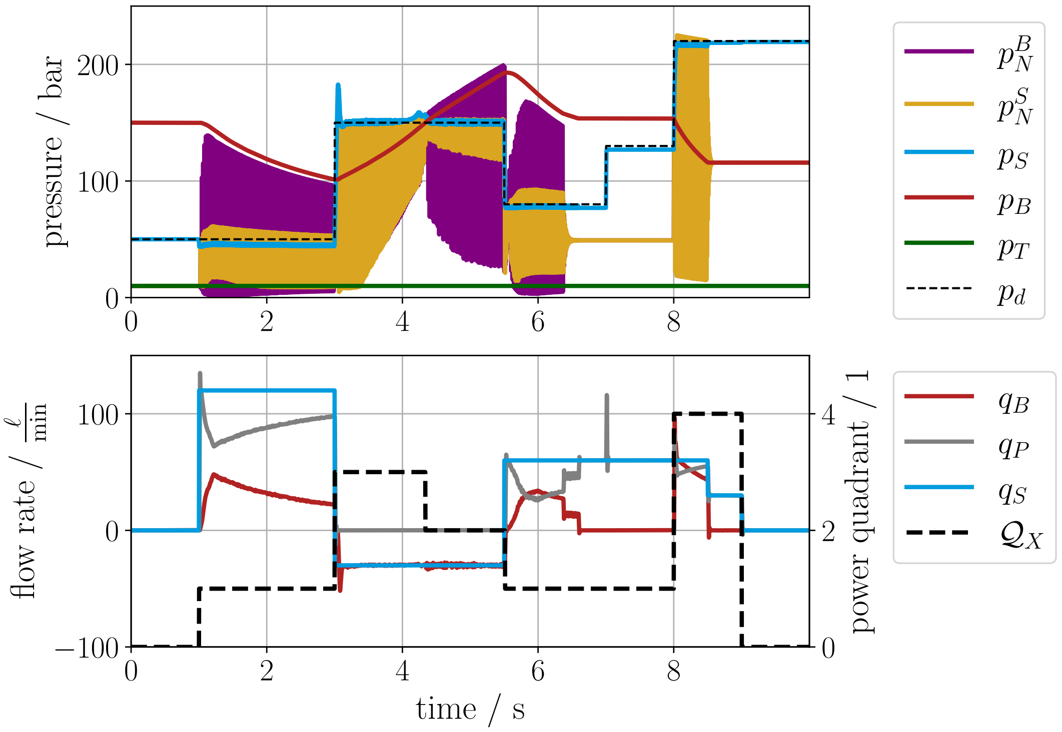
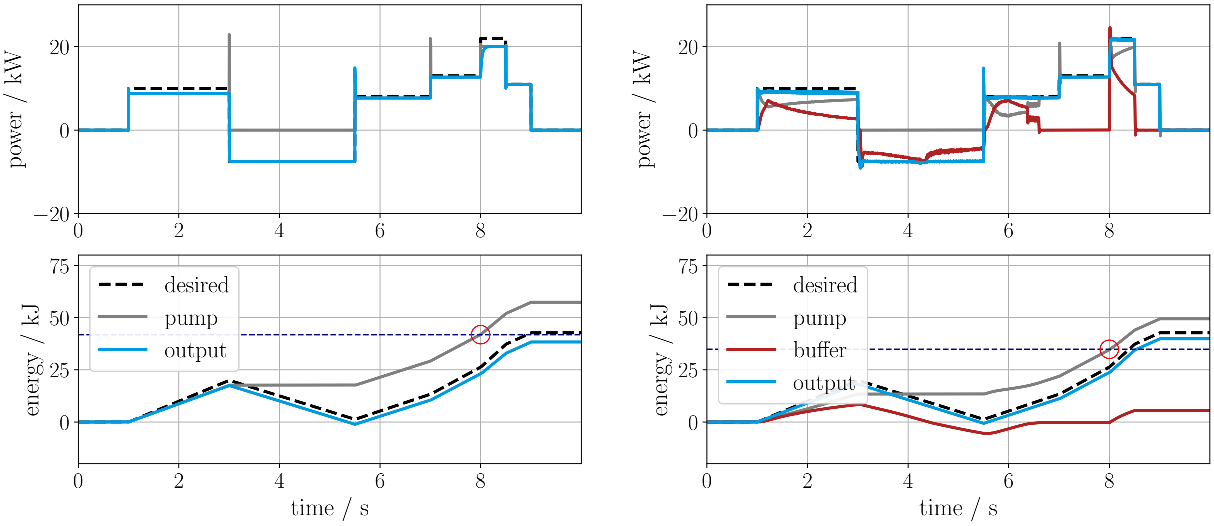


Figure 9: Supply performance with the buffer module using the DHT

both, the DDP and the DHT start to deliver flow, which is indicated by the signals q_P and q_B. The buffer operates in $\mathcal{Q}_1$, which is illustrated by the dashed line in the additional axis for the actual power quadrant in the lower diagram. Like in Subsection 2.1., the signals p_N^B and p_N^S indicate the pressure in the buffer sided and in the supply sided node points of one transformer stage. When p_N^B falls below tank pressure during $\mathcal{Q}_1$, then energy is efficiently released from the buffer by boosting the flow with cheap oil from tank. Similar is valid for p_N^S, when the operating mode changes at simulation $t = 3\,\text{s}$, where a high supply pressure of $p_S = 150\,\text{bar}$ and a negative load flow rate are required, for instance, due to picking up a heavy load for lowering. The power quadrant switches to $\mathcal{Q}_3$ since the buffer pressure is lower than the supply pressure. The total flow q_B is used to load the buffer accumulator. When the buffer pressure exceeds the supply pressure the operating mode of the DHT changes to power quadrant $\mathcal{Q}_2$ for pressure boosting. In this mode of operation a certain amount of q_B must be used for boosting the pressure and only a reduced flow rate can be stored in the buffer. At $t = 5\,\text{s}$ the conditions of the working cycle require an operation again in $\mathcal{Q}_1$ and energy from the buffer is released efficiently, again by boosting a certain amount of fluid from tank pressure to supply pressure.

In certain situations it can be advantageous to deactivate the buffer module, which is easily possible due to the parallel arrangement with the primary hydraulic supply. For instance, at simulation time $t \approx 6.5\,\text{s}$ the buffer module is switched off, because in the following operating conditions the energy from the buffer could only be transformed with additional throttling losses. Thus, the energy in the buffer can be either stored until the operating conditions allow an efficient exploitation or can be saved up for a predictable pressure boost, like occurring at



(a) DDP without buffer module

(b) DDP with buffer module and DHT

Figure 10: Power consumption

simulation time $t = 8\,\mathrm{s}$. In this situation the desired power exceeds the maximum power of the primary motor, like already shown in Fig. 8, but with the additional power of the buffer module the desired pressure can be realized for the demanded load flow rate.

In Fig. 10 the power- and the energy consumption of the DDP without and with the buffer module are presented. In the upper diagrams the power consumption and in the lower diagrams the energy consumption for the considered working cycle are illustrated. Until the simulation time $t = 8\,\mathrm{s}$ the desired output power is within the designated working range of the motor and the deviations result from the simple P-controller used for the DDP in the simulation experiments. But in this time range the results can be directly compared, because as already mentioned from $t = 8\,\mathrm{s}$ the desired power at the output exceeds the maximum power of the motor. Thus, at $t = 8\,\mathrm{s}$ the energy consumption of the DDP without the buffer module is approximately $42\,\mathrm{kJ}$, which is depicted in the lower diagram of Fig. 10a. In the corresponding results with the buffer module, depicted in Fig. 10b, the energy consumed by the pump reads $35\,\mathrm{kJ}$, which is significantly lower due to the buffering and releasing of recuperable energy from the load cycle. Since the red signal representing the energy contribution of the buffer is almost zero at time $t = 8\,s$ the reduced energy consumption can be directly interpreted as energy savings at the motor and, thus, of primary energy.

As already mentioned, from $t = 8\,\mathrm{s}$ the output power is boosted above the maximum power of the motor for a short time, for instance, for an acceleration of a very heavy load. Therefore, a significant amount of energy is used from the buffer module, however, for the whole working cycle considered in this paper the output performance as well as the total energy consumption including the buffer module could be lowered by using recuperable energy from the load.

3. DISCUSSION

The concept of an efficient load sensitive hydraulic power supply represents a parallel arrangement of a DDP and a digital hydraulic transformer connected to a buffer accumulator. For simplicity, in this contribution the DDP is driven by a motor with constant rotational speed, which allows a very energy efficient and cost effective realization of the primary hydraulic supply. However, in a probably more sophisticated approach also a motor with variable speed can be included into the optimization process for minimizing the energy consumption at maximum performance or, furthermore, even different optimization objectives depending on specific operating conditions can be considered. Nevertheless, the effectiveness of the presented buffer concept strongly depends on the actual operating conditions, respectively, working cycles of the machine, in other words recuperable energy must be available.

In the presented study the output pressure is controlled, which requires a specific desired value of p_S which, in turn, must be generated by a certain strategy involving the demand of all individual consumers located in LS-CPR. For this reason the concept is not easily comparable with conventional load sensing systems, like open center or closed center systems. However, the presented concept does not suffer from any piloting or sensing losses. Furthermore, the hydraulic buffer module is preferably suitable for drive by wire applications with smart actuators, which already fulfill the requirements for energy recuperation like, for instance, independent metering.

The digital hydraulic transformer (DHT) represents a highly efficient valve controlled system using an inertance pipe for transforming the hydraulic power. However, in the transformer certain losses due to parasitic effects, like limited valve sizes, flow losses in the pipe or compression losses in the transformer nodes have to be considered. For instance, the step down efficiency is rather high at lower output pressures, because in such an operating case much fluid can be drawn from the tank line. But, since the buffer module is arranged in parallel with primary hydraulic supply the buffer module may be deactivated in operating points with lower efficiency. Thus, recuperation as well as the release of energy can be either suspended or forced in certain situations. Furthermore, if there exist some predictable operating points with extreme power consumption, the energy in the buffer can be saved up and used on demand. Moreover, it is conceivable to load the buffer accumulator directly by the pump through an additional (not illustrated) bypass during phases of low output power in order to have a higher pressure reserve for power boosting.

In mobile applications, for which the presented concept will most likely be beneficial, the space for additional devices is hardly available. But, if only smart actuators are used in the LS-CPR, then all valves are located closely at or directly in the actuator. Thus, new room is generated in the body of the machine, which can be used for the buffer module. In particular, space for the accumulator, the DHT and the output cavity must be spent. The size of the accumulator strongly depends on the strategy of operation; buffering, saving or even preferably boosting. The space required for the DHT depends strongly on the mechanical design. Based on the results from [17, 10] a compact design seems to be possible, where the switching valves and the check valves can be integrated in a single block incorporating coiled or threaded inductances around the output cavity, which in turn may result in a minimized amount of required space.

Finally, the noise due to the valve switching of the DHT is not investigated so far, however, it can be assumed that also the IHT suffers from considerable noise during transforming hydraulic power. But the multiple transformer stages of the DHT constitute additional degrees of freedom by adapting the number of active stages as well as the switching frequency in order to minimize the noise emissions during operation.

4. CONCLUSION AND OUTLOOK

The demand for more efficient hydraulic drives requires also more efficient hydraulic supply units. In fact throttling losses can be reduced by the application of load sensing systems, however, conventional systems are not able to recuperate energy. In this paper the concept of a buffer module for storing recuperable energy using a digital hydraulic transformer based on a PWM switching technique was presented. The basic operation in all four power quadrants has been demonstrated by simulation experiments. The results taught that the energy consumption in an exemplary operating cycle could be reduced significantly by buffering recuperable energy from the load and releasing the stored energy, either with focus on efficiency or even for power boosting beyond the maximum power of the primary motor. Next steps in development are investigations on more realistic working cycles for the present by simulation. Furthermore, an advanced control strategy for improving the control performance as well as for optimizing the energetic performance with regard to specific operating cycles would make sense. Then, certainly a study with a real prototype would be desirable.

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