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Design of Dynamic and Efficient Hydraulic Systems Around a Simple Hydraulic Grid

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ABSTRACT

Through the development of the Innas Hydraulic Transformer, a hydraulic driveline called Common Pressure Rail (CPR) becomes possible. The CPR system profits from considerable advantages over conventional hydraulic drivelines in terms of costs, controllability and flexibility. In CPR systems all cylinders and motors are connected to a single common rail, delivering the same pressure to all connected devices. The control of functions is realized using innas hydraulic transformers (IHT). IHTs enable local control of cylinders or motors without throttling energy. Integrating an IHT with a cylinder and closed loop control creates a Variable Displacement Cylinder or VDC. These devices enable modular design of mobile machinery. Design of flexible machines becomes possible and complex machine tasks are easy to automate without increasing the complexity of the machine.

INTRODUCTION

In 1895 Charles Proteus Steinmetz developed a system of distribution by alternating currents [1]. His system made it possible to connect both mono phase devices such as lighting and multi phase motors to one electricity grid. This marked a break-through for Alternating Current (AC) electric systems. Steinmetz' system is still the basis for the current electricity grid, which has reached an undisputed position. Figure 1 illustrates Steinmetz' development of an electricity grid for single and multi phase loads.

Nowadays, electric systems, which are considered to be the competitor of hydraulic systems, are fully modular. Contrary to current hydraulic systems they are built around a clear-cut and well-defined electric grid. The

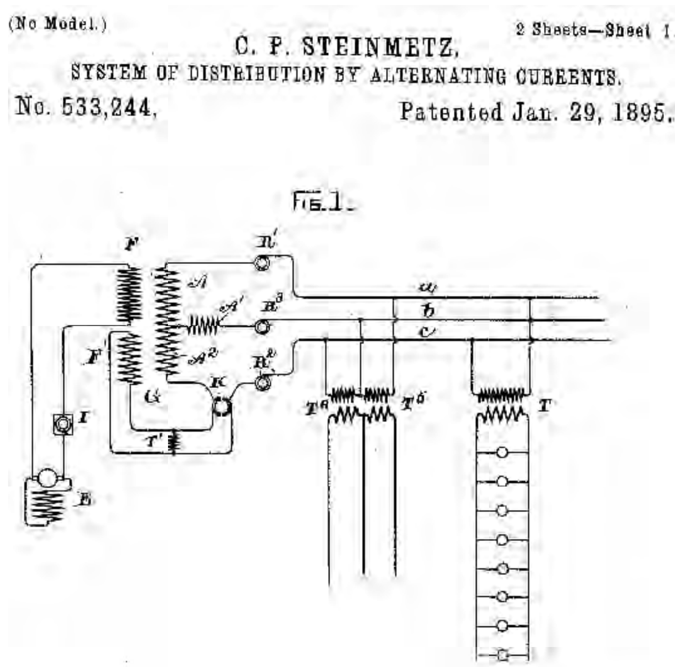

Fig. 1: An electricity distribution system, developed by Charles P. Steinmetz, which enabled both single phase loads (like lighting) as well as multi phase loads (motors) to be attached. CPR hydraulic drivelines equal these electric drivelines in modularity.

number of electric devices can be increased without increasing the complexity of the total system. The complexity itself is solved in the electric devices. These devices, the electric modules or building blocks, can be very complicated or very simple. The level of complexity depends on the demand at the load side: the modules are only complex when needed.

The same level of modularity in hydraulic drivelines can be realised when the hydraulic architecture of machines is built around a hydraulic grid. This grid, the common pressure rail, (CPR) delivers hydraulic energy to all functions. The number of hydraulic functions may be increased without increasing the complexity of the total system [2].

The CPR technology has already been present for more than 25 years but never became mature due to the lack of a low-cost hydraulic transformer with a high efficiency. The development of the Innas hydraulic transformer (IHT) changes this situation. The IHT might be the key enabling technology for the CPR layout [3]. Time will tell whether the Innas hydraulic transformer can force a market breakthrough for modular and flexible CPR hydraulic drivelines like Steinmetz' invention did for alternating current.

This paper describes the Common Pressure Rail and its enabling technology: the IHT. Its also deals with the question why meeting market demands will become easier when a CPR driveline is used. But first an inventory of those market demands is made.

MARKET DEMANDS FOR MOBILE MACHINERY

Market demands, relating to the functional performance of mobile machinery -such as wheel loaders, excavators, telehandlers- could be listed as follows [4]:

- increased flexibility
- easier to use
- increased productivity
- less dependent on operator skills
- easier tuning/ trouble shooting of hydraulics
- decreased operational costs.

Although most mobile machines are described as versatile and flexible, the machine in itself is not a very flexible platform. Today's construction machines are mostly using non-interchangeable attachments. Only the tools like the bucket, a hammer or a cutter are interchangeable. A boom on an excavator for example will not quickly be changed, unless the machine is specially prepared for it.

In the construction sector, finding skilled operators for mobile machinery is another problem. Excavating a high quality profile like a bank or a straight trench requires the operation of multiple cylinders simultaneously. The quality and speed of these jobs are strongly dependent on the operator skills. An emerging market sector, where ease of use is very important, is the rental sector. Here less skilled operators will profit from machinery that is easy to use.

Sensors and measuring systems can provide the input for easier operation. In a simple form, an operator could for example set the digging depth of a trench. During the excavating process, the control watches the maximum depth and limits the movements.

More advanced is a system with Closed Loop Control (CLC). CLC of a cylinder combines a cylinder measurement system and controlling valves. A master control system monitors the position of each cylinder. An operator can activate the machine with advanced joy sticks coupled to the master control. The master control activates the hydraulic valves, which let the cylinders move to the required position and in the required speed.

When a control unit knows the position of each cylinder, and when it is able to control the speed of movements of cylinders, further automation of earthmoving can be reached. Complex movements can be performed by the master control of the machine, requiring less operator skills.

Cylinders with CLC and a master control enable skilled operators to 'teach' special movements or profiles to a machine. If these movements are stored in the master control they can be repeated, also at higher speeds. A step further could be the co-operation with a local (laser) positioning system or GPS. In principle fully automated earthmoving is within reach although it is expected that for most jobs the presence of an operator remains desirable.

Another demand from both the OEM market and the end users relates to the hydraulic heart of the machine - the valve block, often combined with a (multi-) pump system. Due to customer demands regarding accurate control, load independency and efficiency the valve block has evolved to a sophisticated junction. Adjustment of the hydraulics, i.e. the load sensing system, now takes considerable time to fine-tune the hydraulic functions before a machine is fully operational, not only when a machine is manufactured, but also when troubleshooting has to be done or when a new function has to be added. It also requires a high degree of experience and qualification from the staff.

Of course meeting the described market wishes all relate directly or indirectly with operational costs. The problem faced by the OEM and hydraulic industry, is how to meet all market demands without increasing the operational costs.

To be able to fulfill all market demands the hydraulic system of the machine needs to be flexible by itself. The layout should be modular, offering the possibility to attach several hydraulic functions. The complexity of the load (the controller and cylinder or motor) has to be separated from the complexity of the source, (the pump and internal combustion engine). It should allow the automation of functions without stacking complexities to each other. The Common Pressure Rail or CPR systems are offering a hydraulic layout, which can present the solution.

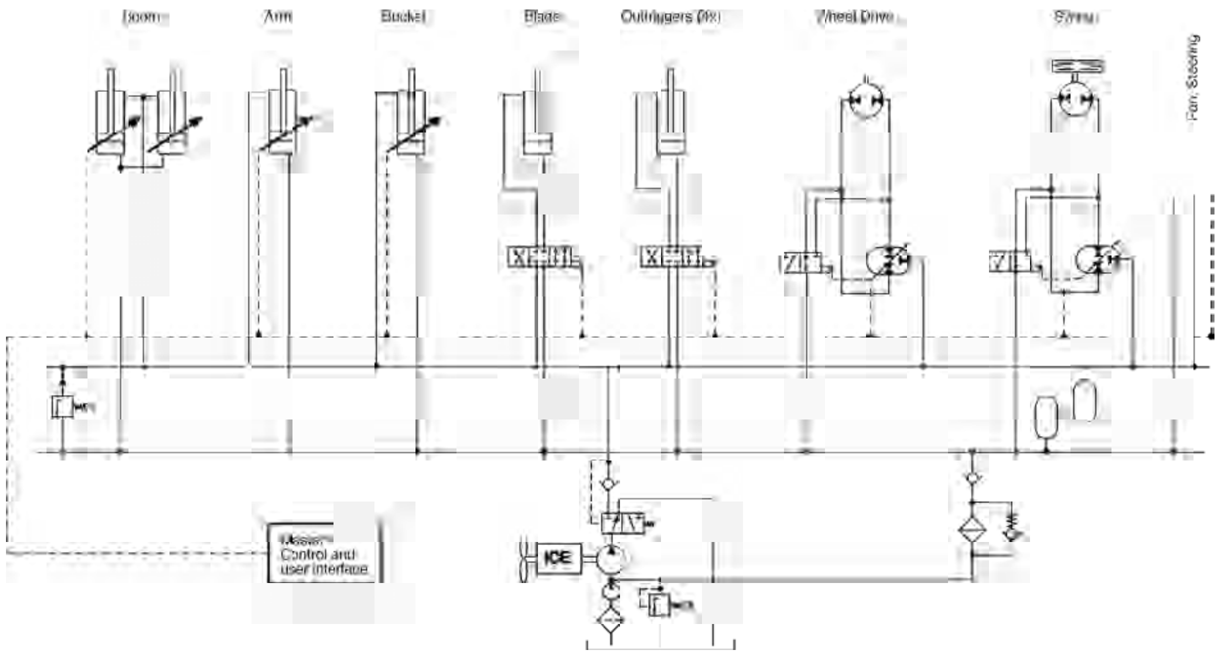

Fig. 2: Hydraulic design for an excavator, based on Common Pressure Rail technology.

CPR: COMMON PRESSURE RAIL

The CPR-configuration is similar to the electricity grid. The electricity grid offers a common (and constant) voltage to all machines and devices that are connected to this grid and need electric energy. On the other side of the grid, power plants are connected to the grid. These plants have one task: to maintain the common voltage level (and frequency) of the grid.

The grid itself separates the power plants from the power consumers. By means of the grid a simple and clear definition is created for myriad electric devices, allowing a combination of simplicity (the grid) and complexity (the applications). It is by definition a modular concept, with vacuum cleaners, washing machines, computers and TV-sets being the modules, all having an individual control.

In the hydraulic equivalent, the common pressure rail is the hydraulic grid, separating the hydraulic power plants (the pumps) from the motors and cylinders. Contrary to the electricity grid, the pressure of the hydraulic grid does not necessarily have to be constant. By means of hydro pneumatic accumulators the pressure level of the common pressure rail can be varied in a controlled way. The energy that is stored in these accumulators can be used for power management and energy recuperation.

Apart from using throttle valves and variable motors, the CPR system is characterized by the use of hydraulic transformers as control device. These transformers can transform hydraulic energy without energy loss. Flow and pressure from the CPR can be either increased or decreased.

The Common Pressure Rail technology is not a new invention. Mannesmann Rexroth introduced a similar hydraulic system about 25 years ago, known as 'secondary control' [5]. This system never led to a market breakthrough due to poor performance of conventional transformers and high component prices of secondary controlled motors and transformers. The development of the Innas Hydraulic Transformer can change this situation radically [6,7].

Figure 2 illustrates the uncomplicated design structure of the CPR hydraulic layout of an excavator. Hydraulic transformers control motors for wheel drive and swing function. Cylinders with integrated transformers are used for the excavating process. Simple throttle valves control those cylinders which are not used frequently or which require little energy (blade & outriggers).

THE INNAS HYDRAULIC TRANSFORMER

Like in the electric equivalent, transformation devices are needed to convert the parameters of the common rail to the load parameters required by the applications. In hydraulic CPR-systems this means that a component is needed that can close the gap between the pressure offered by the common pressure rail and the pressure needed in, for example, a hydraulic cylinder.

In principle, a simple throttle valve could be used to reduce the pressure of the common pressure rail to the pressure needed at the load side. Since a throttle valve can only be used to reduce pressures, the pressure of the common pressure rail would have to be set at the highest pressure that is needed in the system. This, of course, results in high losses, which in most cases are unacceptable today.

The recently developed IHT offers a much better alternative. Instead of dissipating hydraulic energy the IHT transforms hydraulic energy, thereby following the line of constant power (see figure 3).

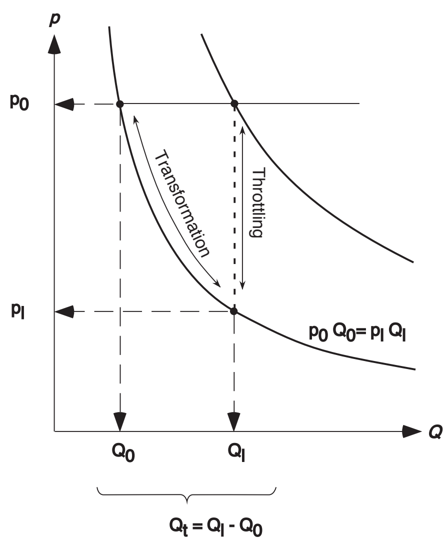

Fig. 3: Pressure-flow-diagram showing the difference between throttling and transformation when going from the pressure of the common pressure rail (line p0Q0 to p0QI) to the point of operation pIQI.

In the example shown in figure 3 throttling results in an energy loss of about two-third of the input power. Conversely, transformation is in principle a reversible process with 100% efficiency. (In reality, internal friction and leakage losses will result in a somewhat lower efficiency.)

Figure 3 shows another difference between throttling and transformation. In case of throttling the output flow equals the input flow. When transforming the output power equals the input power (aside from some losses). Therefore a pressure decrease will result in an increase of the flow (the flow of point pIQI is higher than the flow of point p0Q0). To fulfill the mass continuity equation, a third flow from the tank or from a low-pressure line must be added. A hydraulic transformer is therefore by definition a three-way junction.

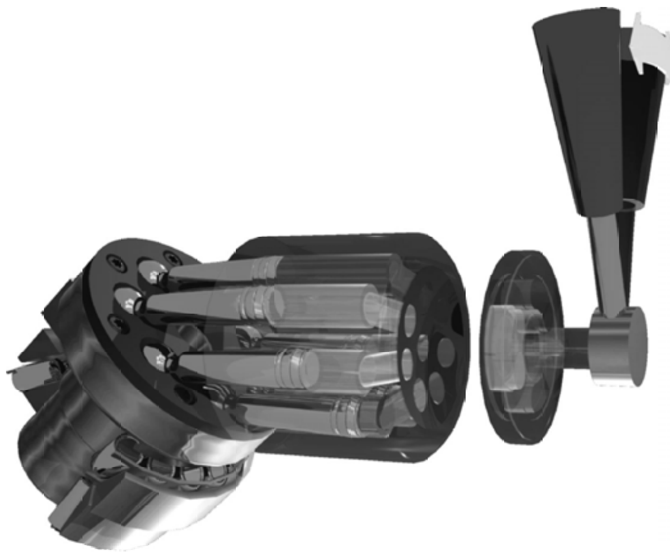

Fig. 4: Principle construction of an Innas Hydraulic Transformer (IHT).

A third difference between throttling and transformation is that the transformation process can also move in the opposite direction: the relatively low load pressure level can be transformed to a flow at the common pressure rail level. Due to the principle of transformation, the load flow into the transformer will in this case have a higher rate than the flow into the CPR. Of course, with a throttle valve a flow will never go from a low to a high pressure.

This possibility to increase the pressure level offers the option to recuperate energy from loads to the common pressure rail. For instance if a forklift lowers a load, the potential energy represented by this load can be converted to the pressure rail and stored in the accumulators. This energy can then be used for other purposes, for example to accelerate the forklift truck again. Also, the pressure level of the common pressure rail does not need to be set at the highest pressure of the system. Instead, a lower 'average' value can be chosen. If a higher pressure is needed the transformer can amplify the pressure to the required level.

The IHT fulfills all these requirements. The basis of the design of the IHT is a constant displacement hydraulic pump or motor like for example an axial piston unit. In principle any positive-displacement unit can be chosen as a basis of design for the IHT, as long as the pressure level in the displacement chambers is changed by means of a commutator, like for example a port plate.

Figure 5 shows a photo of the IHT prototype on the basis of a bent-axis axial piston design. On the photo the end cap of the IHT is removed, showing the port plate mounted in the end cap. As can be seen the port plate of the IHT has three ports instead of the two ports of hy-

Fig. 5: Photo of a IHT on the basis of a 5 cc bent-axis axial piston hydraulic motor (Rexroth A2FM5)

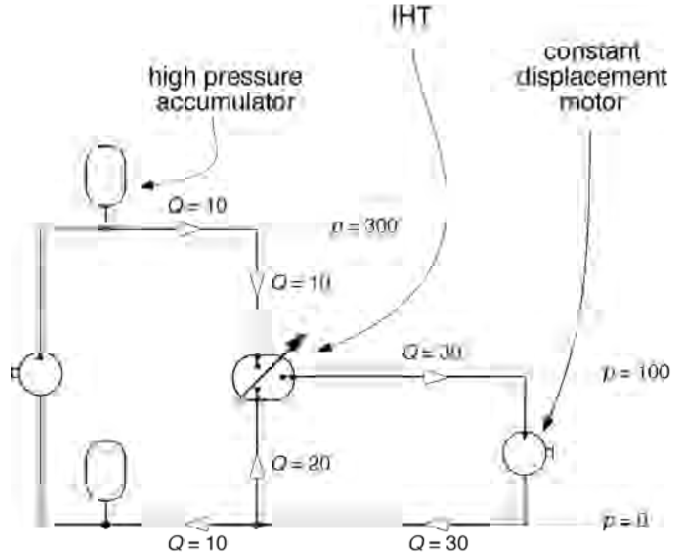

Fig. 6: Example of an application of the IHT controlling a constant displacement hydraulic motor.

draulic pumps and motors. This is necessary for supplying a third 'make-up' flow to the IHT in order to supply the difference between the input and the output flow.

Another difference between the IHT and a hydraulic pump or motor is that the port plate does not have a fixed position but can be rotated to a required position between two end positions. By rotating the port plate the transformer i.e. the output pressure and output flow can be controlled [8].

Since the port plate itself is completely balanced, only a low torque and power is needed to control the IHT. This allows having a direct electric control of the IHT. Furthermore the IHT has a very high dynamic response, because of the high power density of the hydraulic components and the low inertia of the barrel of the IHT.

The application of the transformer is not limited to controlling hydraulic cylinders but can be used in combination with any kind of hydraulic load. Figure 6 shows a combination with a constant displacement hydraulic motor.

The diagram of figure 6 shows two 3-way junctions: one at the IHT and one at the low-pressure line right below the IHT. In the example of figure 6, the IHT combines a high pressure flow of 10 L/min and a low-pressure flow of 20 L/min to an output flow of 30 L/min. At the low-pressure junction the flow coming from the motor is split again, thereby sending 20 L/min to the transformer and 10 L/min to the suction side of the pump. The result is that the pump only needs to deliver 10 L/min at a pressure of 300 bar in order to get a motor flow of 30 L/min at 100 bar.

Shuttle Technology

The efficiency of the IHT can become as high as 90% [9]. By introducing “shuttles” in the barrel of the IHT, this high efficiency can be achieved in a wide range, even at high barrel speeds i.e. at high power levels.

Due to the configuration of the IHT, the hydraulic commutation from one port to another will almost never occur at the top dead centres, but mostly at a point where the plungers move at high speeds. As a result cylinder pressure peaks will occur and port -opening losses influence the efficiency negatively. Although special port geometry -so called concurrent ports- helps to minimize pressure peaks and throttle losses in these valving lands, at high barrel speeds this cannot eliminate hydraulic losses and pressure peaks totally [10].

The prevention of pressure peaks is realised by absorbing a small volume of oil during the passage of a valving land. The so-called shuttle-solution fulfils these requirements. The principle is shown in figure 7 and 8.

The shuttles are small ball shaped pistons that are free to move over a limited stroke between two end positions. The cylinder in which the piston moves is on each side connected to one of the cylinders of the barrel. In the end positions the shuttles act as a check valve, thereby closing off the connection between two cylinders. In between the two end positions the shuttle predominantly acts as a piston, displacing oil from one cylinder to the other, giving the necessary freedom to the compressed or expanded oil in the valving land [11].

This shuttle technology improved the efficiency of the transformer over a broad working area due to lower port opening losses. A lower sound output at high barrel speeds also increased the operating range of the transformers fitted with shuttles. Prototype tests with a 10 cc bent axis transformer showed a doubling of the transformation output up to 20 kW at noise levels normal for hydrostatic machines.

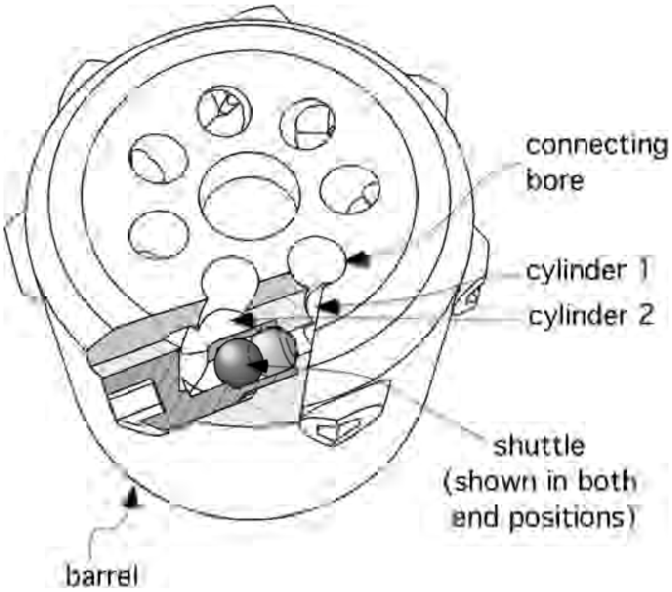

Fig. 7: Cutaway of an IHT cylinder barrel. Ball shaped shuttles improve performance and reduce noise.

APPLICATION IN THE FORK LIFT TRUCK

In order to test the CPR technology for both cylinders and motors the technology is applied and tested by Innas in a forklift truck. Figure 9 compares the two hydraulic diagrams. The original drive system is shown in figure 9.a. The CPR-system is shown in figure 9b. Only two transformers are used in this CPR system: one for the hydrostatic wheel-drive and one for the control of the lift cylinders. Braking energy and energy of lowering the load are recuperated.

Throttle valves are used for the other cylinders. Although this results in some energy losses, the energy consumption of these loads is low compared to the other loads, and the throttle losses will not have a large effect on the total fuel consumption of the lift truck. More details on this lift truck driveline were published in [12,13].

VARIABLE DISPLACEMENT CYLINDERS

A logical step in the development of CPR systems is the combination of the IHT with a hydraulic cylinder, fitted with some sort of position measuring system, and a system bus.

Dependent on the required accuracy and the application of the cylinder, a position measuring system can be used. Another possibility is to use the characteristics of the transformer to determine the cylinder position. This position can be calculated on basis of the amount of oil delivered to or by the cylinder. The amount of oil can be calculated from the number of revolutions of the transformer barrel and the drive plate angle. This is a cheap solution for creating closed loop control.

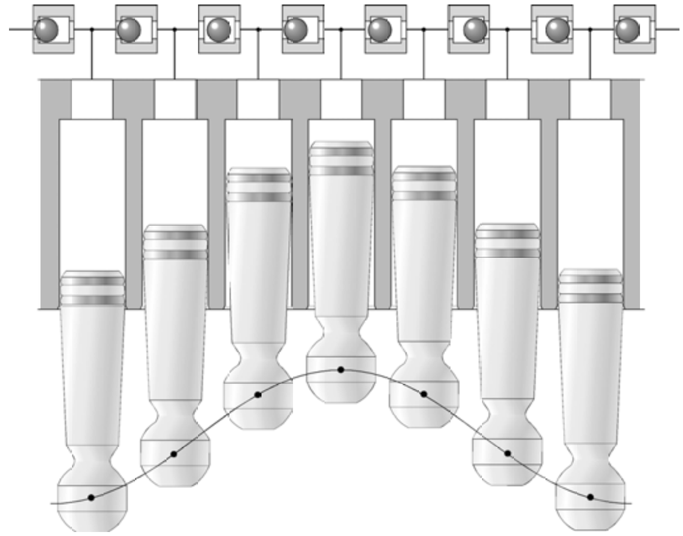

Fig. 8: Shuttles positioned between pairs of cylinders, absorbing or delivering oil during a valving land passage.

The IHT currently being developed by Innas is small enough to fit into the bottom of a hydraulic cylinder. When a local control algorithm is included, a Variable Displacement Cylinder (VDC) results. These modules will form the basis for flexible and easy controllable systems.

The master control of an application will only have to send information through a system bus to a VDC on where to go at what speed. The VDC will realize the required movement, receiving its power from, or recuperating energy to, the CPR.

ADVANTAGES OF CPR SYSTEMS

CONTROLLABILITY AND EASE OF USE

In modern load sensing (LS) systems, the speed with which the supply pump can be varied influences the responsiveness of the LS system directly. This implies a slower control even if, at the penalty of increased costs, faster pump actuators are chosen.

In the CPR layout, there is no interaction between the loads. Also the power source does not suffer from influences caused by the loads. When a speed control is necessary, the VDC's or the IHTs are secondary controlled. Secondary controlled systems display an excellent controllability. In combination with the fast response characteristics of the IHT, this enables very precise control. For the operator the feeling of the joysticks matches excellent with the movements of the machine. This improves performance and shortens the time to get used to the machine.

The concept of secondary control matches with the trend towards bus systems in vehicle control. The fast control

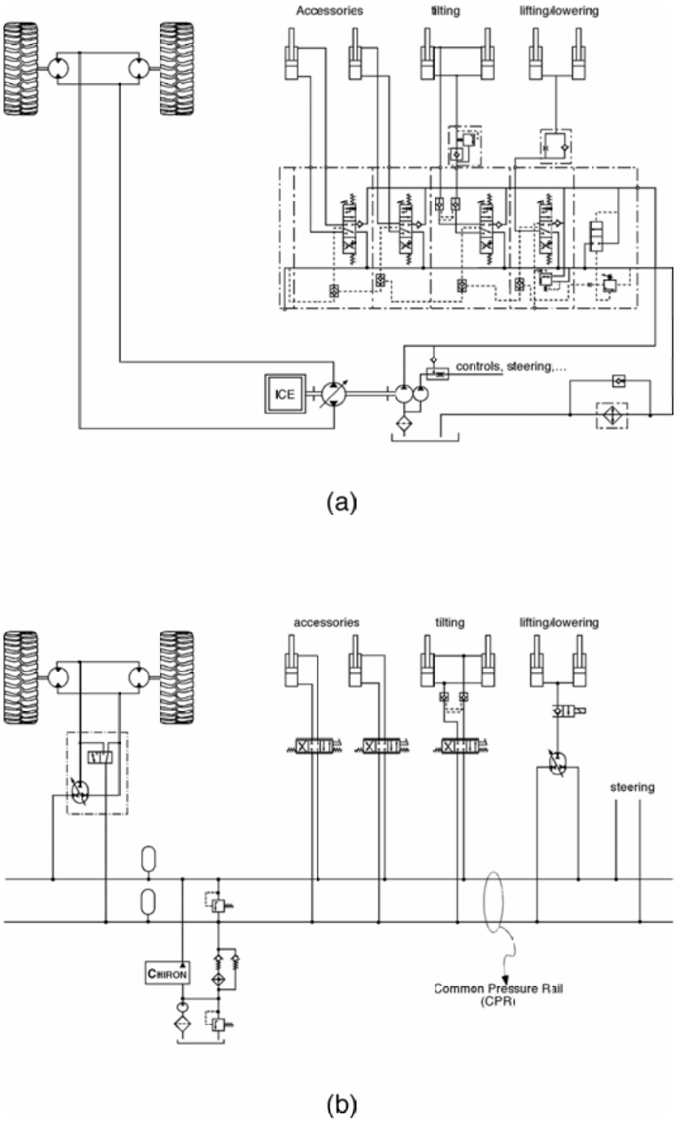

Fig. 9: Comparison of a conventional (load sensing) hydraulic diagram (a) for a fork lift truck with a CPR diagram (b).

algorithms can be implemented in local controllers, which receive their set points and targets from a central master controller, over a bus system. This type of control set-up enables easy synchronization between functions, learning of repetitive tasks and adapting the system to changing circumstances or driver preferences. This opens the way to easy-to-operate machines, which are less dependent on operator skills.

The control of the primary power source can also be simple. An engine pump combination only has to maintain a semi-constant pressure level and to provide sufficient flow. Hydraulic accumulators attached to the common pressure rail enable peak shaving, which decreases the engine power required by the system as a whole. They also enable recuperation of braking energy.

MODULARITY AND FLEXIBILITY

Designing applications around a CPR-grid offers the opportunity to focus on the functions and performance of the machine. For the OEM, this means a vehicle hydraulic system can be based on functional units that can be chosen from standardized series. The OEM will only have to determine the master control strategies, without having to bother with low level local control. If the installed power and accumulator capacity are carefully chosen, there is no risk for functions to interfere with each other. Consequently, there is no need to tune the hydraulic circuit. The design lead-time will be shorter and the level of standardization will be higher.

The flexibility is available for that end user who wants to attach other functions to the machine. If an excavator has to be fitted with a telescopic boom instead of the earth-moving boom, this only requires the right software for the master control apart from fitting the hardware. Extra hydraulic functions can be attached to the CPR: making a feller buncher from an excavator could be just attaching the tool and selecting the right control mode.

PRODUCTIVITY AND COSTS

If VDC's are produced in the same series as cylinders and LS-sections are presently, it is expected that there will be no cost penalty in using CPR instead of LS. Driveline costs must be compared on a system level. CPR systems have the following costs-related advantages:

- Because of the possibility to perform peak shaving and energy recuperation and because of the better overall efficiency, the installed engine power can be reduced substantially. As an example, in the forklift truck prototype, the engine power could be reduced from 28 kW in the conventional layout to 17 kW in the CPR layout. Engine costs will decrease correspondingly.
- The number of installed pumps decreases and often cheaper fixed displacement pumps can be used in CPR systems.
- Costs of time-consuming fine-tuning of the hydraulic system can be avoided when using CPR systems.
- The production costs of an IHT will be comparable with the costs of a load independent LS-section, when produced in the same series and looking at complexity, number of components and materials. Integrating the IHT in a VDC will further decrease the total actuator costs.
- As mentioned before the costs of trouble shooting and tuning of hydraulics will be lower due to the fact that hydraulic functions no longer influence each other. If a problem occurs it will be easy to locate and

changing a component does not require time consuming fine-tuning.

The energy consumption in the CPR layout will be substantially lower than in the LS layout:

- In the IHT-based CPR layout, throttling is avoided.
- The efficiency of the IHT is high, especially in part load conditions.
- Energy can be recuperated and stored into the high-pressure accumulator. (For the excavator this is particularly advantageous when swinging the cabin and load back and forth. Usage of the dissipative swing brake can be avoided).

Finally the productivity of a CPR machine can improve because of the ease of use. Less skilled operators will quickly get used to the machine. Skilled operators will work faster, and with higher quality due to more precise control.

The CPR allows it to easily attach different functions to a machine. The end user can do more with his machine, reducing idle time.

CONCLUSION

Hydraulic systems can be as modular and easy to design as electric systems through the development of a new component: the Innas Hydraulic Transformer or IHT. The IHT enables a hydraulic driveline called the Common Pressure Rail.

CPR systems offer a clear hydraulic grid on which hydraulic functions (cylinders and motors) can be easily be attached.

The CPR systems offer advantages to OEM-ers in designing their machines. The design lead-time will be reduced. The level of standardization will be increased.

The CPR system type is superior to conventional hydraulic systems in terms of controllability, flexibility and costs, offering the OEM market an opportunity to meet market demands without increasing complexity and costs of operation of their machines.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CPR: Common Pressure Rail
CLC: Closed Loop Control
IHT: Innas Hydraulic Transformer
LS: Load Sensing
VDC: Variable Displacement Cylinders