TWO BASIC CONCEPTS OF HYDRAULIC SWITCHING CONVERTERS

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ABSTRACT

Hydraulic switching control attempts to transfer concepts from modern electrical drive control to hydraulics. Both, electrical and hydraulic switching systems can achieve higher efficiency than resistance control. In this paper, the hydraulic pendants of the electrical Buck-Converter and Cuk-Converter are introduced. Basically, the hydraulic switching converters consist of switching elements (fast valves), inductances and capacities. The active valves are typically switching at a certain frequency in PWM-mode. The Buck-Converter is a traditional step down converter, so the pressure at the load is always lower than the supply pressure. The concept of the Cuk-Converter even allows to boost the load pressure up to a higher level than the available supply pressure. But it is much more difficult to realize the hydraulic switching converters than their electrical pendants. The wave propagation in the fluid, the impossibility to realize a pure inductivity and the nonlinearities of the hydraulic elements are major difficulties. This paper gives an idea of the basic converter concepts and the difficulties concerning the realization of such drives. Further the results of simulations and measurements are presented.

KEYWORDS: switching, hydraulic, converters, efficiency

1 INTRODUCTION

A great advantage of hydraulic drives is the high specific force for actuating heavy loads. But conventional hydraulics is suffering from a bad efficiency at high costs if proportional control is applied. For many years now, the fluid power community attempts to raise the efficiency and to lower the manufacturing costs of drives in order to stay competitive with other drive technologies. A promising perspective are switching

concepts in hydraulics [e.g. 1, 8]. One feasible approach is to develop hydraulic switching systems in analogy to electrical engineering. This technology requires fast and high flow rate switching valves to achieve the sufficient switching frequencies and to minimize the pressure losses at the valve orifices. Such valves have been developed recently [5, 6, 11], which gives room for further attempts to realize energy efficient hydraulic switching techniques. Hence and further motivated by the successful implementation of real applications [e.g. 12] the following considerations now can be presented.
In this paper two concepts of hydraulic switching converters are introduced, the Buck- and the Cuk-Converter. Both are similar to their corresponding realizations in power electronics. Yet their analysis, dimensioning and optimization is much more complex, since wave propagation and several nonlinearities play a significant role. Nonetheless excellent performance and high efficiency can be achieved.

2 THE HYDRAULIC BUCK-CONVERTER

The most simple switching converter, which can be transferred to hydraulics is the one direction Buck-Converter. To understand its working principle correctly, the electrical Buck-Converter will be explained first.

2.1 Basic Principle

The electrical schematic circuitry of the hydraulic Buck-Converter is depicted in Fig. 1, which basically consists of a switch S, a diode D, an inductance L, a capacitor C and the load R_L.

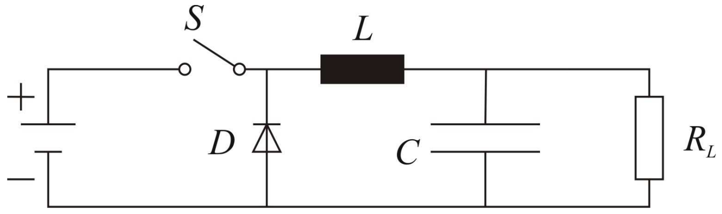

Figure 1. Electrical Buck-Converter

The switch connects the circuit to supply voltage for a certain duration of time. During that time the current in the inductance is increasing. When the switch interrupts the connection to the supply voltage, the inductance is further driving a certain current, because of its stored energy. Thus, the current flows through the diode and the energy in the inductance will be decreased. After the switch is closed again, the current in the inductivity increases again. The switch operates at a certain frequency in PWM-mode. The ratio between the on- and off-time is called duty cycle κ. For the attenuation of the huge voltage ripples at the load due to the switching process a sufficiently large capacitor is situated after the inductance. Another important factor is the switching frequency. To achieve the desired behavior of the drive, the switching frequency must be chosen sufficiently above the natural frequencies of the whole circuit.

The hydraulic Buck-Converter is depicted in Fig. 2. The corresponding elements to its electrical pendant are a switching valve, a check valve, the inductance realized by a pipe and an accumulator. In this simple case the load is represented by an ordinary orifice.

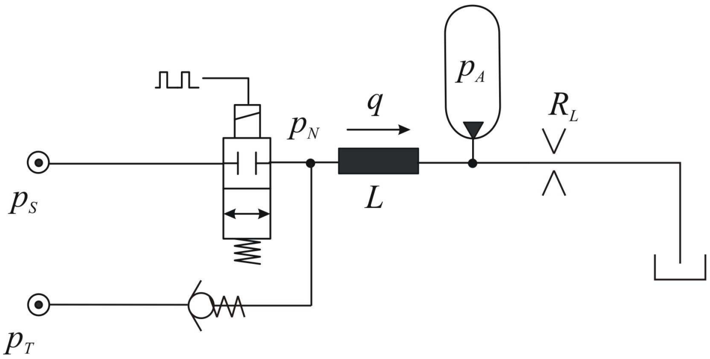

Figure 2. Simple Hydraulic Buck-Converter

When the switching valve opens, the fluid in the pipe inductance is accelerated. To keep the valve pressure drop in an acceptable range, the nominal flow rate of the switching valve has to be as large as possible. After the valve closes, the kinetic energy of the fluid in the pipe initiates a suction of oil from the tank line. This suction effect is responsible for achieving a higher efficiency than proportional hydraulics. Since the flow rate through the check valve causes a pressure drop, one has to rise the tank pressure to avoid cavitation. To keep the tank pressure level as low as possible and to avoid cavitation, the check valve has to be sufficiently large and fast. The pressure ripples generated by the switching process are attenuated by an accumulator.

The whole converter system operates like its electrical pendant in pulse width mode at a certain frequency $f_S = 1/T$ (Fig. 3). This switching frequency must be chosen sufficiently above the natural frequency of the configuration. In contrast to electronics, where the switching frequencies are in the kHz range, typical switching frequencies in hydraulics will be in the range of fifty up to a few hundred Hertz. It is not only the limited valve dynamics of switching valves, but also the hydraulic capacity effects of the fluid in the system that prevent higher frequencies.

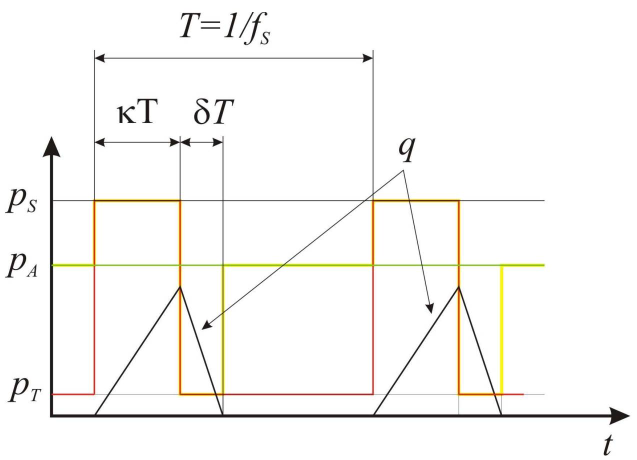

Figure 3. Basic correlations of pressure and flow rate

The control input of the system is the duty cycle $\kappa \in \left]0,1\right[$, which controls the imposed flow rate. The duration until the suction phase ends is called free-wheeling ratio δ. The average flow rate under ideal circumstances (no losses) reads

$$\overline{q} = \frac{1}{2}\frac{\left(p_S{}^2 - p_S p_A - p_S p_T + p_T p_A\right)}{\left(p_A - p_T\right) f_S L}\kappa^2 . \tag{1}$$

If κ reaches a certain value $\kappa^{\#}$, which depends on the load pressure and - taking losses into account - also on the switching frequency, the system structure changes into a further operating mode, which is depicted in Fig. 4. If κ exceeds $\kappa^{\#}$, the free wheeling would exceed the switching period. In this case the flow rate in the suction phase does not return to zero before the next switching period is starting. The behavior of the system changes from flow control mode to pressure control mode. In this case during $0 < t \leq \kappa T$ the converter is connected to supply pressure and during $\kappa T < t < T$ the system is connected to tank pressure. In other words, the pressure p_N between the valves and the inductance can be written as

$$\overline{p}_N = p_T + \left(p_S - p_T\right)\kappa . \tag{2}$$

This is (assuming a sufficiently high switching frequency) simply the average pressure of one switching period.

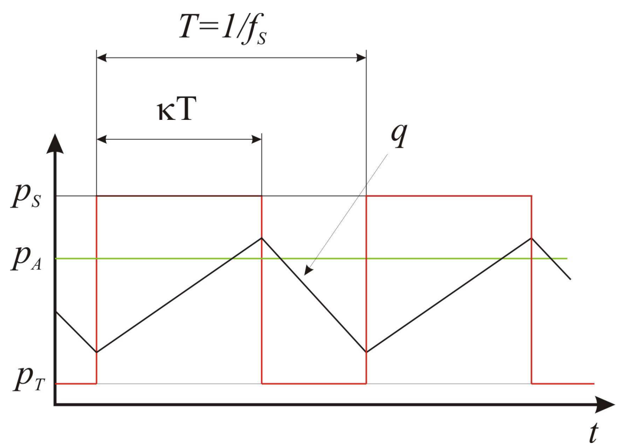

Figure 4. Correlations of pressure and flow rate in pressure control mode

2.2 The Extended Hydraulic Buck-Converter

The configuration depicted in Fig. 2 can only operate in the forward direction, hence it can only be used for one way applications as e.g. motors. A further problem is to provide a sufficient tank pressure, because the one way Buck-Converter only extracts fluid from the tank and itself does not feed back fluid.

Much more interesting is a concept with the capability to actuate a load in both directions. In Fig. 5 the Buck-Converter driving a dead load by a differential cylinder in both directions is depicted. For this purpose the annulus chamber of the cylinder is connected to supply pressure constantly. In this case it is sufficient to hold the tank

pressure by a pressure relief valve. The accumulator in the tank line must be able to store only the maximum oil volume that is needed in the suction phase.
A further promising property of this configuration is the possibility to recuperate energy to the pressure supply during the retrieving stroke. In this case the spill-over of the flow rate rises the pressure p_N above the supply pressure level and thus oil can be fed back to the system line p_S via the check valve.

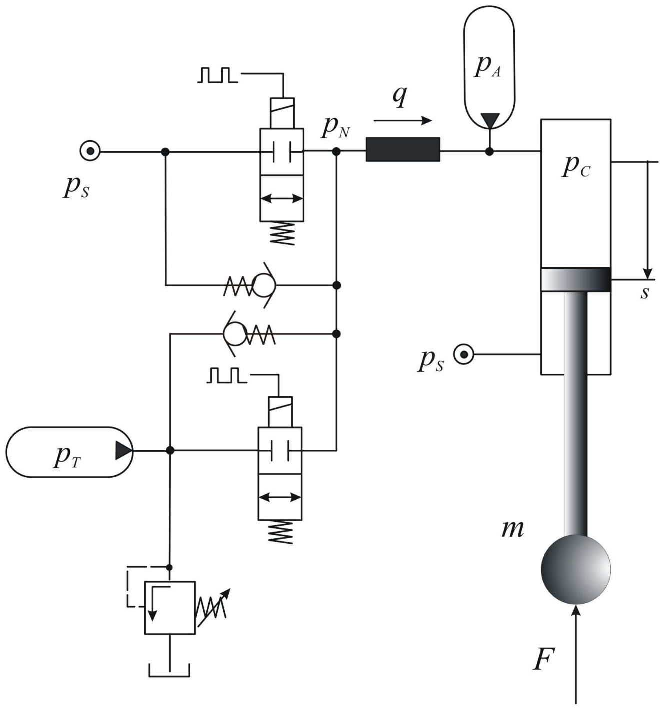

Figure 5. The hydraulic Buck-Converter

3 THE HYDRAULIC CUK-CONVERTER

Another switching hydraulic drive is the hydraulic Cuk-Converter, which is depicted in Fig. 6. The main advantage of this converter is the ability to boost the pressure p_B up to levels higher than the supply pressure. This pressure boost ability of the Cuk-Converter is of particular advantage if pressures beyond the system level p_S are only rarely required.

Basically, the hydraulic Cuk-Converter consists of two Buck-Converter stages, i.e. the boost and the drive stage, in a mirrored arrangement. To boost the pressure p_B the valve V_{ST} is opened for a certain time to increase the kinetic energy in the supply sided inductance. When V_{ST} is closed, the kinetic energy of the fluid boosts the pressure p_B through the free wheeling check valve CV_{SB}. On the other hand the boosted pressure is used by the drive stage to achieve higher forces at the load at excellent efficiency. The converter also operates at a certain switching frequency in PWM-mode, whereas it is necessary to switch always the diagonally situated valves at the same time and the same duration. Depending on the drive direction, always the valve couples $\left(V_{ST}, V_{BL}\right)$ and

(V_{BD}, V_{LT}) respectively are acting simultaneously. Alike the Buck-Converter the control input of the drive is the duty cycle κ. Furthermore, there exist the same operating modes (flow control and pressure control) as for the Buck-Converter.

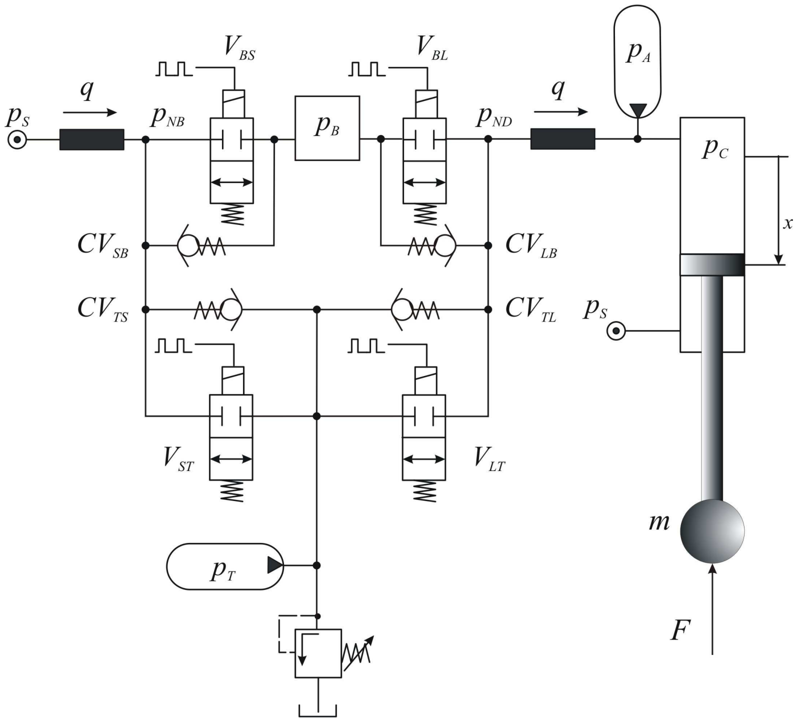

Figure 6. The hydraulic Cuk-Converter

4 LIMITS AND PROBLEMS

Whereas the working principle of a switching converter is rather simple, a lot of physical limitations and several parasitic effects make the realization of the converter a little more sophisticated than in electronics. The major problems are discussed in this section.

4.1 Valve Dynamics

As mentioned before, switching systems demand high flow rate and fast valves to keep the losses low. The size of the valves is prior to reduce the pressure drop in the opened position. These valves have to switch very fast in order to keep the losses in an acceptable range during the switching event. Moreover, the quickness of the valves is very important to realize the desired high switching frequencies. Since the valves are operating in pulse-width-mode, the rise and fall time of the valves bounds the feasible duty-cycles of the hydraulic PWM-signal.
The valves which are available at this time have a nominal flow rate of approximately 45 l/min at a nominal pressure drop of 5 bars and a rise time of approximately 1 ms

[11]. This valve design allows switching frequencies up to 100 Hz with a reasonable duty cycle bandwidth.

The wanted high efficiency requires also large and fast check valves. Such valves, with a nominal flow rate of 30 l/min at a pressure drop of 5 bars and a mechanical natural frequency of around 400 Hz have been developed [6, 7]. A parallel alignment of several check valves to achieve a higher nominal flow is enabled by their compactness.

4.2 Parasitic Effects

The available switching valves mentioned above offer a wide range of efficient hydraulic switching applications. However, the valve dynamics is not the only limit in switching systems. A number of parasitic effects exist, which define the difference between the theoretical working principle and the real design.

4.2.1 Parasitic Inductivities

The faster the dynamics of a hydraulic process, the more the inertia of the fluid with connections between the acting elements plays a superior role concerning the performance and the durability of the system. This inertia must be taken into account in the design of a converter.

The parasitic inductivity effect of long supply lines can be controlled by appropriate accumulators. More problematic is the parasitic inductivity after the valve metering edge, in the phase of a falling switching edge. In this case a too large parasitic inductivity causes cavitation, which can be hazardous to the valve and produces a bad noise.
The mastering of parasitic inductivities is a challenge in the design of a fast switching hydraulic system.

4.2.2 Charge Losses due to Capacities

To avoid cavitation it is not sufficient to keep the parasitic inductivities low. Besides quite sophisticated concepts to avoid cavitation [4] by additional sub-systems, there exists the simple solution to spend some hydraulic capacity to compensate the effect of the parasitic inductivities, especially at the node point (pressure p_N). But this volume has to be charged and discharged at every switching cycle. This leads to very short but very high peaks in the flow rate at the beginning of each switching state, which inevitably brings further losses.

4.3 Wave Propagation

The most important element of the Buck-Converter is the inductance, which is realized simply as a pipe. Since the oil is not an incompressible fluid the pipe represents a system with distributed parameters, which implicates the effect of wave propagation. Due to this effect the flow rate through a pipe is not changing uniformly, but nearly in a stepwise fashion. Because of the traveling waves in the pipe, the pressure in the converter node does not have exactly the desired rectangular signal form. Moreover, the sharp switching edges comprise a huge amount of higher frequencies, that may excite the natural frequencies of the pipe, which can be a disadvantage for the efficiency and especially the noise. Thus wave propagation in the pipe has to be studied in the detail.

4.4 Nonlinearities

Generally, the switching converters have a nonlinear behavior, because of their intrinsic structure. But in hydraulics several basic components own a nonlinear characteristic in contrast to the electrical pendants, like resistances or capacities.
The main nonlinearities are given by the characteristics of the switching and check valves and of the gas spring in the accumulator. The huge specific capacity of the gas spring has to be paid by a strictly bounded working range and a rather progressive spring characteristic. In addition to that, the currently commercially available accumulators are too slow for switching converters because of the orifice at their inlet.

4.5 Noise

Due to the switching process pressure variations between supply pressure and tank pressure are generated within a few milliseconds. These sudden changes, which are essential for the efficiency, excite a very broad band frequency spectrum which can lead to an unpleasant noise, which must be held in tolerable limits by an appropriate converter design.

5 SIMULATIONS

In the following section selected simulation results of certain configurations are presented. In all cases of simulation the wave propagation in the main pipes (inductances) is considered by Zielke-Suzuki models [10]. The pipes have a length of $1.7\ m$ and an inner diameter of $8\ mm$. The size of the switching valves corresponds to the currently available components mentioned above. Further only the dynamics of the active switching valves is taken into account and a constant supply pressure and a constant tank pressure is assumed. Further in all cases the switching frequency is 50 Hz.

Only the most interesting pressures and flow rates are illustrated. However, the position and velocity diagrams are neglected, because the simulations only represent the open loop case.

5.1 The Hydraulic Buck-Converter

In this Section the simulation results of the hydraulic Buck-Converter, which is depicted in Fig. 5, are presented. The diagrams in Fig. 7 show the pressures and flow rates in the extending direction at a hydraulic duty cycle of 50%, when only the supply sided switching valve is acting. The left diagram shows the nearly rectangular signal of the pressure p_N. The ripples in the high pressure phase are due to wave propagation in the pipe. After the closing of the switching valve the pressure falls below the tank pressure level and oil is sucked from the tank line via the check valve. The corresponding flow rates are depicted in the right diagram of Fig. 7. Since the flow rate through the check valve is returning to zero before the next switching period is starting, the converter operates in flow control mode. The load pressure p_A is well attenuated as can be seen in the left diagram.

The right diagram of Fig. 7 indicates an unwanted back flow rate through the supply sided check valve is appearing for a short duration of time. This flow rate is in principle unwanted, but this effect comes from the interaction between charging the node volume and waves reflected from the inductance pipe's end.

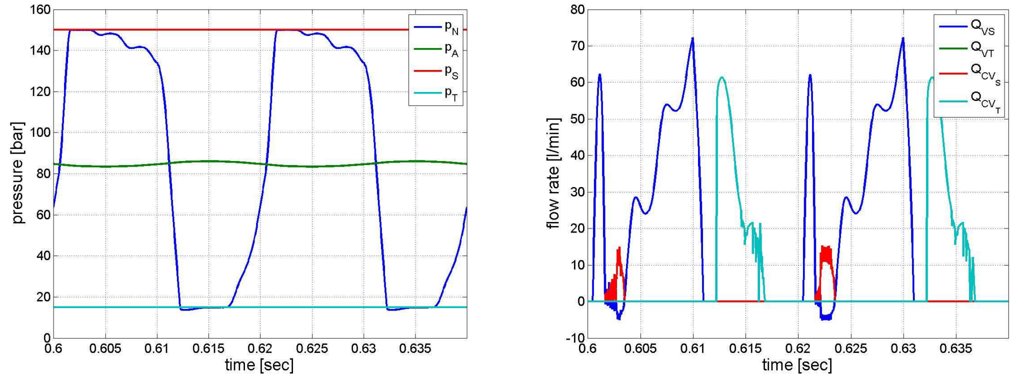

Figure 7. Pressures and flow rates for acting the pressure valve only

In Fig. 8 the main results for the retrieving motion (only the tank valve is actuated) at a duty cycle of 50% are presented. In contrast to the previous case the overshoot of the kinetic energy of the inductance imposes a flow through the supply sided check valve and thus energy is recuperated. Also in this case the combination of capacity charging and incoming reflected waves imposes a short unwanted suction phase.

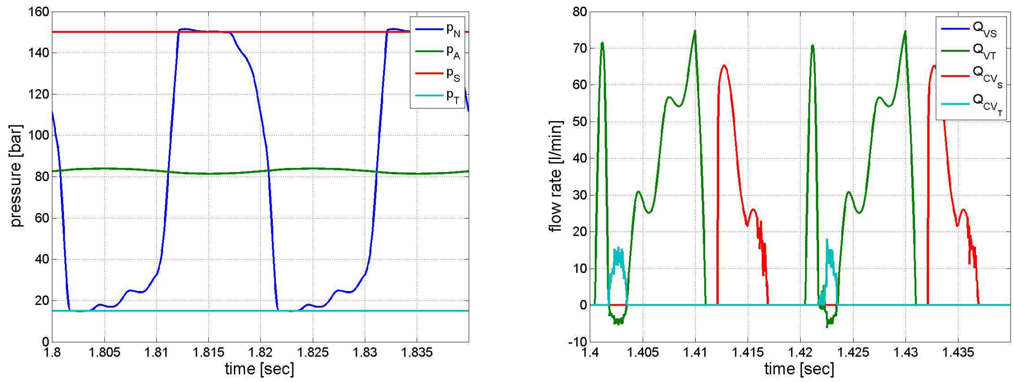

Figure 8. Pressures and flow rates at retrieving motion

It must be mentioned, that the working point of the application depicted in Fig. 5 depends on the cross-section ratio of the cylinder. If this ratio does not fulfill a certain condition the Buck-Converter is may not work efficiently.

5.2 The Hydraulic Cuk-Converter

The following diagrams present the simulation results of the hydraulic Cuk-Converter, which is depicted in Fig. 6. For the sake of brevity only the forward movement is treated. As mentioned before, in this moving direction the valves (V_{ST}, V_{BL}) are operating. In Fig. 9, the upper left diagram shows the main flow rates through the booster stage, as the flow rate $Q_{CV_{SB}}$ is responsible for boosting the pressure p_B. The curves in the upper right picture present the flow rates through the drive stage, where the flow rate $Q_{CV_{TL}}$ is responsible for a high efficiency.

The more interesting signals concerning the Cuk-Converter are depicted in Fig. 10. There, all relevant pressure signals are illustrated. The node pressures p_{NB} and p_{ND} are switched alternately between the boost pressure and the tank pressure. In this case the boost pressure is nearly $200\,bar$ at a supply pressure p_S of $100\,bar$. An interesting fact is, that the booster capacity can be much smaller than the capacity at the load side. This is a consequence of the synchronized switching of the valves.

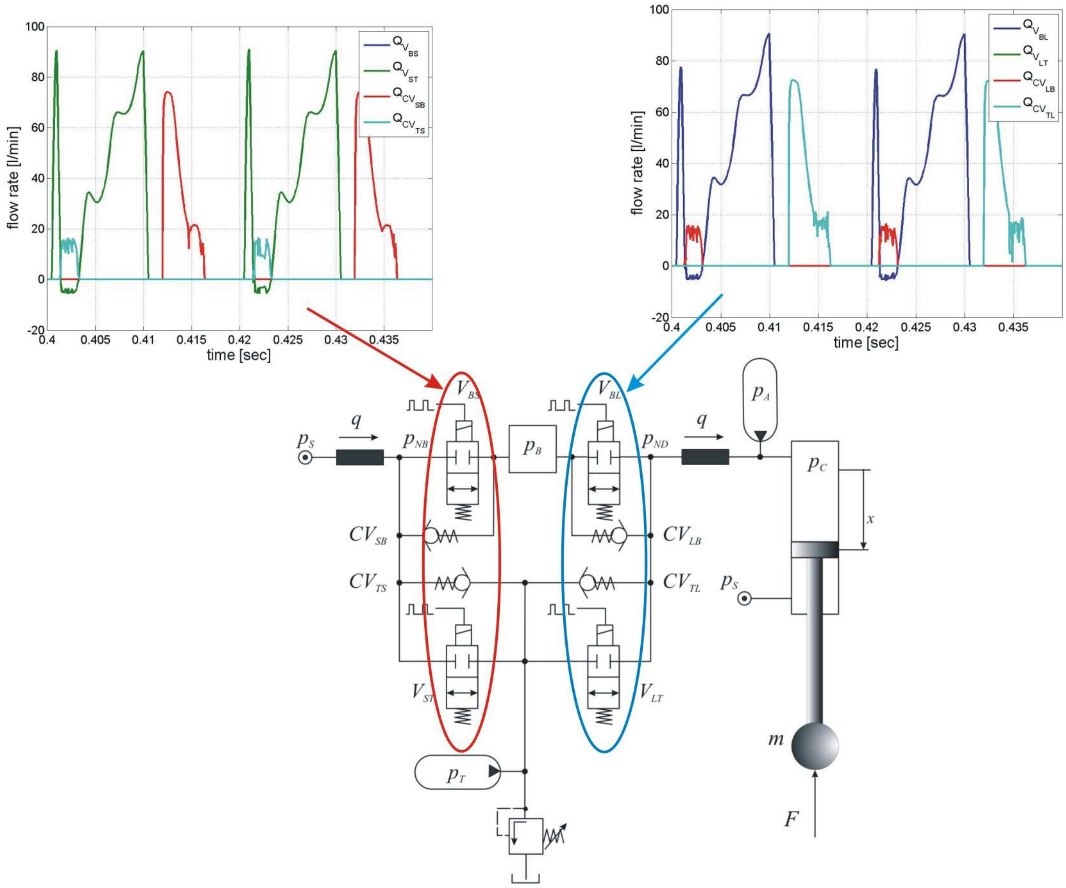

Figure 9. Flow rates of the hydraulic Cuk-Converter in forward motion

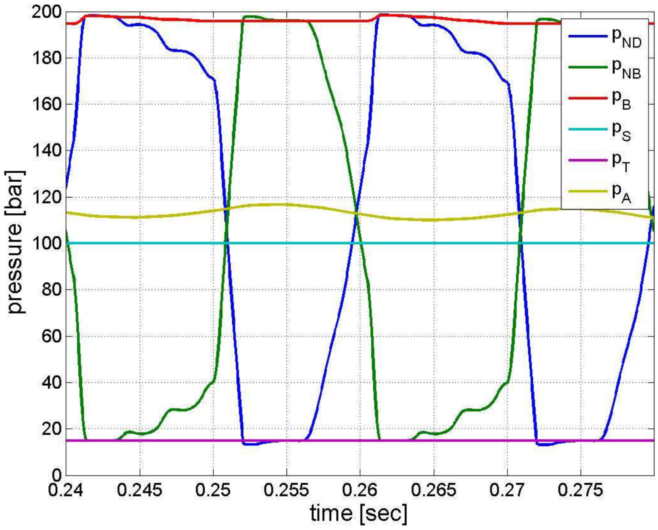

Figure 10. Pressures of the hydraulic Cuk-Converter in forward motion

6 MEASUREMENTS

In the following, measurements of the first prototype of the hydraulic Buck-Converter are presented. The schematic of the testrig is depicted in Fig. 11. With it two types of loads can be considered:

- a 2/2-flow control valve and
- a differential cylinder with a dead load.

The two different loads can be piloted via a 4/2 switching valve. The real test bench is illustrated in Fig. 12.

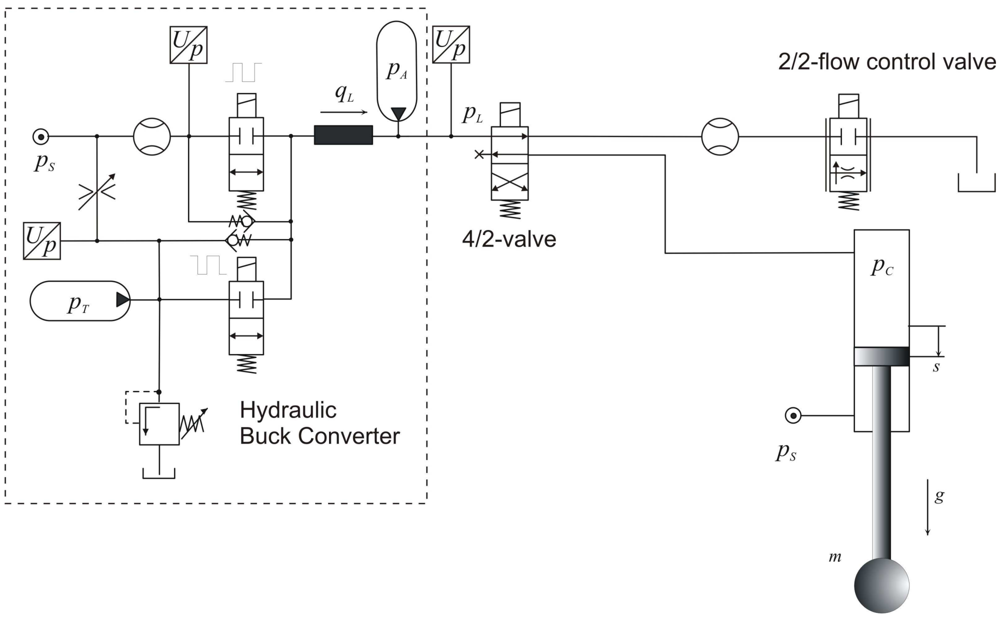

Figure 11. Schematic circuit of the testrig

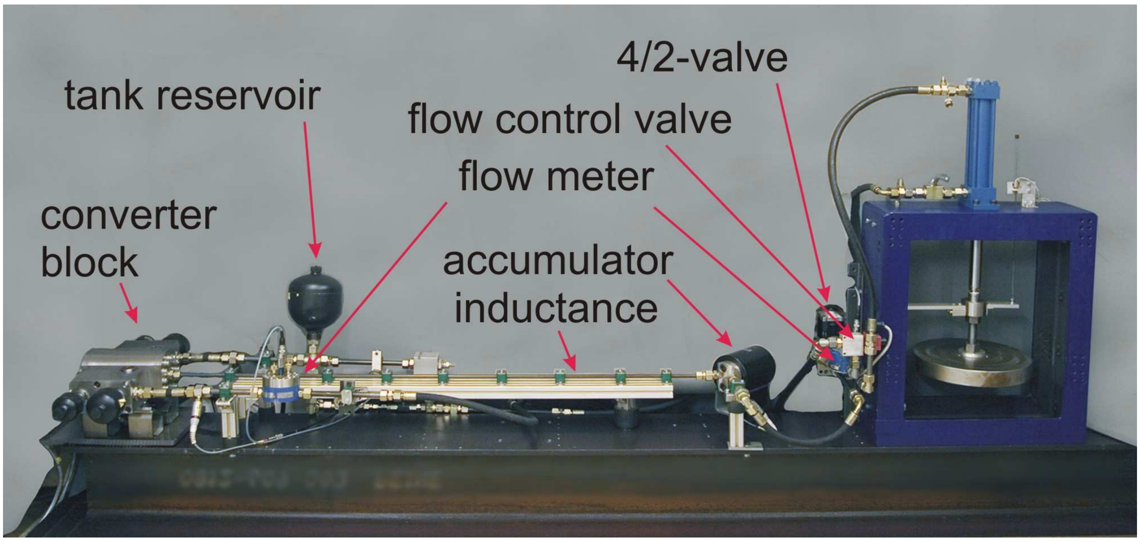

Figure 12. Real test rig of the hydraulic Buck-Converter

6.1 Characteristic field of the hydraulic Buck-Converter

The first measurements of the hydraulic Buck-Converter are done with a 2/2 flow control valve as a load. This arrangement allows a simple evaluation of the efficiency and other characteristics in the steady state operation.

This type of measurements corresponds to the schematic of Fig. 2. Since this configuration only operates in the forward direction, the tank line needs a permanent refill. This is done by an adjustable orifice (Fig. 11).

The signals of the supply pressure, the tank pressure and the load pressure are recorded. Since the Buck-Converter is a node between supply, tank and load the flow rate from the tank line can be derived from the supply line and to the load line signals. This takes also the leakage into account. The formula for the efficiency in one working point reads

$$\eta = \frac{p_L Q_L}{p_S Q_S + p_T (Q_L - Q_S)} . \tag{3}$$

For comparison with resistance control the efficiency of a corresponding proportional drive is defined by

$$\eta = \frac{p_L}{p_S} . \tag{4}$$

The characteristic diagram of the Buck-Converter, is derived from a series of measurements. For this purpose the duty cycle κ is varied between 20%,…,50% in steps of 2%. The flow rate to the load is adjusted by the preset of the 2/2 flow control valve. All measurements of each working point are taken in a steady state, at a switching frequency of 50 Hz.

The main results are illustrated in Fig. 13. The upper left diagram gives the flow rate to the load, i.e. the flow control valve. In the lower left diagram the grid of the according pressures is depicted. In the upper right diagram the reconstructed flow rate from the tank line is presented, which is responsible for the increase of the efficiency. The lower right diagram shows the characteristic field of efficiency (colored surface) in comparison to the proportional drive (white surface). The maximum increase of efficiency of about 30% is achieved at the lowest duty cycle and the highest flow rate through the load. A further promising property of the Buck-Converter is, that its characteristic diagram is nearly flat. That means, that the efficiency is nearly independent of the operating point. Only at small flow rates, the measurements are looking worse than resistance control. But this resulted from dynamic problems with the flow control valve. The authors are ensured, that the Buck-Converter is never worse than proportional control.

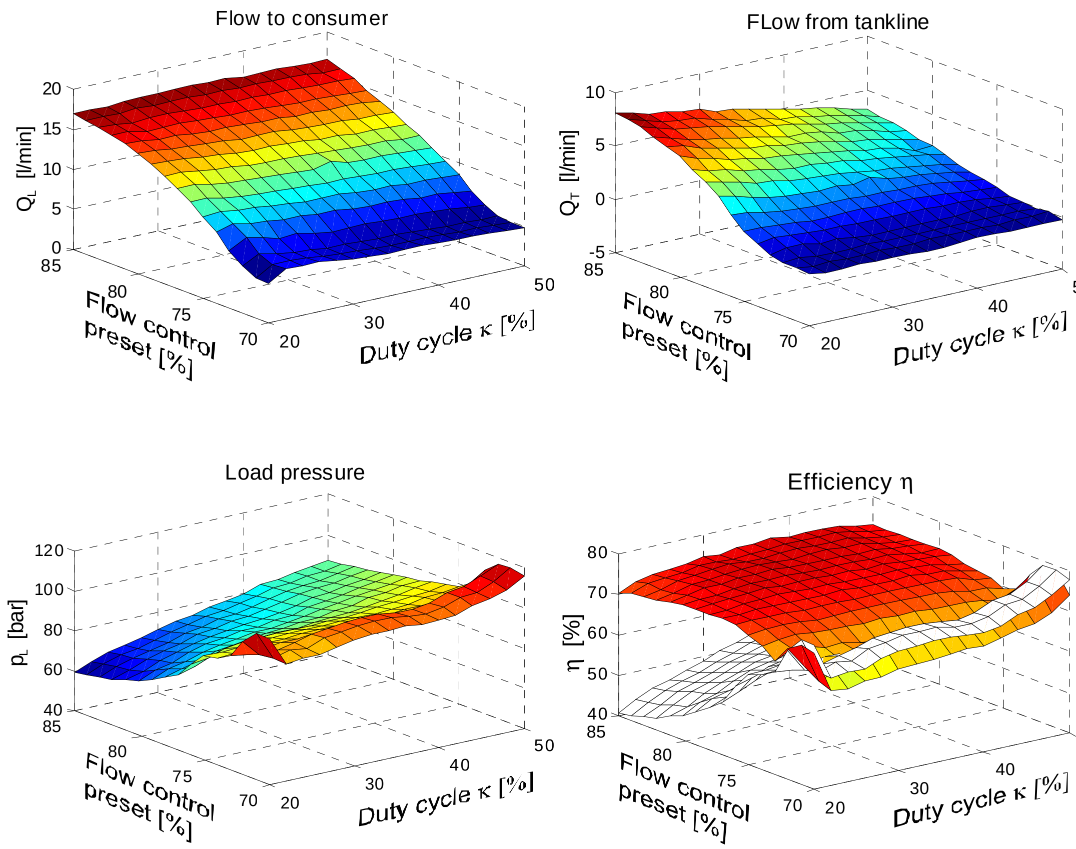

Figure 13. Measurements of the Hydraulic Buck-Converter via a flow control valve

6.2 Measurements with a linear drive as load

In this section the motion control of a linear drive with a hydraulic Buck-Converter is presented. As shown in Fig. 11, the converter is connected to the differential cylinder. The annulus chamber of the cylinder is connected to supply pressure permanently, to drive the load in both directions. In this experiment the dead load is only a small mass in comparison to the inertia of the converter inductance. The switching also happens at a frequency of 50 Hz.

The experiment was designed as a step response of the velocity of the piston. The load is accelerated from a rest position to a constant velocity at constant duty cycle. Also the deceleration of the load is measured.

Since the flow rate is not measured directly by a flow meter in this case, it is reconstructed from the velocity of the piston. The formula for the efficiency for the forward motion reads

$$\eta = \frac{A_{Piston} v_{Piston} p_L}{p_S Q_S + p_T \left(A_{Piston} v_{Piston} - Q_S \right)} . \tag{5}$$

The proportional drive completely annihilates the energy in the retrieving motion, hence the efficiency is zero. But in contrast to the proportional drive, the Buck-Converter is able to recuperate energy. This case is not treated here.

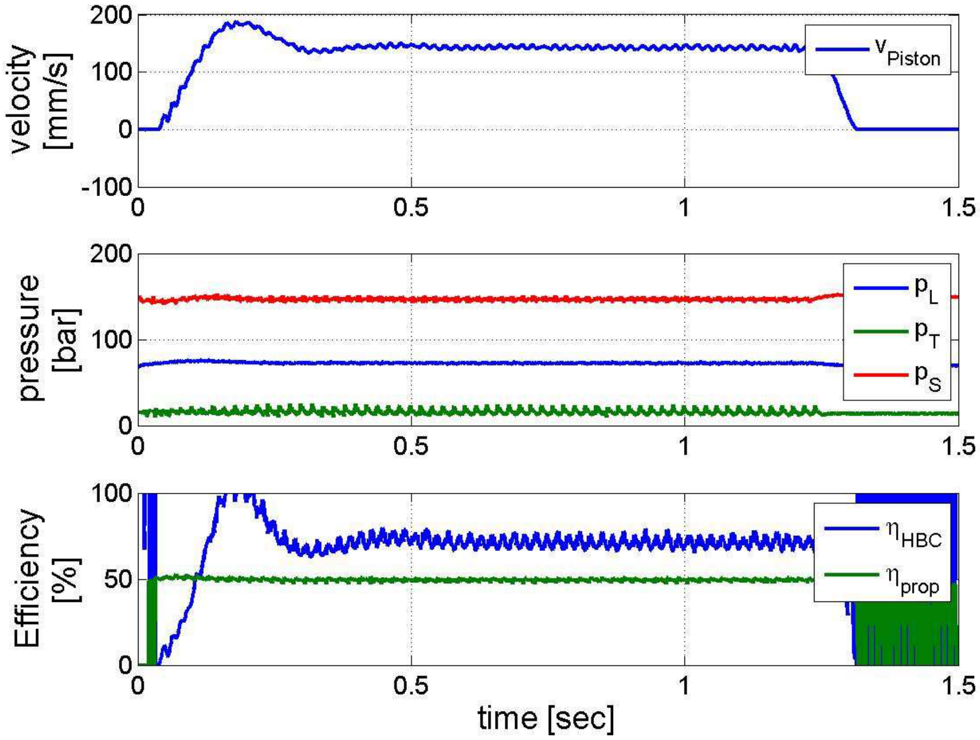

Figure 14. Measurements of the Hydraulic Buck-Converter driving a dead load via a differential cylinder

In Fig. 14, the results of one selected measurement are illustrated. The first diagram presents the step response in the velocity of the piston. Due to the switching of the valves there appear some velocity ripples, but as mentioned before, the dead load is small in comparison to the converter inductance. Higher load inertias result in reduced velocity fluctuations.

The relevant signals (p_S, p_T, p_L) are depicted in the second diagram. Only small pressure pulsation occurs, thus the decoupling and the attenuation is working well.

The efficiency is depicted in the third diagram of Fig. 14. The definition of efficiency in Eq. 5 is only reasonable for steady state conditions, hence the initial efficiency oscillation in the diagram is not meaningful. In steady state the average efficiency of the drive is significantly higher than with a proportional drive.

7 CONCLUSIONS AND OUTLOOK

In this paper two promising concepts of hydraulic switching converters were introduced. The hydraulic Buck-Converter represents the most simple drive transferred from electronics to hydraulics. The hydraulic Cuk-Converter is even able to boost the pressure to higher levels than the supply pressure. So far only a testrig of the hydraulic Buck-Converter has been realized. The measurements already approved the expected results. Further investigations are necessary, to get the converters more compact, less noisy and yet more efficient. Components such as switching valves, check valves and fast accumulators have to be further advanced to make the switching hydraulic drives broadly applicable. Both presented converter principles have the advantage of high efficiencies, which is essential in times of unnecessary energy cost and the necessity to solve the greenhouse problems. Moreover not only the high efficiency, but even the possibility of low cost manufacturing of the switching concepts may attract the interest of industrial companies.

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