Hydraulic Switching Control for Modern Drives and Actuators

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Abstract: : Digital hydraulics – the control of a hydraulic system by on-off valves – has a sub-class doing control by the repeated operation of a single or a few valves at relatively high frequencies, e.g., by pulse-width modulation. This class is called hydraulic switching control. The more prominent are switching converters, sometimes called switched inertance hydraulics. However, numerous other concepts for switching controls have been proposed, studied, or are already applied in practice. They offer different advantages, such as for instance low cost, simplicity, high precision, or energy efficiency. This paper provides examples of such drives, starting from the hydraulic buck converter to quite specific solutions as a micro-positioning device or a hydraulic stepper drive. It also discusses to which extent such drives can support embedding within a cyber physical environment, or an "Industrie 4.0" environment, respectively.

Keywords: hydraulic, switching valves, switching control

1 Introduction

Over a considerable while now hydraulic drives have been gradually losing their strong position in many areas of machine building, on-road and off-road vehicles, and aerospace; more and more they have been replaced by electro-mechanical drives which over the years have gained high dynamical performance and offer several striking advantages. There is definitely a widespread view that hydraulic drives are out-dated technology which cannot cope with any of the modern challenges, such as energy efficiency, ease of control, planning, installation, maintenance, or adaptation to actual or future requirements imposed by "Industrie 4.0" or Cyber-Physical environments.

This loss of importance is quite often lamented by fluid power people from industry and academia, arguing that the strong advantages of hydraulic drives are unclearly seen and honoured by machine builders.

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In [1] Peter Achten accuses the fluid power industry of low innovative strength. He adopts the main figure of Franz Kafka's novel "The Trial" to demonstrate the guilt of the fluid power industry regarding its blindness to clearly see this alarming situation. In [2] the author of the present paper and two fellow campaigners discuss the role of digital fluid power for a strong innovative push in hydraulics, as requested by Achten.

In a workshop on "Smartness and Fluid Power" at the last Digital Fluid Power Workshop in Linz participants discussed which properties are requested by users to make fluid power more competitive. The word "smartness" seems to reflect the attractiveness of modern products for users much better than hard technical properties such as efficiency, power to weight ratio, force density, or bandwidth. Such tough performance terms stress the engineers' rather than the users' viewpoints. Even though this workshop did not deliver a clear list of properties characterising smartness of fluid power drives it showed that many identify easy handling by the users as important features and stressed the relevancies of real applications with its specific operative scenarios. Thus, there are hardly any universal but rather context specific smart solutions. Typically, a drive system has two user categories: the machine builder, who has to select and integrate the drive, and the final machine user. Unspoken, thus only implicitly addressed, "Industrie4.0"/ Cyber-physical Systems aspects play a role in the background. The main reason why these issues are not explicitly addressed in such discussions is probably that they can have so many facets and are rather intangible from a generic viewpoint. The machine and plant builders seem to expect that the consideration of these system aspects will be challenging and a prerequisite for the effective and efficient realisation is that subsystems, such as drives and actuators, can be handled in a simple way. This relates to hardware, control, and software aspects, all are interlinked and their modelling will be part of this game.

When the author started his research into hydraulic switching control more than two decades ago, he considered it a new generic concept and targeted mainly the solutions of efficiency, reliability, and cost problems of hydraulic servo drives.

Of course, the broad application of switching control in modern electrical drives has been the main motivation for trying out this concept in hydraulics too. Several projects with industry for the development of fluid systems (not only drives) for specific purposes and his observations of the modern developments successful in industry have taught him that there is no universally superior solution. More often, case-specific concepts which combine fluid power with mechanical or electrical components in a clever way are the more competitive. Of course, smartness in the sense of ease of realisation of "Industrie 4.0"/Cyber-physical Systems solutions will gain more and more relevancy.

Therefore, in this paper hydraulic switching control is widely treated within the context of some applications. The expected or realised benefits, the challenge towards the realisation of a practicable system, the limitations by state of the art components, where applicable, "Indutrie4.0" related aspects, and an outline of required additional R&D work are given.

2 Proven practical applications of hydraulic switching control

This section shows that switching control is an established technology in some areas and not a fully novel approach. It can be seen by the the most evident proof that switching control can work in practice and should help to overcome fundamental objections against this technology.

2.1 Anti-lock braking system (ABS)

ABS has become a standard car technology over recent decades. Control is done by two switching valves per individual brake operating with a switching frequency of some tens of Hertz. This ABS system is a natural upgrade of classical hydraulic brake actuation and a very low cost solution. The pulsation volume during valve switching is not disturbing but a useful alarm signal to the driver of a critical state.

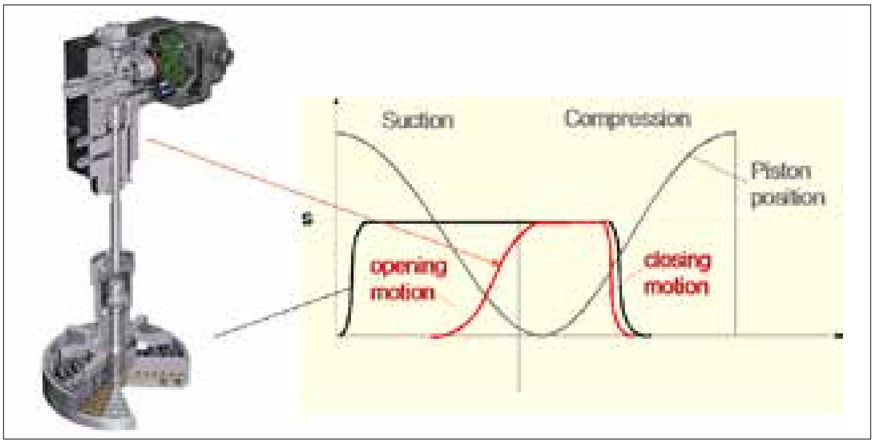

Figure 1. *Hoerbiger HydroCom: hydraulic actuation of a compressor valve for fast control of compressor delivery*

Switching control firstly keeps cost low and secondly facilitates a simple control in view of the unknown friction conditions between tyre and road. Continuous valves would be more expensive and control would have to be bothered with hysteresis, zero-point offset, and leakage. The valves are maximised for low cost, not only regarding themselves but also for low cost assembly of the modulator unit.

These facts have made hydraulic switching control the superior technology for ABS, at least so far. It is probably the better known successful application of switching control and, hence, an archetype for many other applications.

2.2 Compressor valve actuation (Hoerbiger HydroCom)

Large compressors are driven by large AC engines or by gas turbines and power requirements might be within the Megawatts range. Fast control of compressor delivery by engine speed variation is infeasible. Therefore, delivery is controlled by an actuation of the suction valve. This is basically a check valve, in many cases a ring type valve as invented by Hans Hörbiger in 1895 [3]. As shown in *Figure 1*, a compact hydraulic actuator pushes the plate valve open for some while to reduce the compression phase and reduce the delivery in this way. In order to limit losses a very fast closing motion within a few milliseconds is required. In order to avoid excessive wear of the valve plates, a soft landing has to be realised. This is typically done via some passive hydraulic cushioning mechanism.

Hoerbiger recently launched a purely electrical version for this actuation, called eHydroCom [4]. It avoids some disadvantages of the standard HydroCom, namely the need for a hydraulic supply unit and for the supply lines from this unit to the actuators in the forms of hoses. Hose maintenance efforts, oil as a burnable substance within the environment of dangerous gases, and the space requirements for the whole hydraulic power supply equipment are additional burdens of the HydroCom motivating customers to prefer the electrical solution.

Figure 2. *Hoerbiger eHydroCom: electric actuation of a compressor valve for fast control of the compressor delivery [4]*

The separate supply unit and the supply lines are frequently argued against hydraulic drives. This development from the hydraulic to the pure electrical solution tells that the whole system must be seen. Integrated drives, where the actuator, the electric prime mover with the pump, the lines, valves, the tank and all other auxiliary components assembled in one compact actuator module could be an answer. Such solutions can be very competitive as the hydraulic scheme can realise certain functions much easier than an electro-mechanical drive.

■ 2.3 Hydraulic micro-positioning

In [5] a hydraulic micro-positioning drive for milling machines is presented. It was developed for a special multi spindle milling machine of Anger Machining [6]. The latest version can position two separate

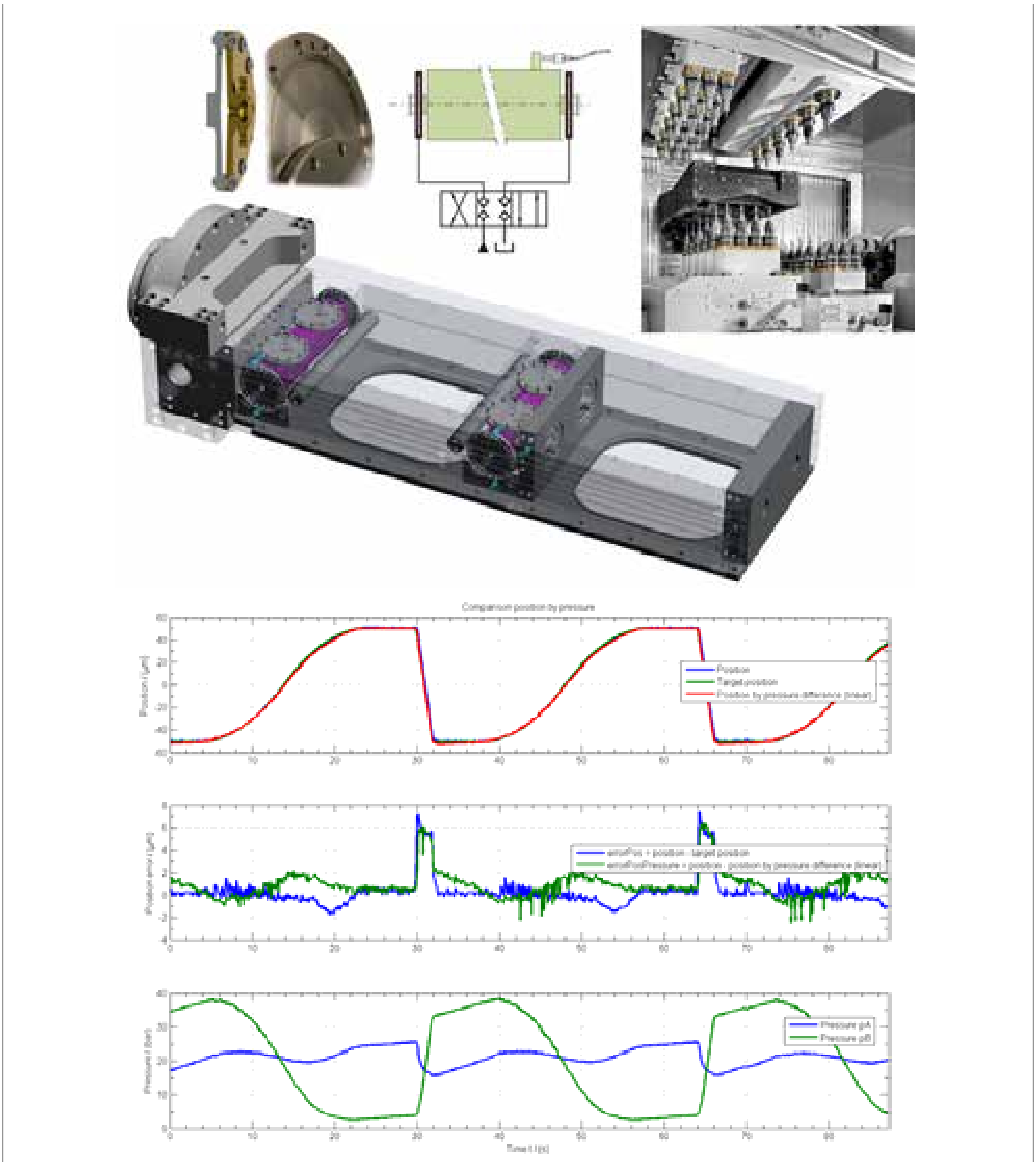

Figure 3. *Hydraulic micro-positioning system; provides µm precise positioning of the work-piece; the uppermost diagram shows that there is an excellent correlation between the position and pressure differences of both membrane cylinder chambers*

work-pieces relative to the work-piece holder in order to compensate for tolerances of the individual milling or drilling tools and spindles, respectively, or of the work-piece clamping system.

The basic mechanism of this precise system consists of two membrane cylinders (see sketch in Figure 3) which are hydraulically actuated by switching valves. Performance figures of this system from some test cycles are also given in *Figure 3*.

The first hydraulic micro-positioning system exploiting the membrane cylinder concept has already been realised in 2012 but servo valves were used for control. This system is in industrial operation in the car industry. Also a piezoelectric positioning system was evaluated, as offered by a leading company for such technologies. This evaluation by Anger and by its customer, a major German car company, gave clear preference to the hydraulic system because of higher stiffness and lower cost.

The digital hydraulic concept had already been envisaged back then but available development time was too short. The digital system, as developed recently, has several striking advantages:

- no leakage; offers the option to use a decentralised power pack to avoid complex piping and hosing,
- higher precision,
- no zero point drift and hysteresis problems,
- lower oil cleanliness requirement.

The potential cost reduction of the whole micro-positioning system is the replacement of the position sensor by a pressure difference sensor. The first diagram in Figure 3 shows a test of this concept by measurements which clearly demonstrate the feasibility.

This micro-positioning technology could contribute to the realisation of "Industrie 4.0" ready machines by the following items:

- automated fast error correction as a basis for lot size one production,
- faster machine ramp-up with automated machine setup,
- condition monitoring and predictive maintenance of the machine by observation of changes in the machine setting (spindle positions, ...),
- realisation as an integrated module.

3 Hydraulic switching converters

From a fundamental scientific viewpoint hydraulic switching converters are of high interest. Considering that the hydraulic ramp invented by Joseph Michel Montgolfier in 1796 is a hydraulic switching converter, all the actual work on this technology are just attempts to realise such principles for modern drive conditions with advanced components.

3.1 Converters exploting fluid inertia

Most modern work on switching control, which started with that of Brown and co-workers in 1987, see [7, 8], employs the hydraulic inductance (or inertance) of a fluid in a tube for storing the energy surplus resulting from pressure differences between input and output lines. Numerous research groups are dealing with the subject of addressing system simulation, experimental investigation, component development, and control. [9 to 19] are a representative collection of relevant work.

In a recent master's dissertation [20] at the author's institute, a multi hydraulic buck converter (MHBC) was investigated. The idea of using several converters in parallel and running them in a phase shifted mode was first presented in [14]. *Figure 5* sketches the concept and shows some computational results from this study.

It shows that pressure pulsation of a phase shifted operation of N parallel converters is of the order O ($1/N^2$) only. That fact will most likely make load-sided accumulators for pulsation attenuation obsolete, an important advantage which has been experimentally confirmed in [20]. A corresponding pressure plot of the high and low pressure supply

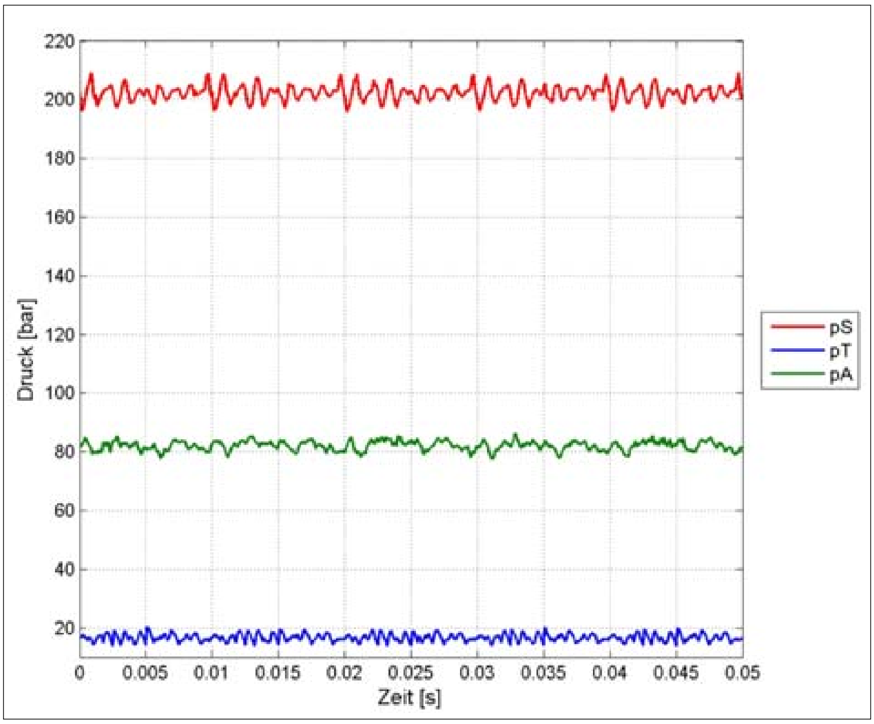

Figure 4. *Pressure curves of supply lines (pS, pT) and consumer line (pA) for a N=4 MHBC without an accumulator for pulsation attenuation at the consumer side; result taken from [20]*

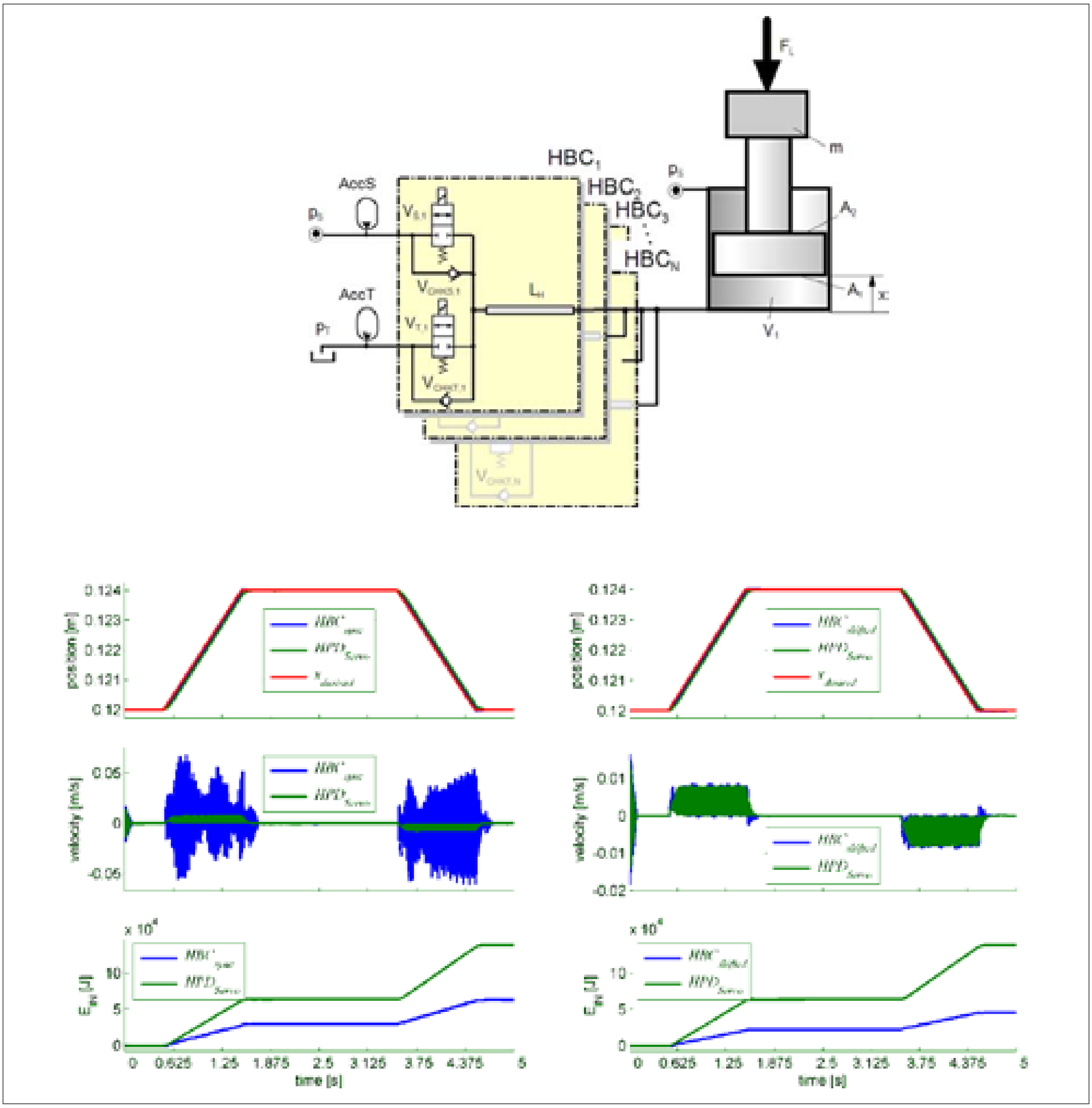

Figure 5. *Hydraulic linear drive controlled by N hydraulic buck converters; schematic and simulation results for N=6 and a switching frequency of 50 Hz of each individual buck converter*

lines and the consumer port in *Figure 4* confirmed this theoretical finding experimentally.

The parallel arrangement has further striking advantages:

- Redundancy: if one HBC unit fails the remainder can still run albeit with some performance loss.
- Standardisation: standard HBC units can be optimised and manufactured to achieve high lot size production and low cost; any number of HBC units can be combined to achieve the required maximum flow rate or redundancy.
- Both advantages may be relevant for "Industrie 4.0" production systems. In a lot size one production a machine should not fail during production of this one piece, particularly, unless these are large pieces requiring lengthy operations. Standardisation of components and sub-systems facilitates their model based planning and control as well as the handling of virtual models used within the cyber domain.

3.2 Converters with a solid inertia element

Using a fluid in a tube as inertance element has two main disadvantages:

- Wave propagation in the inertance element limits the attenuation of pulsation due to fast switching and, if standing waves are excited, losses increase and

cavitation may be provoked.
- The inertance elements are lengthy; curling of the pipes to a coil leads to additional energetic losses and reduces efficiency (see [12]).

In [21, 22] an energy saving switching converter is studied which uses the inertia of a piston. If this piston is connected with a spring and operated close to the resonance frequency of that spring mass system, it is an ideal flow rate controller, as the average flow becomes independent of the consumer pressure. In this case it is called a hydraulic resonance converter following the naming convention in power electronics which uses an analogue concept to drive resistive loads.

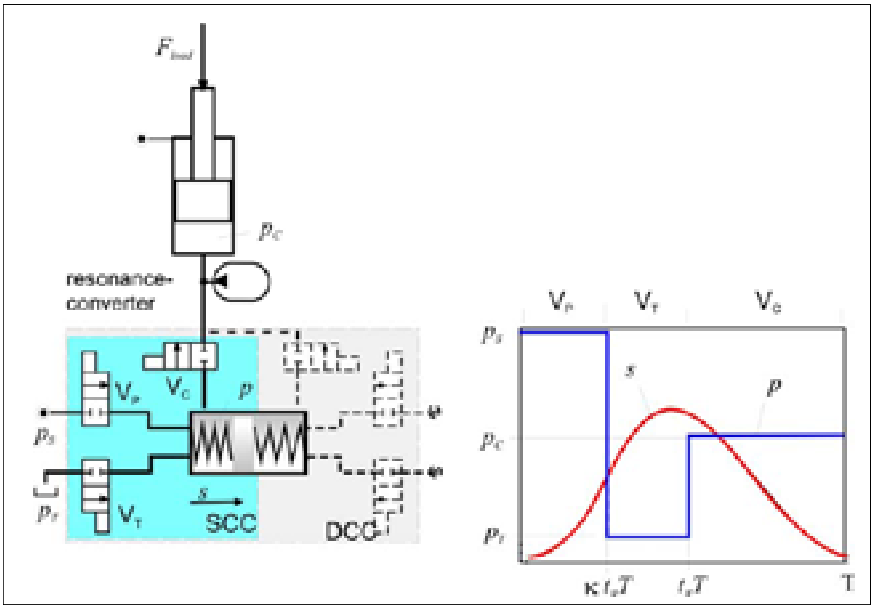

Figure 6. *Schematic of a 'Single chamber' (SCC) and a 'double chamber' (DCC) resonance converter and idealised piston motion and pressure curves*

It follows from a simple dimensional analysis of the mechanical state equations that the required mass drops with the square of the operating frequency. Very compact sizes for usual hydraulic system pressures are obtained for 200 Hz. The concept is shown in *Figure 6*. This symmetric concept has six switching valves. It can also operate as a boost converter, thus generating output pressures p_C higher than the system pressure p_S. Basically, this converter avoids losses due to fluid compressibility, hence higher efficiencies than with fluid inertance should be possible. Promising efficiency results have been found experimentally and theoretically in [21, 22] but for very low operating frequencies within the range of only 15 to 20 Hz as no fast switching valve was available at that time. Of course, similar to the MHBC several of such converters could be placed in parallel to avoid a load-sided accumulator and to realise drives with high stiffness.

There are other modes of operation, e.g. in a pulse frequency control mode or as a hydraulic stepper drive [23, 24]. The stepper drive is intended for realising sensor-less positional control. It exploits a displacement piston which always performs a full stroke from one end stop to the other in order to discharge a precise fluid quantity to the output, e.g. to a plunger cylinder. Schematics for realistion with and without energy saving are given in *Figure 7*. Many more schematics exist for realising this principle. Currently, the author's research group is developing a non-energy saving stepper drive for sensor-less positional control for special machine tool applications with positional accuracy of ±5 *μ*m [25]. It should facilitate a first time correct production even with some varying product properties such as dimensional and material strength date variations, a clear improvement helping to realise "Industrie 4.0" type production.

The master's dissertation [24] deals with the model- based design of an energy-saving stepper drive prototype and the experimental investigations. The mechanical design and some results are shown in *Figure 8*.

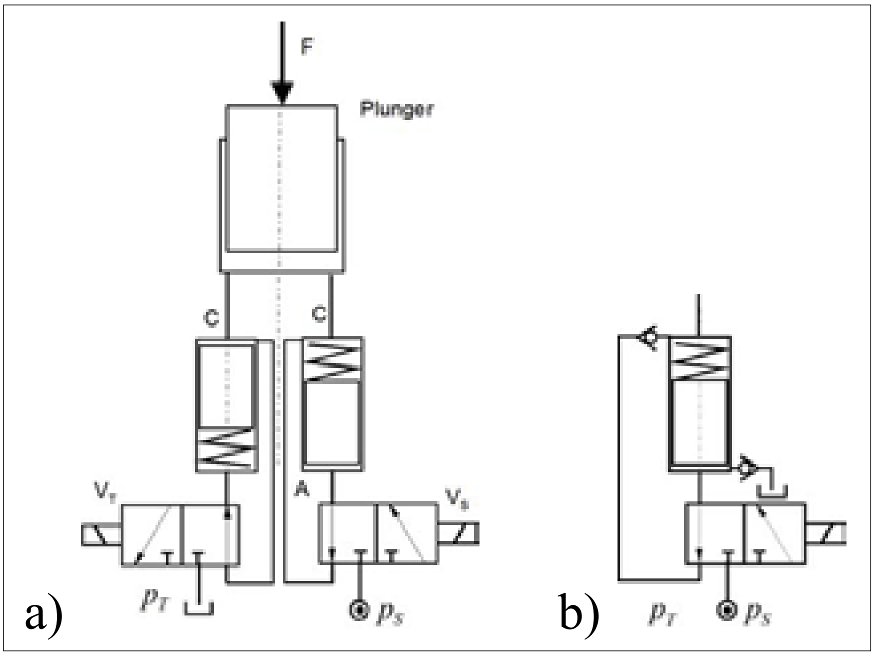

Figure 7. *Hydraulic stepper drive: a) non-energy saving; two stepper units to accomplish stepwise motion of the plunger in both directions; b) energy saving stepper unit (unidirectional)*

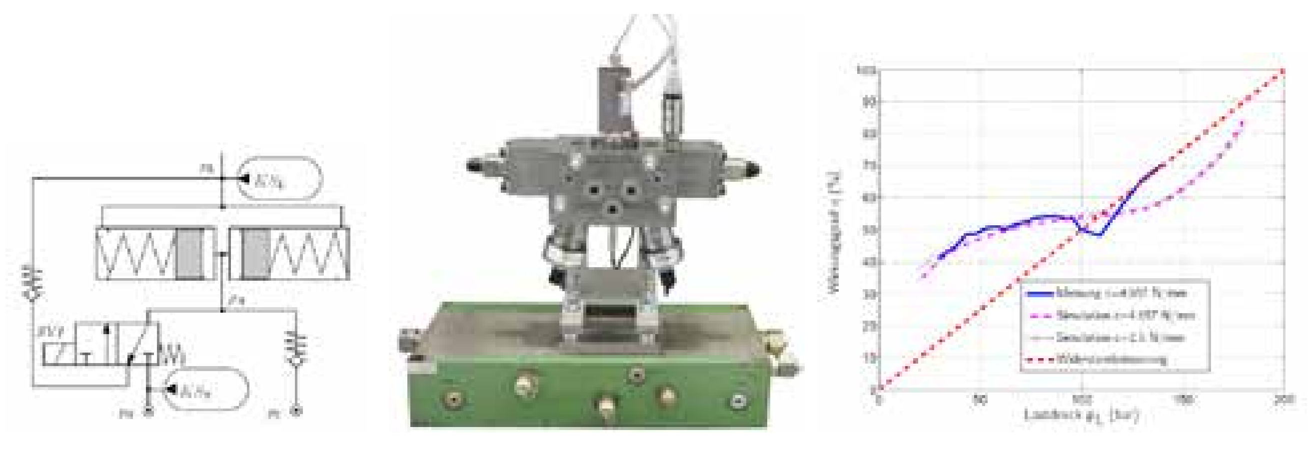

Figure 8. *Hydraulic stepper drive - energy saving variant: counteracting pistons balance linear momentum; hydraulic schematic, prototypal realisation, and simulated versus measured efficiencies*

4 Components for hydraulic switching control

Everyone doing some R&D in switching control will face the problem of missing sufficiently powerful switching- and check-valves as well as accumulators. Many of these people do some work on component development as well. This concerns mainly the fast switching valve, undoubtedly the key component not only for switching control but for all kinds of digital fluid power. In switching control the performance criteria are the switching time and frequency, nominal flow-rate, maximum flow-rate, durability (number of switching cycles), electrical actuation power (average and peak values), noise, compactness, and repeatability. Drastic improvements with respect to all these criteria are necessary to reach a satisfactory state.

Over the last ten years there have been numerous attempts by academia and some from industry and the situation is definitely much better than before. However much still needs to be done to reach a state where switching control development is not strongly limited by available key components. [26] discusses the requirements for digital valves and gives some overview about their advancement over recent years. A very big step forward concerning available large and fast valves was reported at the recent 14th SICFP Conference in Tampere in [27]. A new switching valve, named HPV Gen2, which features a nominal flow-rate of 150 l/min at 10 bar pressure loss and a switching time of 3.5 ms; it is currently available as an A-sample.

5 Potential application of switching control in machines, plants, and vehicles

The main motivation for using switching control will differ from case to case. The potential advantages are:

- energy saving and energy recouperation,

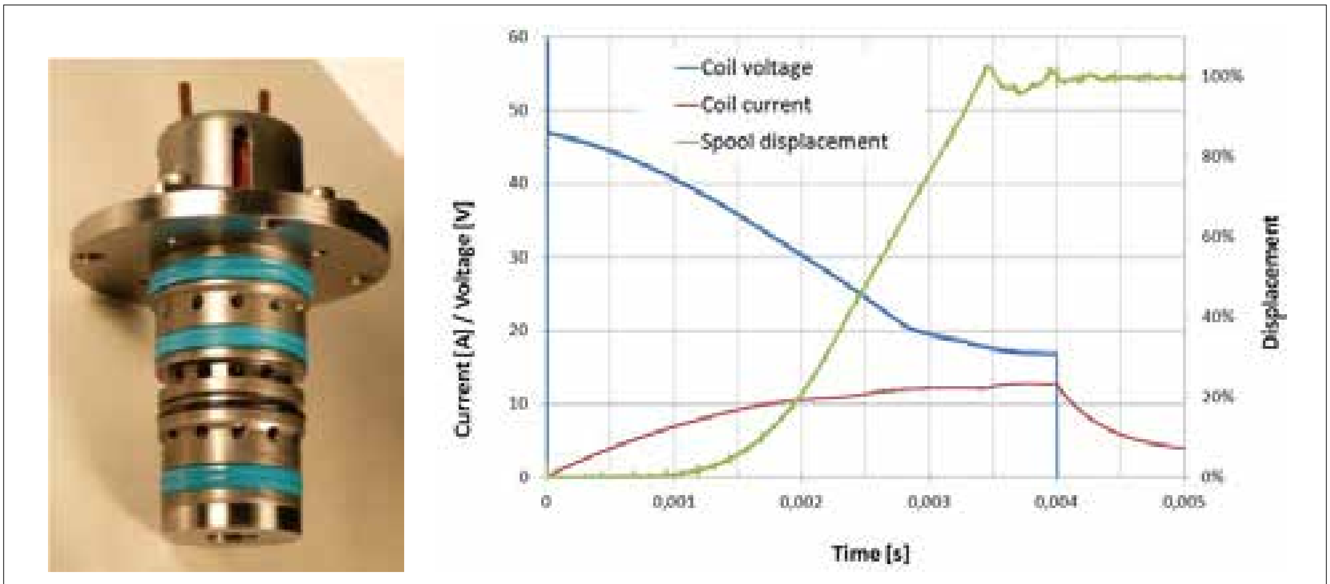

Figure 9. *Recently published Bosch Rexroth switching valve HPV Gen2 as an A-sample; valve has a nominal flow-rate of 150 l/min at 10 bar pressure loss [27]*

- less oil cleanliness requirements,
- easier control, for instance by avoiding zero point drift or hysteresis,
- cost savings,
- compactness,
- lesser number of valve types needed: better standardisation and easier spare handling.

Not all the advantages can be realised in every specific application. In practice the advantages must be really convincing to outweigh the risks which applications of new technologies always entail. The following examples are the author's appraisals of the applicability of switching control. They should show in which way switching control can realise one or more of the mentioned advantages, giving the machine-, plant-, or vehicle-builder and their customers a benefit.

5.1 Agricultural machines

In agricultural machinery there is a trend towards:

- better motion control in terms of speed, precision, and operating band-width,
- despite the current efforts to establish electrical drives for implements, hydraulic actuation will also have a prominent position in the future,
- further general progress relies on an advanced 'mechatronisation' of farming technology, i.e., on the availability of proper sensors, measurement devices, controllers, process models, communication systems, drives and actuators. Proper means of sufficient technical performance, low cost, ease of installation, durability and maintainability under the given harsh operating, stabling, repair shops and service personnel expertise circumstances, compactness, and standardisation of interfaces, to name just a few.

A drive or actuator technology alone cannot make a successful solution without the other components required to realise a certain wanted functionality. Cost and robustness are very tough requirements. Cabling and connectors are potential sources of machine failure and, possibly substantial cost factors. This requires care in design, assembly, and maintenance. Sensor avoidance, where possible, is an important cost saver and robustness improver.

Energy costs are economically relevant for such drives and actuators which consume major shares of energy. Another aspect is peak power and from which energy source it is covered. If the power limit of the tractor is largely consumed by the main operating processes of the tractor and the implement, the power required by additional functions for advanced motion control might exceed the power limit. Then, an energy efficient actuation system for that motion control will be important not because of energy cost reasons but to realise a desired performance under practically existing power limitations.

In a master's dissertation [28], a doctoral thesis [29], and a publication [30], automatic level control of mowing and harvester pick-up devices, respectively, were investigated. In both cases hydraulic switching control was applied. In [28] standard industrial switching valves were used powered by booster electronics to speed up switching. In [29] excellent dynamical performance could be demonstrated with a novel switching valve, developed by a student. Level control of such devices requires the same distance to ground sensor. For the harvester this sensor should measure the ground profile over the working width of the harvester even below the swathe and furthermore be able to detect obstacles in the swathe such as big stones or animal cadavers. So far, this technology is not been realised in practice because appropriate sensors and low cost switching valves with adequate performance are as yet unavailable.

5.2 Production machines

The prominent application areas of hydraulic drives are presses. Numerous hydraulic concepts are in use. Digital cylinder drives are discussed for large presses in [27, 31]. In both cases, the gap between the discrete force levels of the digital cylinder system are compensated by continuous elements; in [27] by a proportional valve in [31] by a variable displacement pump. The latter drive is intended for very large forces (~10 MN) and powers (several MW).

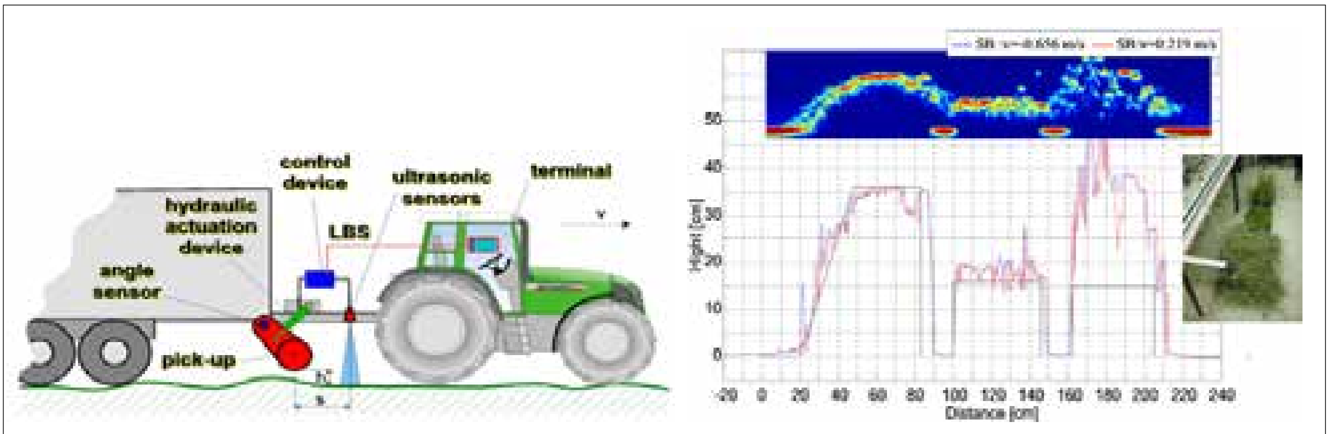

Figure 10. *Automatic level control of a harvester pick-up [30]*

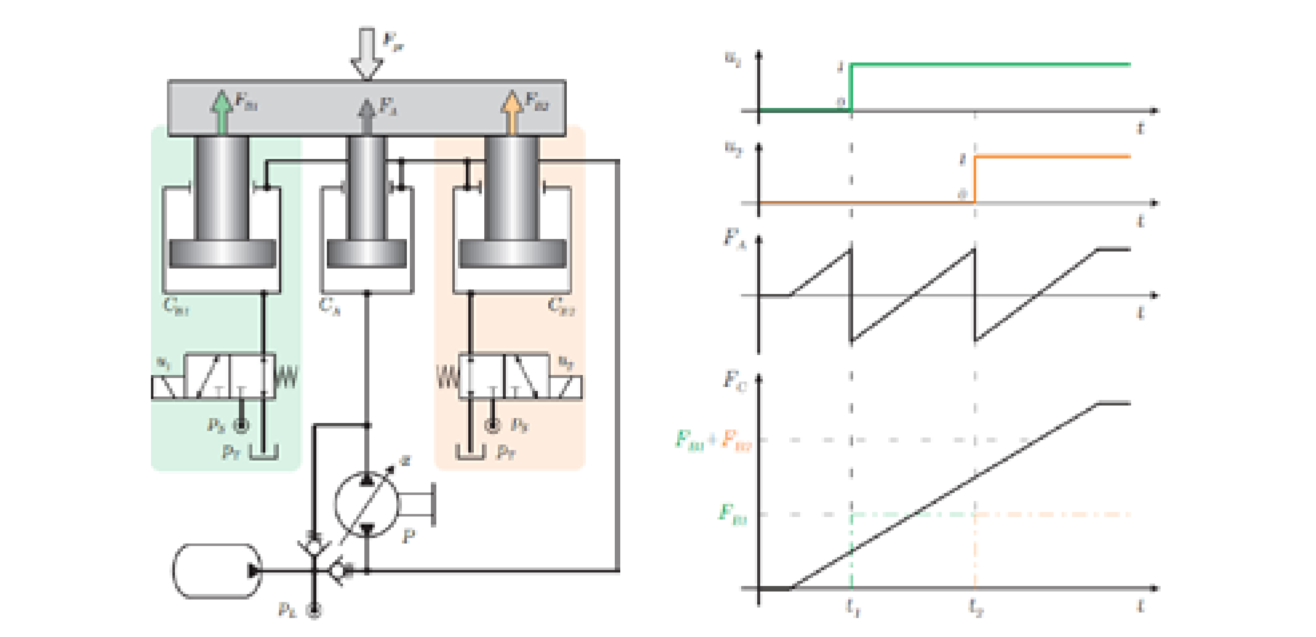

Figure 11. *Concept of a hybrid press drive; if required, booster cylinders are switched on to increase force [31]*

Pure primary motion control by variable displacement pumps requires a significant amount of large pumps on site, which is unfavourable and costly. The basic control intends primary pump control to define the motion and the digital (booster) control to generate high enough forces. This is an example of a mixed continuous and digital control. The concept is only useful if extreme forces and power are required.

In Section 2.3 a micro-positioning device for a milling machine was described. Hydraulics could be also be used to compensate other unwanted effects such as for instance, load or thermally induced deformations of machine tool structures or oscillations, such as mill chatter. For the latter passive, semi-active, and active hydraulic methods might be employed. Switching control could be an option, e.g., in the form of the hydraulic stepper drive mentioned in Section 3.2 to save a positional sensor. Even for dynamic problems (e.g., mill chatter compensation) switching control could be used, e.g. to adjust the parameters of a passive compensator in a simple way.

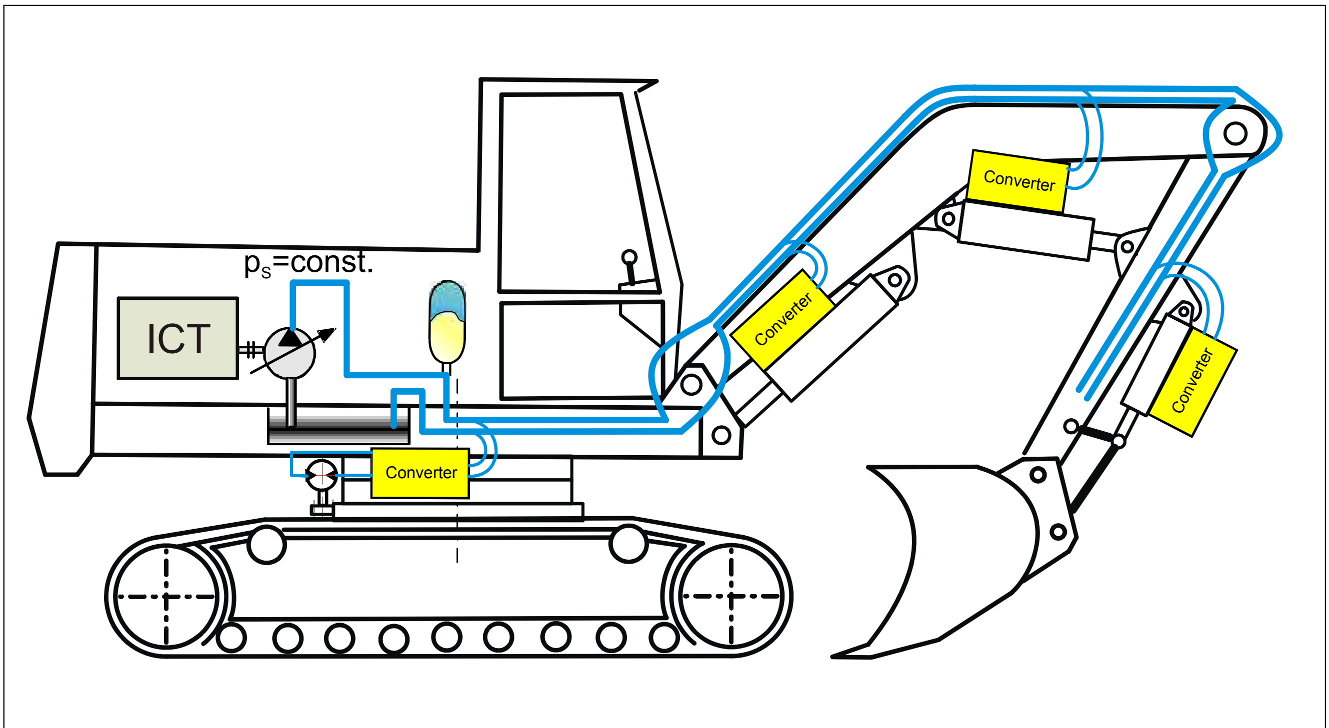

Figure 12. *Constant pressure supply system with energy efficient switching converters for an excavator*

There is no generic hydraulic switching control concept for a wide class of problems in machine tools but definitely many opportunities for realising superior solutions in specific cases.

5.3 Vehicles

Earth moving machinery is an important branch for hydraulics. Energy saving, low cost solutions for smaller machines, high productivity for larger machines, and the compliance with exhaust emission standards (Tier regulations) are the dominating requirements of the current development. Several hybrid concepts also including electrical drives are under discussion. The potential energy or fuel savings from such concepts would be small (see, e.g. [32]).

From a conceptual viewpoint a constant pressure supply system with hydraulic transformers (or converters) for feeding hydraulic power to each consumer with low losses and energy recouperation ability is the conceptually simplest solution. Accumulators can store the energy, the prime mover (diesel engine) can run under optimum conditions which save fuel and favour low emissions, and high power is quickly available when needed, which improves productivity. Such a constant pressure supply system was proposed by P. Achten (see, e.g. [33]) for passenger cars with displacement machine type transformers. For excavators' switching converters such as the hydraulic buck- or resonance-converter, are attractive alternatives. A simple concept and straightforward control for the different actuators can be realised. Peak power can be taken from the accumulator, which serves mainly as device to store recuperated energy. This lowers the power requirements on the prime mover (Internal Combustion Engine). However, a practical application requires several conditions to be fulfilled; the more important are:

- cheap and robust components (fast switching and check valves and accumulators) must be available,
- total machine investment costs to be only marginally higher and an economic benefit must be obvious, e.g. fuel cost savings, productivity increase,
- robust systems which can stand the harsh operating conditions of such machines,
- no other degradation compared to the state of the art such as for instance noise level.

These requirements are currently not met. Particularly cheap and practically proven key components are missing.

6 Conclusion

This paper gives some overview about hydraulic switching control. Several applications have existed for years whilst others have been around for a short time. Many more concepts have been proposed and investigated but have not yet been applied because of insufficient components or missing system understanding.

Hydraulic switching control is not a silver bullet which can solve all existing problems in hydraulics and which will largely replace known solutions. It can be successful in several cases, provided the required components exist; a good concept is selected, and fits well to the remaining parts of the system. For switching control Bob Koski's general statement [34] about the main success factor for hydraulic drives is probably also valid: "The sake of hydraulics depends much more on qualified engineers in the machine, plant, and vehicle building industries who have sufficient hydraulics know-how, than on the innovative strength of fluid power industry." The hydraulic schematic, the control concept, the required operation scenarios, the sensor and communication systems, human machine interfacing, must be coherent with the performance and cost requirements, to obtain a superior solution.

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Digitalna hidravlika na sodobnih pogonih in aktuatorjih

Razširjeni povzetek: Digitalna hidravlika je koncept izvedbe regulacije hidravličnega sistema, za katero je značilno ponavljajoče se vklapljanje enega ali več paralelno vezanih dvosmernih, dvopoložajnih (on/off) ventilov ob relativno visokih frekvencah in uporabi npr. pulznoširinske modulacije. Ta koncept regulacije, ki danes predstavlja alternativo tradicionalnemu krmiljenju s servo- ali proporcionalnimi ventili, zaradi tega imenujemo tudi hidravlična preklopna regulacija. Razen običajnih vklopno delujočih hidravličnih pretvornikov so bili ti sistemi obravnavani v številnih študijah in raziskavah. Zaradi prednosti, kot so npr. nizka cena, preprosta izvedba, visoka natančnost ali energetska učinkovitost, se tovrstni koncept regulacije uspešno uporablja tudi v praksi. Predlaganih in tudi raziskanih je bilo veliko različnih konceptov te tehnike, a se v praksi niso uveljavili zaradi trenutno še neprimernih gradnikov ali pa zaradi pomanjkanja razumevanja delovanja in prepoznavanja njihovih potencialov.

Prispevek sistematično podaja pregled najpomembnejših primerov uporabe tovrstnih vklopno delujočih pogonov: od običajnega hidravličnega vklopnega pretvornika do specifičnih rešitev, primernih za uporabo v napravah za mikropozicioniranje ali v hidravličnih koračnih pogonih. Podan je tudi odgovor na vprašanje, v kolikšni meri so tovrstni pogoni primerni za uporabo v t. i. kibernetsko-fizičnem okolju in v okviru koncepta »Industrie 4.0«.

Nekateri predstavljeni primeri tovrstne tehnike so znani in se uporabljajo že dolga leta, druge uspešne aplikacije so se pojavile šele pred kratkim. Med prve zagotovo sodi že dolga leta uporabljan ABS-sistem, ki je v zadnjih desetletjih postal del standardne opreme avtomobilov. Med uspešne aplikacije iz zadnjega obdobja pa zagotovo sodi uporaba digitalne hidravlike na področju aktuatorjev ter stacionarnih strojev in naprav: izvedba krmiljenja aktuatorja kompresorskih ventilov ali pa npr. modula za hidravlično mikropozicioniranje na obdelovalnih strojih. Vse bolj obetavna pa je uporaba tovrstne tehnike na področju poljedelskih in gradbenih strojev in ostala področja stacionarnih strojev in naprav, še posebej hidravličnih stiskalnic, vključno z različnimi pretvorniki in koračno delujočimi aktuatorji.

Ključne besede: hidravlika, preklopni ventili, preklopna digitalna hidravlika