HYDRAULIC SWITCHING CONTROL – OBJECTIVES, CONCEPTS, CHALLENGES AND POTENTIAL APPLICATIONS

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Abstract: *Hydraulic switching control operates via the switching of valves. Numerous principles exist, some of which are already routinely applied, some others have been studied, but many more are possible. A successful realization of many switching techniques requires fairly advanced hydraulic components, foremost fast switching valves, fast check valves and compact accumulators which can resist high load cycles, and a sound understanding of the relevant processes by advanced modelling, simulation, and experimental analysis. Switching control can bring the following advantages: lower costs, higher robustness, better standardization, easier control due to better repeatability and less hysteresis; better energetic efficiency by the application of energy saving converter principles; generation of very fast motion for relatively high loads. Some elementary switching principles and switching converter principles are described in this paper. The authors expect an early industrial application of novel switching techniques in heavy duty and in agricultural machines.*

Keywords: *Hydraulic switching control, switching converters, buck converter, electric hydraulic analogy.*

1   Introduction

The idea to employ switching systems for realizing some sort of hydraulic transformers is an old idea as the hydraulic ram of Montgolfier from 1796 and Pollard's work on pulsating hydraulic power transmission (1964) [1] show. The major motivation for the current attempts to realize hydraulic switching control is the success of switching control in modern electric drive technology.

Hydraulic switching control is a sub-domain of digital hydraulics, which is characterized by performing control only by the use of components with discrete states (see [2]). In hydraulic switching control these discrete state components are switching valves. Control input parameters are some timing characteristics of these valves which can be: the pulse-width of a pulse width modulated valve switching, the duration of individual pulses, switching frequencies, or the phase shifts of switching pulses of different valves, to mention just a few.

The basic motivations for switching control are:

- To use the simple component switching valve instead of the more complex servo or proportional valves, to achieve one or several of the following goals: lower costs, higher robustness, better standardization
- Easier control: better repeatability, less hysteresis
- Better energetic efficiency by the application of energy saving converter principles
- Generation of very fast motion for relatively high loads

Like in power electronics, the variety of possible switching concepts is very large and there is not just one optimal solution for many applications but rather a few optimal for a small class of applications. Some concepts evaluated so far are:

- Non energy saving concepts: Elementary switching control concepts [3], the LCM ' Digi-Actuator' [4], combinations of pulse code and switching control concepts [5].
- Energy saving switching control principles: the Gall&Senn principle [6], buck- [7], resonance- [8], wave- [9], motor-converters [10, 11].

Some hydraulic switching principles are routinely applied since decades in the following applications: ABS break systems, variable valve timing for compressor valves [12], clutch actuation of gears in passenger cars [13], on-line gap adjustment of continuous casting segments [14, 15]. All these drivers require relatively low power and flow rate, respectively. Fast switching valves for such power ratings can be realized much easier than for higher flow rates and also pulsation and noise excitation levels are relatively low. The application of switching control to high power drives is facing the following main challenges:

- Appropriately powerful fast switching and check valves, and fast, compact, and reliable accumulators.
- The sound understanding and the mastering of pulsating phenomena and of acoustic noise.
- Control algorithms for switching control, which not only provide a proper control of the intended motions, force, or pressure but which also cope with the challenges of switching control, in particular with pulsation.

Switching control is also a useful technology for other than mechanical actuation. Not only modern diesel fuel injection, in particular common rail systems, apply switching principles but also the cooling of rollers employs this technology to realize the so called thermal crown in steel and aluminium rolling [16, 17].

There is no limitation of the application of such switching control concepts in principle. Currently, the only reasonable question is which applications are best suited for an early application of these technologies. This is not just a technical matter but depends even more on the disposition of end users to take the front runner role. To convince potential end users a single advantage, like just being more efficient, may be a too weak argument, there must rather be several advantages. In the next chapter some switching control concepts are presented. In chapter 3 areas of early applications of hydraulic switching control are discussed. An outlook on the further development of switching control will be given in chapter 4.

2   Switching control concepts

2.1   Electric – hydraulic analogy and duality

Hydraulic and electric machines are power converters with one mechanical port, a shaft or a rod. Electrical machines employ a dynamical principle for torque or force generation, respectively. This corresponds to hydrodynamic machines, like turbines or centrifugal pumps. Hydrostatic machines, however, employ a static principle which is dual to the dynamic principles. In the dynamic principles machines, torque or force depend on the flow variable, i.e. on the electric current or on the flow rate, respectively; in hydrostatic principles machines torque or force depend on the pressure. We limit this investigation to hydrostatic machines. The duality of static and dynamic machines has significant consequences for switching control.

A very elementary circuit for switching control of an electrical motor is shown in Figure 1a. The current i of the electric motor which is driven by a PWM voltage signal has a small fluctuation due to the flattening effect of the motor inductance. The angular speed's (ω) fluctuation is even smaller, because the inertia of the rotor and of attached moving mechanical parts have a flattening effect too. Both flattening effects are very expressed due to the high switching frequencies of modern drives, which are in the order of 10^4 Hz. That leads to a quite constant speed.
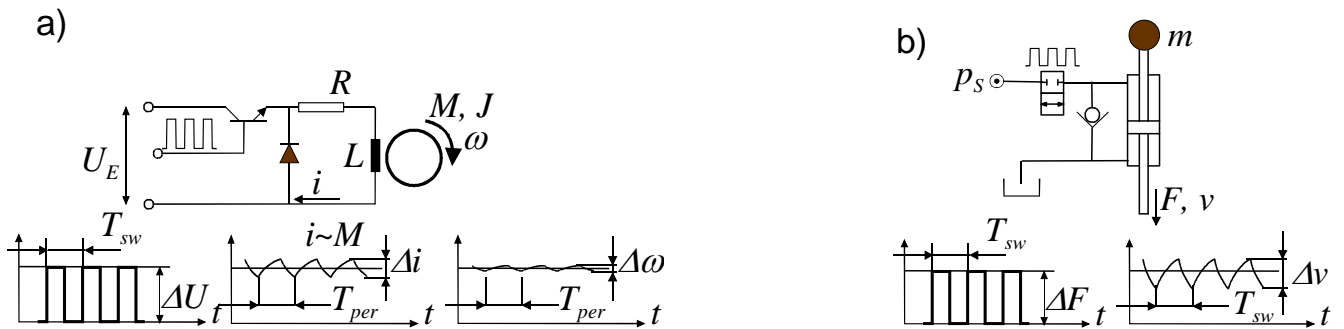
Figure 1: Elementary switching control circuits of a) an electrical motor, b) a hydraulic actuator

Hydraulic elementary switching control, as shown in Figure 1b, intrinsically generates higher speed fluctuations because the acceleration corresponds to the hydraulic force F which is approximately a rectangular signal. This requires extra devices to get rid of the strong pressure pulsation due to switching, particularly if the mechanical inertia of the system to be actuated is relatively small.

A further main difference between electrical and hydraulic switching systems is the high capacity of hydraulic systems. In Figure 1b, for instance, that capacity stems from oil compressibility in the chambers of the cylinder and in the connecting lines. One hardly can get rid of this capacity, which causes energetic losses in combination with the resistance of the valve at higher switching frequencies. There is some resonance effect resulting in an energy optimal switching frequency (see [18]). In electrical switching systems parasitic capacities are a negligible problem unless switching frequencies are extremely high.

On the components level a strong analogy exists between electrical and hydraulic switching systems. This concerns mainly the key component valve, the performance of which is a limiting factor for advancements in switching control. The availability of fast electric 'valves' is a major reason why electrical engineering leads the way. The progress there, for instance with respect to switching frequency or power range, was guided by advancements in power semiconductors technology.

2.2   Elementary switching control principles

In elementary switching control just one or more valves are put in front of a hydraulic cylinder or motor, respectively. There are no other components, like pulsation attenuation devices or transmission lines, which exhibit a significant dynamics at the actual operating condition, between valves and the actuator. The simplest circuit is shown in Figure 2, comprising just two 2-2 way valves. Switching frequency is a major operation parameter for the performance of such a system since high frequencies flatten pressure and velocity pulsation significantly.
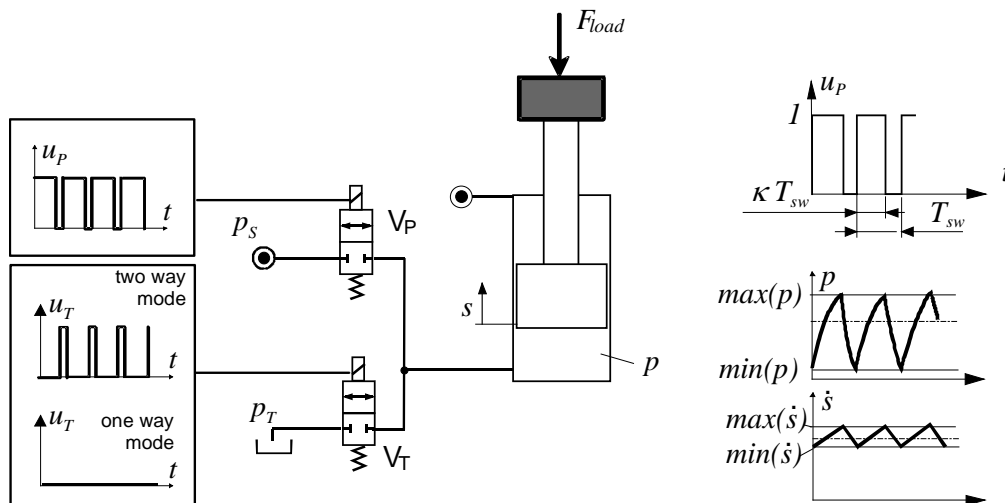

Figure 2: Elementary switching control schematic (left) and typical signals in one way mode of operation (right)

One way mode

In the so called one way mode of operation, only one switching valve is actuated. To lift the load F_{load}, valve V_P is actuated, e.g. employing PWM control with a frequency $\omega/2\pi = 1/T_{SW}$ and a duty cycle κ, to lower the load V_T is activated. The one way mode switching cannot provide better efficiency than resistance control with continuously operating valves. If there is no flow from the tank line to the cylinder in a load lifting operation, continuous or switching control give the same energetic efficiency η.

$$\eta = \frac{F_{load}}{p_S A} = \frac{p}{p_S} \tag{1}$$

The fluctuation in chamber pressure p and in piston velocity $\dot{s}$ depends on several parameters. In [19] the following approximate value for the nondimensional pressure fluctuation $\psi_{fl} = (max(p)-min(p))/p_S$ is derived under the assumptions of constant supply pressures p_S, p_T, a very fast switching, and that the nonlinear state equation can be linearized around the mean values of pressure and speed and at position $x_0 = \xi_0 s_{max}$.

$$\psi_{fl} = \frac{(1-\kappa)\kappa}{b+\xi_0} \frac{\left(g\, c_\omega - f_{load}\, \bar{a}_\omega\right)}{c_\omega} \frac{2\pi}{\varepsilon} \tag{2}$$

The meaning of the nondimensional quantities in this result is given by the following set of relations

$$p = \psi\, p_S; \quad \xi = \frac{s}{s_{max}}; \quad t = \tau/\omega; \quad v = \frac{d\xi}{d\tau}; \quad \varepsilon = \frac{p_S}{E}; \quad b = \frac{V_0}{A\, s_{max}}; \quad c_\omega = \frac{p_S A}{m\, s_{max}\omega^2}$$

$$a_\omega = \frac{Q_N}{A\, s_{max}\omega}\sqrt{\frac{p_S}{p_N}}; \quad f_{load} = \frac{F_{load}}{m\, s_{max}\omega^2}; \quad g = a_\omega\left(\sqrt{1-\psi_m} + \frac{\psi_m}{\sqrt{1-\psi_m}}\right)$$

$$\bar{a}_\omega = \frac{a_\omega}{2\sqrt{1-\psi_m}}; \quad v_m = \frac{g\, c_\omega - f_{load}\, \bar{a}_\omega}{c_\omega}\kappa; \quad \psi_m = \frac{f_{load}}{c_\omega} \tag{3}$$

The fluctuation of the nondimensional speed v around its mean value v_m is of order $O(1/\omega^2)$. ψ_m is the nondimensional pressure mean value. p_S is the system pressure, s the piston position, s_{max} the cylinder stroke, t is the physical, τ the nondimensional time, V_0 is the dead volume of the cylinder chamber at $s = 0$, m the moved mass, A the piston area, Q_N the nominal flow rates of both valves (at nominal pressure loss p_N). An analysis of Eqs. (2), (3) shows that pressure fluctuation can be reduced by a high switching frequency ω, by a valve with a low nominal flow rate Q_N, and by a high dead volume V_0. Q_N, however, is determined by the required speed of the system, higher V_0 limits the stiffness of the system which may deteriorate the control performance of a closed loop drive. Therefore, the only independent parameter to improve fluctuation is switching frequency.

Large drives which are running relatively low maximum speed require smaller ω to stay below a certain pressure fluctuation level than high speed, short stroke drives.

Two way mode

In this mode pressure and tank valves are switched alternately. Under certain conditions this may yield better or worse efficiency than the one way mode of operation. A better efficiency is obtained if the oscillation of the load m are such that in phases when V_T is switched on oil is sucked from the tank line, a worse efficiency in opposite case.
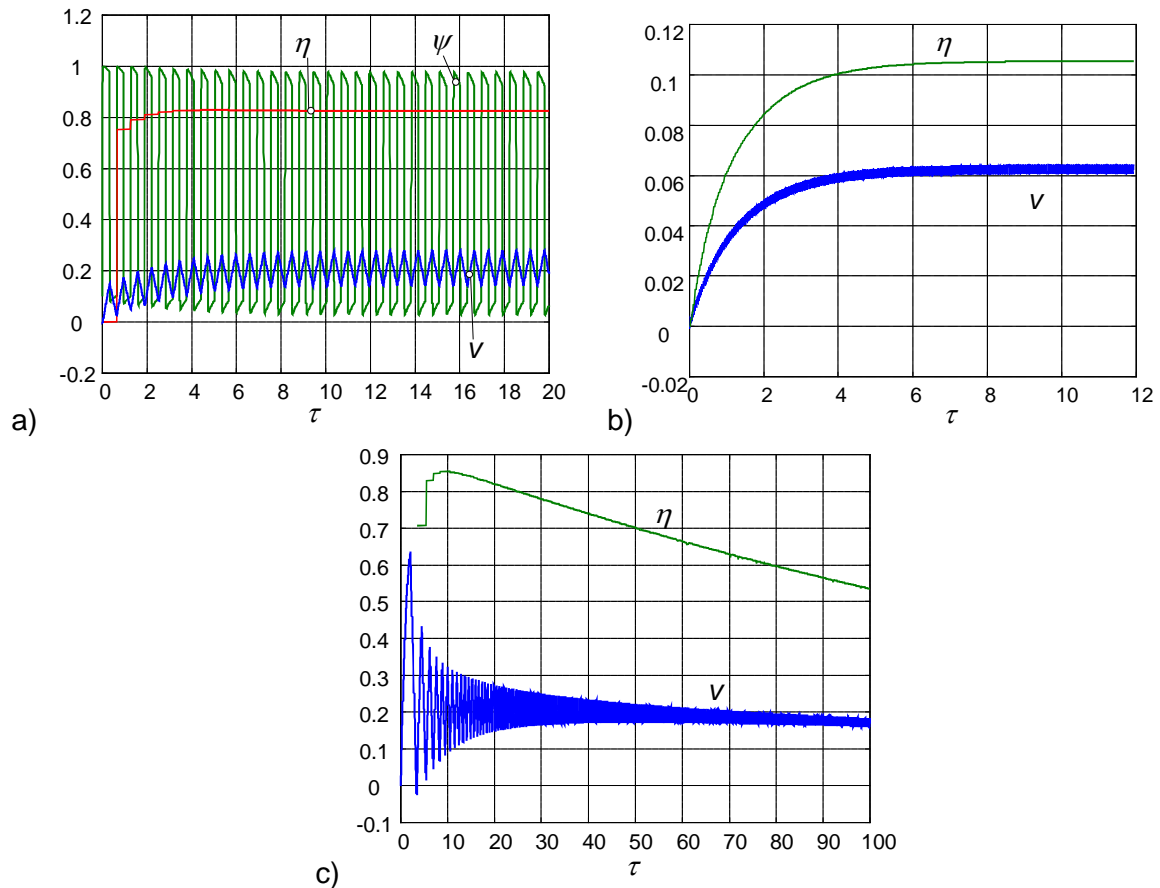
Figure 3: 1 Results of a numeric computation of an elementary switching system in dual mode; switching frequency is: a) identical to natural frequency of the system; b) twenty times the ntaural frequency ; c) wobbled between one tenth and five times the natural frequency; values of the other parameters: $a_\omega = 1$; $c_\omega = 1$; $f_{load} = 0.5$; $\kappa = 0.5$; $(b+\xi_0) = 1$.

Figure 3 shows results of numerical simulations of an elementary switching system according to Figure 2 in two way mode at different switching frequencies. High efficiency is obtained if this frequency is below and up to the natural frequency of the hydraulic drive's free oscillation, determined by the load inertia m and the compliance of the hydraulic cylinder. Going much beyond that frequency reduces fluctuation but efficiency drops and may even fall below that of resistance control because part of the flow from the pressure line is transferred to the tank line. This can be avoided with check valves as has been proposed in [6]. The major drawback of this type of switching control is that a good efficiency is bound to high pressure fluctuation, because only if pressure p reaches nearly system and tank levels in each switching cycle, a good efficiency can be obtained. This requires the frequency not to go much beyond the natural frequency of the system and, therefore, also the speed fluctuation will be high in many cases.

The considerations presented so far were based on the assumptions that

- the supply lines have constant pressure and are not disturbed by the strongly pulsating flows going to or coming from the switching system

- the line between the valves and the actuator are ideal, thus do not exhibit significant impedances.

Particularly for very high frequencies this requires adequate components, e.g. fast response accumulators, and special care in the design of the hydraulic system.

2.3   Switching converters

Converters use some intermediate system between the switching valves and the actuator to resolve the trade-off problem of elementary switching control mentioned before. Figure 4 shows schematics of four switching converters.

Wave Converter

This converter type was investigated in [9, 20]. By resonant switching standing waves are generated in a properly designed pipe network. This network acts as a filter that annihilates lower order pulsation (several low order Fourier Spectrum components) such that at the exit port only very small pressure or flow rate oscillations occur. The output pressure is proportional to the pulse width κ.

The resonance condition requires the length L of the first order twin pipe to have half wavelength. For a switching frequency of 100 Hz L is approx. 6 m. This length condition is the main drawback for a practical implementation unless switching frequencies > 500 Hz are possible.

Resonance Converter

It employs an oscillating mass in form of some piston which is supported by a spring. By switching the cylinder chamber alternately to pressure-, tank-, and exit-line the piston oscillates and hydraulic fluid is transmitted to the consumer. The system operates close to the resonance frequency of the spring mass system utilizing the frequency response characteristics close to the resonance point for flow rate control. More information and results are given in [8, 21]. This system can be made fairly compact for switching frequencies beyond 100 Hz. It is a step-down and step-up converter, thus even output pressures exceeding the system pressure can be realized. The optimal timing of the consecutive switching of the valves is critical for efficiency.

Buck Converter

This is a very simple system and corresponds directly to most electrical switching power supply devices. More can be found in [7, 22]. It is a step-down converter but can also recuperate energy from the hydraulic system. The inductance pipe's length depends on the switching frequency, the higher the shorter this pipe.

Motor Converter

It follows same principles as the buck converter, only the inductance element is not the fluid inertia of a pipe but the rotary inertia of a pump-motor unit (see, e.g. [7, 8]). The advantage is that this inertia can be controlled independently from the capacitance and resistance of the system. The disadvantages of this concept are the costs and weight of the pump-motor unit and the hydraulic capacitance in such units which is a source for losses at higher switching frequencies.
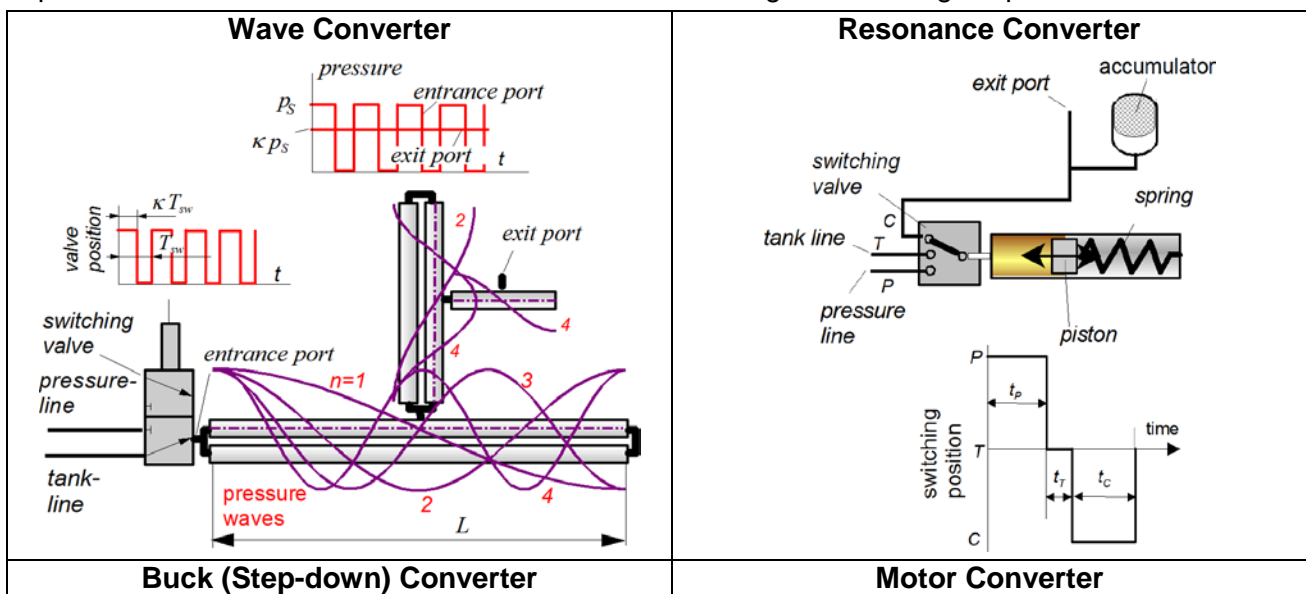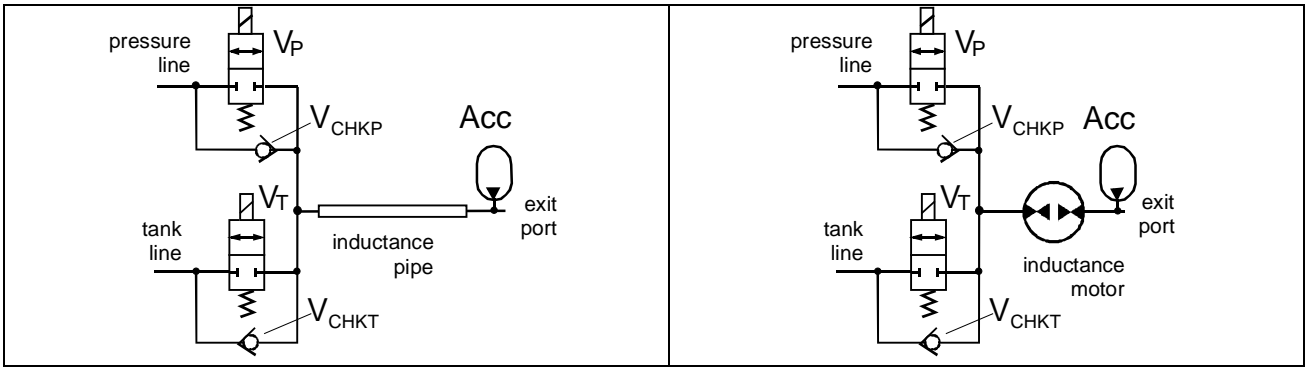
Figure 4: Four types of switching converters

2.4   Exemplary results of the hydraulic buck converter (HBC)

An extensive study of the HBC, its principles, modelling, components design, and control, can be found in the thesis [22], some results concerning its application to mobile robots in [23, 24, 25], and the application of several HBCs in parallel to avoid the accumulator (Acc in Figure 4) in [26]. Figure 5 presents some steady state performance results of a low power HBC prototype. This converter can also recuperate energy which yields a substantial energy improvement over a resistance control concept.
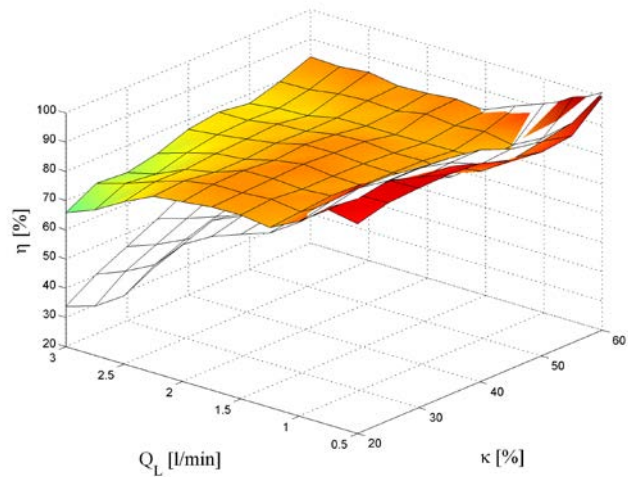

Figure 5: HBC prototype and its steady state efficiency results; (system data: inductance pipe: length: 1.2 m, diameter 3 mm, oil: Shell Tellus 15 cSt @ 40°C; switching valves: LCM FSVi (Q_N=10 l/lin @ 5 bar); switching frequency: 100 Hz; accumulators: piston accumulators, developed by the authors; find all data in [22] and [24]).
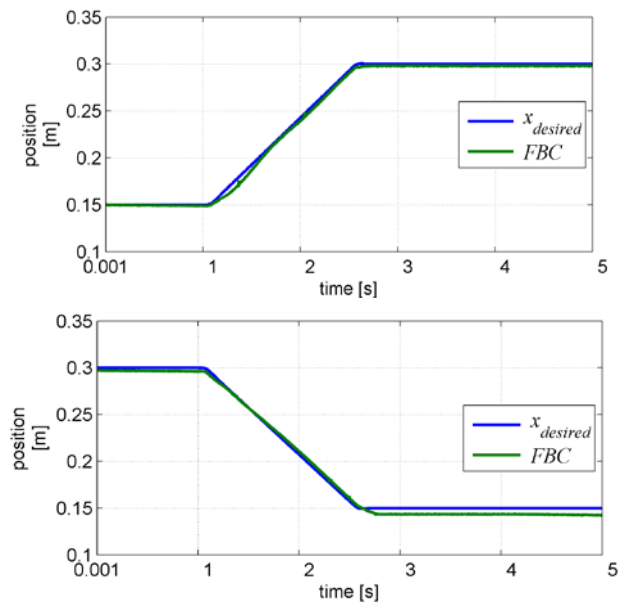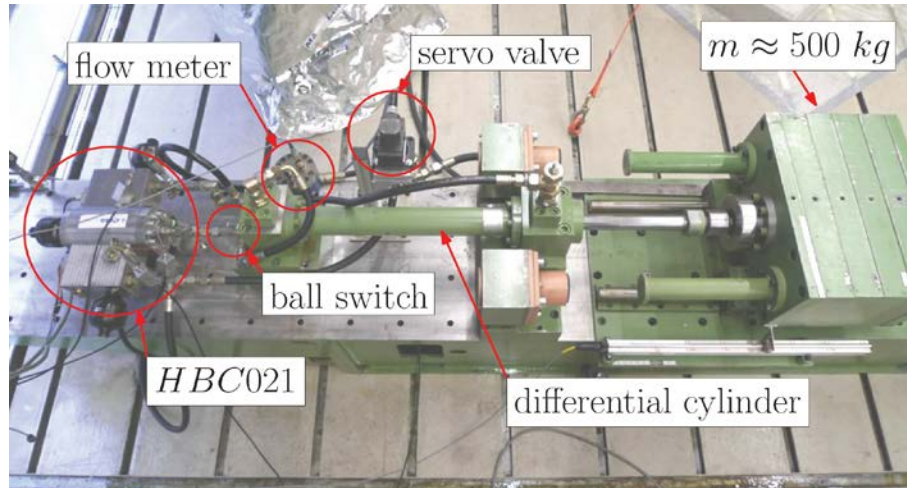
Figure 6: HBC (as shown in Figure 5) in motion control, lifting an lowering a load (Cylinder: 63 mm x 45 mm piston/rod size, stroke x_{max} = 600 mm); applied control concept: flatness based controller (details in [22]).

Assessment of the HBC:

Pros: This is a simple system which can reduce energy consumption considerably; energy recuperation is possible.

Cons: The size of the inductance pipe may be a problem, unless higher switching frequencies are possible; winding of the inductance pipe to a coil deteriorates efficiency; the accumulator is a highly loaded system and makes the system soft; this requires some sophisticated control to achieve a good dynamical performance; arrangement of several HBCs in parallel and running them in a phase shifted operation is a means to skip the accumulator and improves dynamical performance; performance can become as good as with fast servo-valves, yet with much lower energy consumption (see [26] for details). Such multiple converter concepts facilitate also a simple standardization, since power rating can be easily adjusted by an appropriate number of converter units. A schematic of such multiple converters is shown in Figure 7.
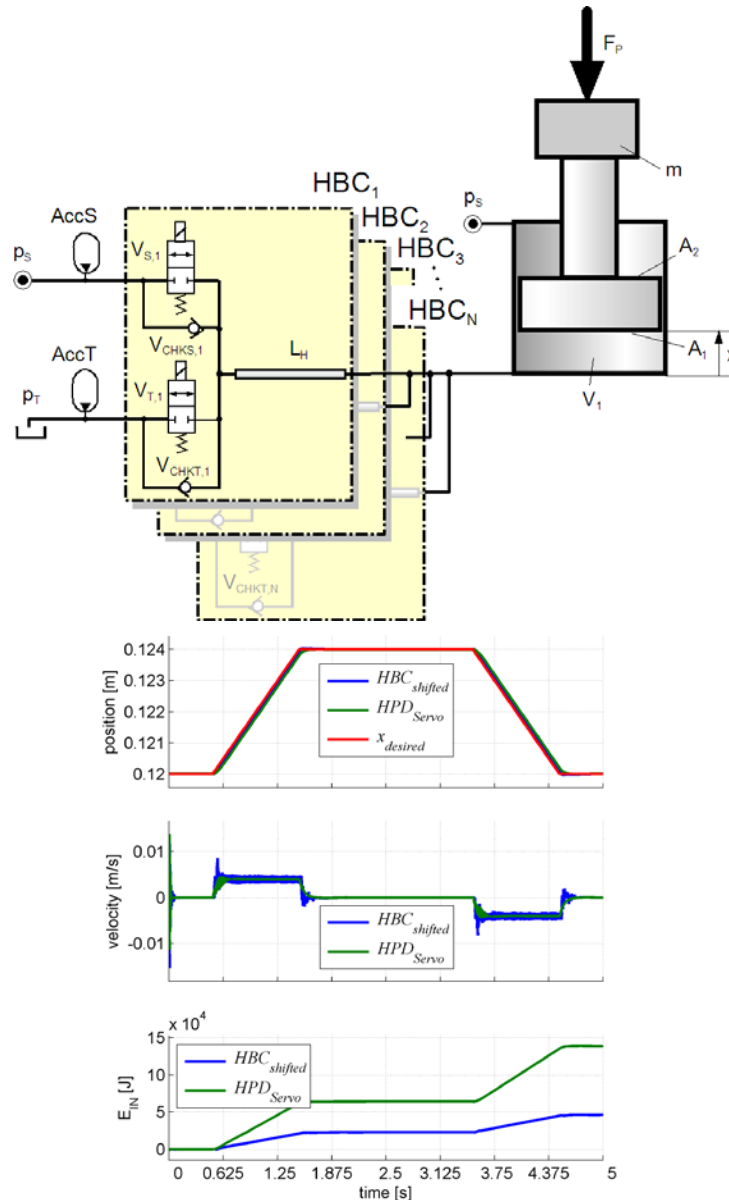
Figure 7: Schematic of a multiple (N) HBC system driving one cylinder and computed performance comparison with a servo drive for the case of a ramp like motion (for details see [26]), some data: The cylinder areas are 1.2 and 0.6 m² and the dead volume in the piston chamber is 150 *l*, which is sufficient for a good pressure attenuation in case of a phase shifted HBC configuration. A typical velocity for positioning the piston is 4 mm/s, which requires a flow rate of about 300 l/min in this case. Such large flow rates cannot be reasonably handled by a single hydraulic buck converter with state of the art switching valves. Thus, the presented simulations consider 6 HBCs in parallel, which operate at a switching frequency of 50 Hz. The pipe inductance of one individual HBC is about 2.5 m with a hydraulic diameter of 10 mm.

3   Favourable domains of early applications of switching control

Practical implementation of hydraulic switching control is a challenging undertaking despite its long history as a basic idea. It is a fairly new technology, if it has to meet today's requirements on hydraulic drives, since it needs also very advanced components and system understanding. Implementation in advanced machinery or plants requires some risk taking. The question is, which branches and areas of applications are most favourable for switching control. The authors see the following domains:

- **Metal production systems**: they require high forces, high dynamics and high precision, the conditions are often very crude, the systems, particularly in steel production, very extended. Servo-hydraulic drives show excellent performance in terms of dynamics and precision; their drawbacks are: high oil cleanliness requirements, which puts high burden on system installation and maintenance, wear of valve metering edges, drift problems concerning valve zero position, and high energetic losses, for instance due to the leakage of zero lap or under lapped servo valves, and high costs.
  Digital hydraulics and switching hydraulics are a promising alternative, to avoid some of the mentioned deficiencies of servo-drives. This requires switching valves with a fast dynamic response, and appropriate control concepts.
  Energy saving is not yet a topic of utmost importance. But there is a gradual increase of awareness of customers and, may be, stronger legislative regulations in the one or other field. In steel production, for instance, the political pressure to reduce CO_2 consumption and the fact that the core processes, like blast furnaces or steel making by basic oxygen furnaces are already highly optimized processes put some pressure on other energy consuming processes, like the many mechanical drives and actuators, even though their relative share of total energy consumption is very low.

- **Agricultural machinery**: there is an ongoing trend of mechatronization; this affects also drives and actuators; in [27] the example automatic level control system of a pick-up employing hydraulic actuation is presented; agricultural machines technologies must be low cost, capable of standing the often hard operating conditions, and very service friendly. Switching valves are definitely much more robust than servo or proportional valves and cheaper. An important aspect is also standardization of components leading to a smaller range of product variants which is a major condition for low cost production; this is highly supported by switching control since impedance forming is done by other means but the valve's nominal flow rate or the spool position.
  Energy saving is definitely an aspect of high relevance in future; firstly, to save fuel costs, but secondly, to enable higher actuation functionality under the given power limitations of the tractor's engine or the power transmissions. Currently, there are initiatives (for instance, [28]) to install high voltage power supply systems to overcome power limitations of mechanical and hydraulic transmissions between tractors and implements and to improve efficiency. This should be a strong motivation to think about new concepts for hydraulic drives for such machinery.

- **Tool machines**: Hydraulic servo drives have been a dominant technology in tool machines till the upcoming of modern speed variable electrical drives. Hydraulic drives have lost ground and are mainly limited to such drives where either very high forces or high compactness are required. There is a trend toward hybrid drives, combining speed variable electrical motors with a hydrostatic transmission (see, e.g., [29, 30]) for high load applications. The hydrostatic transmission provides force amplification but can also provide, for instance, gear shift, load holding, and fast emergency stop. In such symbiotic drives switching, if needed, fast switching, are basic operations. Particularly in the latter case, typical components and hydraulic processes of hydraulic switching control become relevant. In [31] a hydraulic micro positioning drive for tool machine applications is mentioned. Even though this particular case employs servo valve technology for control, switching control is an interesting alterative in terms of cost, compactness, and robustness. In particular compact actuators will gain more importance for increasing the functionality of tool machines under the condition of already very complex systems which leave little room for additional components. For the success of hydraulic actuation in this field new solutions for the complete hydraulic system must be found. The objectives are to get an overall compact and modular actuation system for functions with high forces, little room space, ultimate response, and high robustness. Hyrid combinations with electrical drives are also a direction of novel advantageous drive solutions which would benefit from advanced digital hydraulic components.

4   Conclusions

Hydraulic switching control is an alternative to existing analog control techniques with several advantages. In contrast to many other hydraulic innovations it requires a whole bunch of innovations for a successful realization: principles, components, and a new system design approach which considers the coupling between dynamical processes, hydraulic pulsation, mechanical oscillation acoustic noise and the design of the system. If a critical mass of such innovative elements exists and can be obtained from several vendors, a rush of digital hydraulic systems will occur. This and the energy saving options will enable new functionality for several machine systems at fairly low cost and with adequate performance. Also electro-hydraulic hybrid drives and actuators will benefit from advancements of hydraulic switching control, both on the components and on the system level.

Acknowledgement

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