# THE CAPABILITY OF HYDRAULIC CONSTANT PRESSURE SYSTEMS WITH A FOCUS ON MOBILE MACHINES

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*The objective of this paper is to sign out capabilities of the constant pressure (CP) principle as an alternative to the established Load Sensing (LS) principle in mobile machines. Examples of recent applications are illustrated and a method to estimate potentials for a successful implementation is presented. The reasons that avoided a widespread realization of CP systems in mobile machines in the past are reviewed and checked whether they are still significant.*

**Keywords: constant pressure, variable displacement unit, secondary control, hydraulic transformer, energy recuperation, mobile machines**

## 1 INTRODUCTION

Being confronted with rising energy costs due to the global need to protect the environment and to conserve fossil resources, the rise of energy efficiency is a main incentive for extensive research and development work in most technical sectors. This trend is also recognizable in the hydraulics branch where efficiency is a characteristic property of single hydraulic components as well as for complete systems.

In component design, especially in hydrostatic drives, where energy efficiency has been driven to a quite high level in the last decades, it is technically most demanding to achieve further improvement. In system engineering, it is state of the art to adapt parameters and properties of a hydraulic system during design phase to the task wherever possible.

Whereas in industry hydraulics processes are periodic and many are fully automated, in mobile hydraulics the operating conditions are much more unsteady and depend on numerous factors. Different load curves, changing operators and climatic conditions and even multiple work tasks must be considered for layout.

## 2 CONSTANT PRESSURE SYSTEMS IN MOBILE MACHINES

According to the name, operating pressure in constant pressure (CP) systems is controlled at a constant level. Using hydraulic accumulators, system pressure level is dependent on the loading conditions of the accumulators and thereby “quasi constant”. In Kordak (2003) the term “impressed” is employed as analogy to electro technology. Traditionally there is a conflict in differentiation of the terms constant pressure systems and systems with “impressed” pressure, although system properties are almost identical. In this paper the term “constant pressure” is used for grids with and without hydraulic accumulators where operating pressure is kept on a constant and almost stable level.

For low-tech applications, a constant pressure system can be achieved using a constant displacement pump and a pressure relief valve to charge a hydraulic accumulator. Stand of the art are variable displacement pumps, equipped with a pump control unit to adapt flow rate to the demand of the consumers. Hydraulic-mechanical pump controllers are still in use, but will be replaced gradually by electro-hydraulical types. With the help of hydraulic accumulators, the capacity of a system can be enlarged to bridge the time gap which is needed to manipulate the variable displacement unit. Unrestricted parallel operation of multiple consumers is possible as long as pump swiveling unit and accumulators can balance pressure drops and until sum flow demand reaches maximum pump flow rate. Even multiple parallel pumps can be added if necessary.

Furthermore, energy recovery is enabled at CP systems. Consequence of back feeding to CP grid is a hydraulic backflow at system pressure (or above). The recovered energy can directly be provided to other consumers, can be stored in hydraulic accumulators for subsequent usage, or at the existence of technical precondition be reverted to energy supply (e.g. electric motor/generator). Because of these qualities, the CP pressure principle is employed in large scale stationary applications, for example in laboratory and industrial grids or even in aircrafts as describes Biedermann (2005). In this paper, CP systems are classified into a conventional and advanced category.

## 2.1 Conventional CP systems

The main characteristics of the conventional CP system are throttle control and relatively simple system architecture. Motions of rotary and linear actors are controlled by directional valves and by flow control valves. Due to small inertia of the slide valves and to the permanent high pressure level, conventional CP systems show a fast responding behavior and high accuracy in control. System-related losses are higher compared to LS, especially because of increased leakage due to permanent high pressure level. Depending on the load range, high losses may occur, especially if the machine works in large variations of load pressure and if the average load pressure is much lower than the setting of the pump controller.

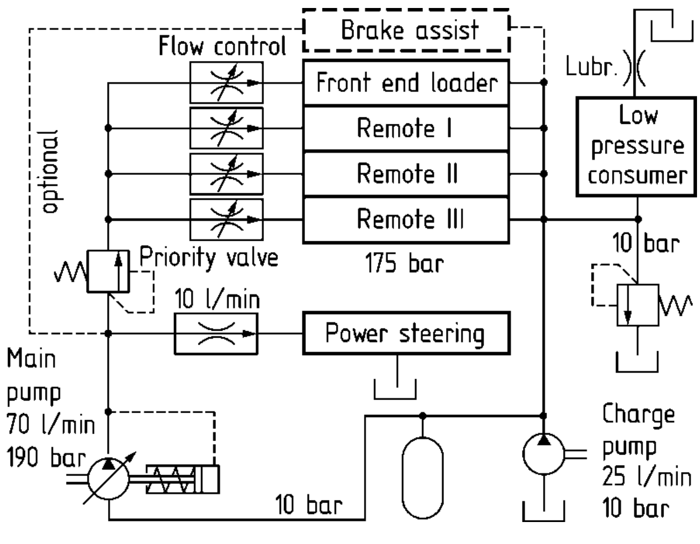


**Fig. 1:** Conventional CP system at the example of a tractor in Garbers and Harms (1980)

The gap between impressed operating pressure and load pressure is throttled at the direction valves in the lines to the consumers. Examples for the employment of conventional CP principle with variable displacement pumps in mass-produced mobile machines are John Deere tractors produced in between 1960 and the early 1990's. A typical hydraulic diagram for CP in tractor application is displayed in Fig. 1.

A recent application is represented in Bauer (2008) with the actual field chopper series Claas Jaguar. In design phase, it was considered that operating conditions for working hydraulic functions are almost constant. Some of the hydraulic functions are fully automated during operation processes (e.g. steering, height setting of the front attachment, moving of the spout) and require high dynamic responding at predominantly low flows. Regarding these conditions, in combination with the relative uncomplex and robust system architecture, CP was the adequate choice for Claas engineers.

## 2.2 Advanced CP systems

The distinguishing feature of advanced CP systems is the controlled adaption of the hydraulic consumers to the constant operating pressure. The parallel installation of throttle controlled hydraulic lines is enabled, but usually used to supply consumers with minor energy demand.
The following technologies are employed in advanced CP systems:

- secondary control
- hydraulic transformers
- the Digital Hydraulic Transformer

Secondary control is a hydrostatic drive concept to avoid throttling losses on rotary consumers operating in a CP grid. The displacement of a variable displacement motor is controlled by a mechanism, typically in speed or torque control loop, to fulfill the demand of the consumer. Multiple dissertations on the theme of secondary control have been made at the Institute for Fluid Technical Drives and Controls of the Rhineland- Westphalian Technical University Aachen, e.g. Murrenhoff (1983).

Kordak (2003) gives an overview of several secondary controlled solutions, especially in industrial applications and test stands. Using examples of a bucket wheel excavator, a lattice tower crane and a driverless transport system for containers, it is demonstrated that secondary control is adaptive for mobile applications, too.

A great number of research projects on the subject of energy recovery by secondary control, in many cases at the example of an excavator swing drive, indicate that the interest of science and industry in this subject is quite high in the past decades until today, e.g. Ji and Zhilan (1993); Kordak (2003); Petterson and Tikkanen (2009).

For more efficient operation of fixed displacement units and linear drives at CP grids, hydraulic transformers are represented in Kordak (2003) and Shih (1984) as a technical solution for infinitely variable hydraulic pressure and flow transformation (Eq. 1). They consist of a speed controlled variable displacement motor mechanically coupled with one or more hydrostatic units of fixed or variable displacement.

$$p_{in} \cdot Q_{in} = p_{out} \cdot Q_{out} \tag{1}$$

To enable better performance and reduce manufacturing costs at the same time the Floating Cup (FC) principle was developed for hydraulic transformers. Using the example of a fork lifter (Fig. 2), the FC transformer in combination with constant displacement units (traction drive) and linear motors (lifting cylinder) was analyzed in Vael et al. (2009). Simulations demonstrated reductions above 50% at primary energy consumption, prior to recuperation at the traction drive and high efficiency of the hydraulic transformer.

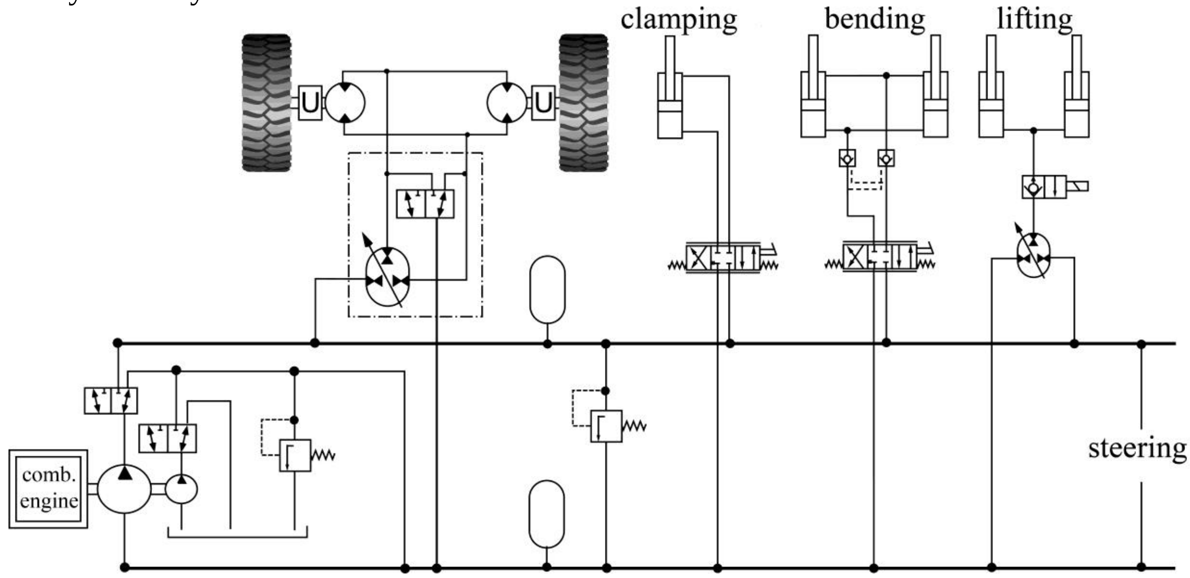


**Fig. 2:** Advanced CP system with hydraulic transformer at the example of a fork lifter Vael et al. (2009)

The Digital Hydraulic Transformer (DHT) (Fig. 3**)** as a further device for hydraulic pressure and flow transformation is demonstrated in Bishop (2009). The DHT offers the ability for energy recovery. Because of limited displacement volume during a stroke, the DHT is rather applicable for linear and swivel drives than for continuously rotary drives. The transformation ratios of the DHT are generally staged, the displayed example enables $2^4 = 16$ ratios.

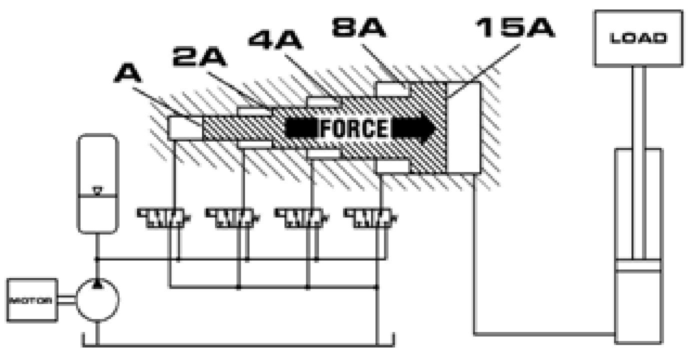


**Fig. 3:** Digital Hydraulic Transformer (schematic) in Bishop (2009)

## 2.3 Energy efficiency of advanced CP systems

Regarding the main system properties, advanced CP systems seem to be first choice concerning energy efficiency within widely-used hydraulic principles. The prevention of throttle losses at direction valves in part-load operational range (Fig. 4**)** makes CP principle very attractive at first view. Furthermore, recovery of kinetic and potential energy promises an improvement of the system efficiency.

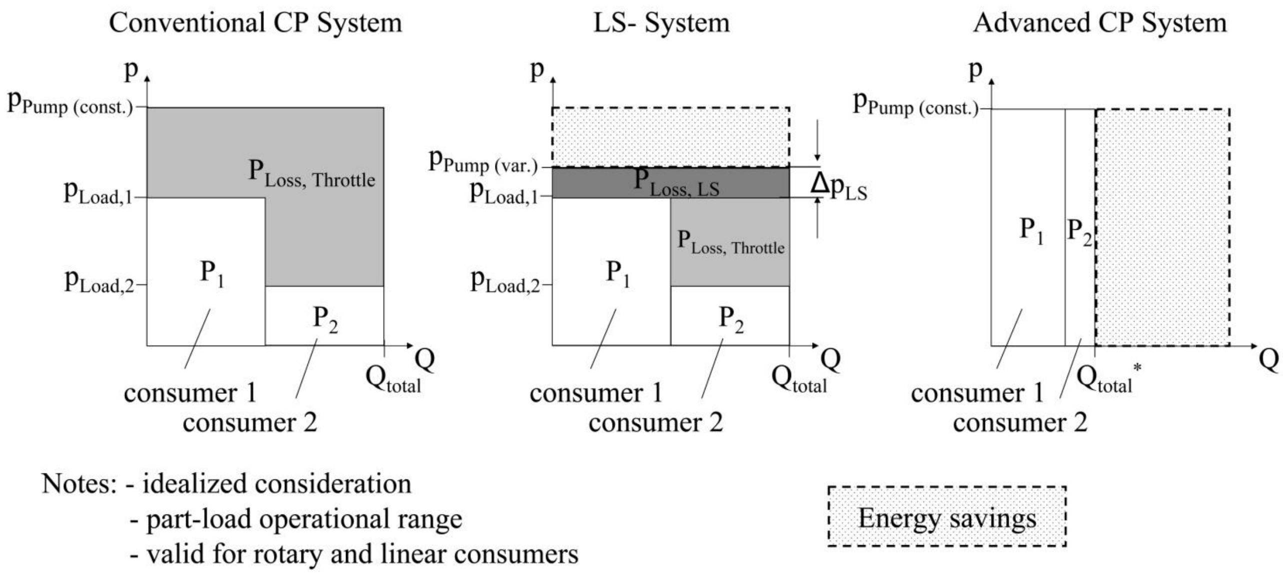


**Fig. 4:** Principle related losses at CP- und LS systems in Geimer (2009)

An advanced CP system incurs additional energy losses. Due to the permanent high pressure, increased leakage occurs at valves and drives. Hydraulic flow losses may decrease at CP principle thanks to reduced flow at increased pressure at the transportation of hydraulic power to the consumers. Nevertheless these losses still exist. Because of economic reasons, throttle control can additionally be used to operate consumers at the CP grid.

A more critical aspect employing secondary control in advanced CP grids is the energetic efficiency of variable displacement units at small swiveling angles. The efficiency map of a motor is exemplarily displayed in Fig. 5:

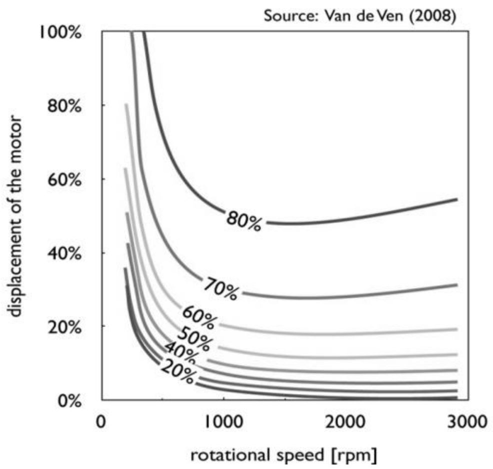


**Fig. 5:** Efficiency map of a variable displacement motor

Especially in part-load operational range, the high efficiency of variable displacement units is not maintained. The primary advantage compared to throttle controlled drives decreases because small swiveling angles at smaller power demand cannot be avoided. An approach to face this problem was demonstrated in chapter 2.3 by Vael, Achten, Inderelst and Murrenhoff. (2009) at the example of a fork lifter.

# 3 INTERPRETATION OF POTENTIALS: ENERGY SAVING IN MOBILE MACHINES WITH ADVANCED CP TECHNOLOGY

The successful implementation of advanced CP technology in a mobile machine relies predominantly on additional value for the user compared to previous technical solution. Beside performance and usability, the total costs of ownership are sales-relevant. While machine acquisition costs will increase in all probability due to additional expenses in production, the amortization must be supported by lower running costs, first of all by the reduction of fuel consumption. The required improvement in energy efficiency for the complete machine is possible at the employment of advanced CP technology due to:

- a better exploitation of hydraulic energy by reduction of system-related losses
- recovery of potential and kinetic energy.

For a rough estimation of potentials for energy saving that considers both aspects, the following method is used at the Chair of Mobile Machines:

The three factors

- EC (Energy Conversion in a hydraulic line)
- SLP (Spectrum of Load Pressures at a hydraulic consumer) and
- OB (Operating Behavior of a hydraulic drive)

are defined to describe the hydraulic system.

To enable an objective and repeatable procedure, it is advisable to evaluate all rotary and linear consumers separately. Additionally, criteria to rate the characteristics (e.g. stationary, rarely changing or frequently changing operating behavior) need to be set up.

The specific values “EE” (Energy Exploitation) and “ER” (Energy Recovery) are calculated by multiplication of these factors:

$$EE = EC \cdot SLP \tag{2}$$

$$ER = EC \cdot OB \tag{3}$$

For an excavator, a wheel loader and a field chopper, the procedure is exemplarily displayed at a quite simple inspection in Fig. 6.

| Application | Hydrostatic Drives | | Factor EC: Energy Conversion (low: 1, medium: 2, high: 3) | | Factor SLP: Spectrum of Load Pressures (constant: 0, low: 1, medium: 2, high: 3) | | Factor OB: Operating Behavior (stationary: 0, rarely changing: 1, changing: 2, freq. changing: 3) | | Potential EE: Energy Exploitation EE=EC*SLP | | Potential ER: Energy Recovery ER=EC*OB | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | rotary drives | traction drive | high | 3 | high | 3 | changing | 2 | 9 | 6,0 | 6 | 6,2 |
| | | swing drive | high | 3 | high | 3 | freq. changing | 3 | 9 | | 9 | |
| | | fan drive | low | 1 | low | 1 | rarely changing | 1 | 1 | | 1 | |
| | linear drives | boom | high | 3 | high | 3 | freq. changing | 3 | 9 | | 9 | |
| | | stick arm | medium | 2 | medium | 2 | freq. changing | 3 | 4 | | 6 | |
| | | bucket | medium | 2 | medium | 2 | freq. changing | 3 | 4 | | 6 | |
|  | rotary drives | traction drive | high | 3 | high | 3 | freq. changing | 3 | 9 | 5,0 | 9 | 5,4 |
| | | fan drive | low | 1 | low | 1 | rarely changing | 1 | 1 | | 1 | |
| | | - | - | - | - | - | - | - | - | | - | |
| | linear drives | lift frame | high | 3 | high | 3 | freq. changing | 3 | 9 | | 9 | |
| | | bucket | medium | 2 | medium | 2 | freq. changing | 3 | 4 | | 6 | |
| | | steering | low | 1 | medium | 2 | changing | 2 | 2 | | 2 | |
|  | rotary drives | traction drive | high | 3 | high | 3 | changing | 2 | 9 | 2,0 | 6 | 2,8 |
| | | fan drive | low | 1 | low | 1 | rarely changing | 1 | 1 | | 1 | |
| | | spout (rotary) | low | 1 | constant | 0 | changing | 2 | 0 | | 2 | |
| | linear drives | front attachment | medium | 2 | constant | 0 | changing | 2 | 0 | | 4 | |
| Note: mechanical driven chopping unit | | spout (linear) | low | 1 | constant | 0 | changing | 2 | 0 | | 2 | |
| | | steering | low | 1 | medium | 2 | changing | 2 | 2 | | 2 | |

**Fig. 6:** Method: Energy saving potentials in mobile machines with advanced CP technology

By consideration of further information, as

- regarding selected machines with machine specific data
- classifying the real hydraulic power consumption of the different drives
- more detailed criteria for evaluation of operating behavior and the spectrum of load pressure
- additional weighting of the factors,

this method can be upgraded to the demand of the user.

Optional layouts for a clearly arranged presentation of the evaluation results are shown in Fig. 7:

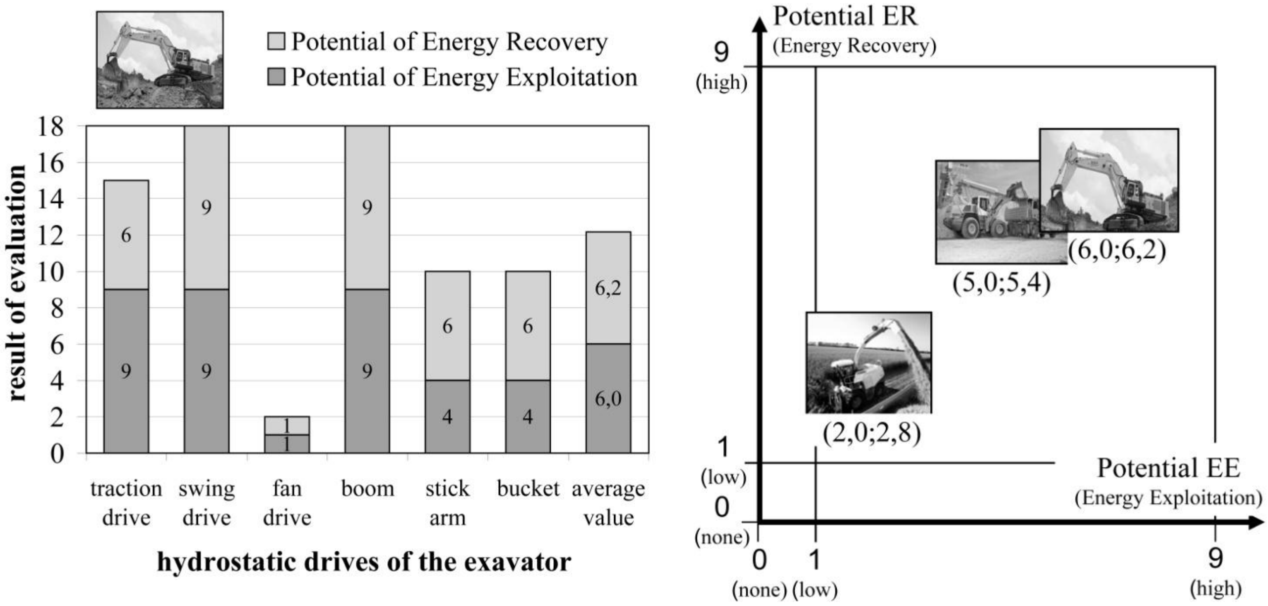


**Fig. 7:** Layouts for displaying the evaluation results

# 4 CHECKUP: ARE THERE SIGNIFICANT REASONS TO FORGO ADVANCED CP PRINCIPLE FOR MOBILE MACHINES?

Multiple research projects and publications demonstrate, predominantly on the topic of secondary control, that the interest in the employment of advanced CP systems is quite high. Although the awareness of the capabilities of the advanced CP technology exists, in the area of mobile machines it is only used for niche applications. The reasons that avoided a widespread implementation in the past, in contrast to industrial application, need to be checked whether they are still significant.

The following reasons for the delayed implementation of advanced CP systems in aircraft hydraulics are named in Biedermann (2005):

- insufficient experience and a lack in methods
- high development effort for components and software
- open safety aspects

In the opinion of the author, these reasons are absolutely valid for mobile machines, too. For mobile machines, the aspect "cost pressure" has to be considered additionally. Whereas in aircraft construction upscale development costs and expensive precautions are in most cases inevitable and thereby accepted, in mobile machines the budget is much more limited.

The insufficient experience in employing this kind of system technology causes a certain uncertainty and handicaps implementation. For the development and initiation of advanced CP systems, a deep knowledge in digital systems for measurement and control is absolutely necessary. Kordak (2003) describes this necessity as follows: "As the special characteristics can be more easily compared with electrical drives with closed control loop control than with conventional hydraulic drives, project design together with the application of secondary controlled drives is still only used by a small group with specialist knowledge". To solve this problem, investment in technical trainings and more specific research projects to acquire methods and trained employees may help.

For the implementation of controlled adaption of the hydraulic consumers to the constant operating pressure in a selected machine, high development effort for components and software is necessary. If available, components, e.g. variable displacement units and controllers, need to be configured for the requirements. In many cases, adequate products (e.g. hydraulic transformers) exist in prototype stage but are not available for the market. Nowadays, computing power and control rates should be sufficient because performance of electronic controllers and micro computers increased exponentially in the last years. Generating software with robust control and monitoring strategies requires additional efforts for implementation.

To ensure operational safety of advanced CP systems, compared to conventional hydraulic systems, increased measures are necessary. A well known problem for variable displacement units is overspeed because of exceeded power input at small load torque. Failure in control of a secondary or malfunction of a speed sensor may lead to this critical situation and in extreme case to a self-destruction of the drive. To face this effect, diverse approaches have been studied by Geerling (2003).

Another aspect to be considered is power limitation at energy recovery for the protection of the prime mover. Generally, in the design phase safety relevant issues of advanced CP systems need to be inspected systematically to identify critical situations. An adequate method could be Failure Mode and Effect Analysis. Counteractive measures can be derived from this analysis.

Regarding the reasons listed above, it is obvious that few technical barriers exist today as reasons to avoid the implementation of advanced CP systems in the mobile sector. Particularly economic reasons prevent the application of this technology in today's mobile machines. Being confronted with high development costs at predominately piece numbers, many machine manufacturers and their component suppliers still refuse the risk of investments in further research and development of these technologies. In the opinion of the author, machine acquisition costs will probably increase because of additional expenses in development and production. A successful implementation of the technology relies particularly on extra value for the user, e.g. faster responding and higher precision, in combination with a short amortization time of the extra costs, mainly by reduced fuel consumption.

## 5 CONCLUSIONS

Established niche applications in mobile machines demonstrate that constant pressure (CP) principle can successfully be employed in this sector. Considering the special properties, even conventional CP system is still an option for modern and energy efficient applications as the actual example of a field chopper proves. Beside principle-related fast responding behavior and high accuracy in control of hydraulic drives, recovery of potential and kinetic energy offers additional advantages.

By the employment of secondary control, the operation of rotary drives at CP grids may be much more energy efficient compared to throttle controlled drives. The aspect of low efficiency of variable displacement units in part-load operational range at small swiveling angles has to be considered. A technology for an enhanced energetic efficiency of constant displacement drives and linear drives in a CP system is the hydraulic transformer principle.

Evaluating reasons that avoided a widespread implementation of CP technology in mobile machines in the past, it may be concluded that no significant technical barriers still exist. Due to economic reasons, majority of machine manufacturers and their component suppliers fear the investments in the development of new applications. Additional research projects to deepen experience and technical trainings may help to advance CP systems to an attractive alternative to established Load Sensing (LS) principle in mobile machines. Public research facilities, e.g. the Chair of Mobile Machines in Karlsruhe, Germany, may support hydraulic industry and machine manufacturers in this enterprise.

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