The Ninth Workshop on Digital Fluid Power, September 7-8, 2017, Aalborg, Denmark

DIGITAL DISTRIBUTOR VALVES IN LOW SPEED MOTORS – PRACTICAL APPROACH

Per N. Lindholdt, Henrik B. Larsen
Diinef AS
Tordenskjoldsgate 9
4612 Kristiansand, Norway
www.Diinef.com
Email: p.lindholdt@diinef.com, h.larsen@diinef.com
Phone: +45 2088 5038, +47 9302 5600

ABSTRACT

This paper presents the implementation of a new electronic controlled distributor valve system for High Torque Low Speed digital motors. Valves are pilot operated, out-wards opening poppet-type on both high- and low-pressure side.
An implementation on large radial piston motors with eccentric shaft is shown, and examples of valve operation and the impact of timing of valve operation is demonstrated with measurements and simulation.
A brief description of a digital motor program is given, and improved efficiency, increased power capacity, displacement control and other features are presented.

KEYWORDS: Digital HTLS motors, Digital valves, Digital distributor valve systems

1 INTRODUCTION

The digital distributor valve system presented here is developed for HTLS hydraulic units, and the main feature of this system is the ability to connect each cylinder to high- or low-pressure independent of the cylinder pressure and piston speed and position, thereby gaining immediate control of displacement. Pilot operated valves are used to achieve sufficient actuation forces. The presented solution has Patent Pending.

The system differs from solutions that have been presented earlier by e.g. Artemis Intelligent Power Ltd [1], which uses electrical actuation. These valves can keep an open position when affected by flow forces, but the actuators can neither open nor close the valves against pressure differences. The approach supports efficiency at high speed units, but makes them less suited for HTLS motors where low speed and stand still combined with fast directional changes often occur.

1.1 Digital distributor valve systems for high speed units [2]

Electronic controlled distributor valves have been known for decades and most of the published valve solutions are essentially check-valves with electrical actuators, the first and best established shown in [1].

These solutions have dedicated high- and low-pressure ports. To move the valves the right pressure condition must apply inside the cylinder [1,3]. This working method is here referred to as ‘pressure balanced actuation’ as valves opens and closes primarily by cylinder pressure and supply pressures and flow forces. One major advantage of this approach is that valves are opened only when pressures on each side of the valves are close to each other, and this supports low noise, high speed capability and low valve losses.

Limitations are inherent when a motor or pump should be started, stopped or controlled at low speed, and for those purposes additional means are required [4].

1.2 Digital Distributor Valves for HTLS units

In [2] is presented a solution that allows valves to be changed freely without awaiting cylinder pressure to change. The solution with this characteristic is referred to as “forced actuation”. The proposed solution can be symmetric and handle a switch of pressures on

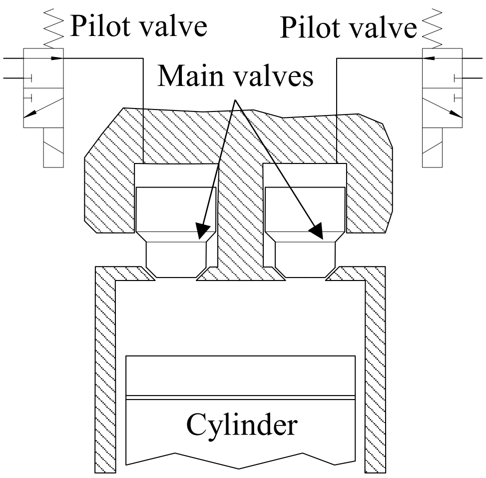

Fig. 1: Valve system utilising forced actuation. The solution is symmetric

the supply ports as well as four quadrant operation (by-directional, “over-centre” shift of torque direction). A single cylinder with the system is shown in Fig. 1. Although slightly simplified, it is seen that the valves will open if pilot chambers are connected to tank, and in case cylinder pressure increase with both main valves closed, the higher pressure main valve will open at a cylinder pressure dependant on the pilot, i.e. overpressure protection is inherent. This also sets one limitation on the free shifting, as it is not possible to close valves against overpressure in the cylinder.

1.3 Generic solution

Each cylinder is equipped with two pilot operated main-stage poppet valves, connecting the cylinder chamber to high- and low pressure. The pilot valves are 3-way 2-position spool type, with solenoid actuation and spring return. Depending on the required no-power functionality, the no-power state of pilot valves may connect the pilot area A3 to either tank or pilot pressure. Fig. 2 shows a slightly simplified main stage poppet valve and Fig. 3 shows an example of a hydraulic circuit for a single cylinder.

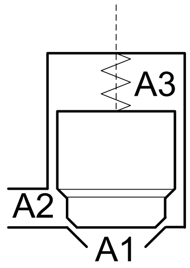

Fig. 2: Simplified Main stage poppet valve

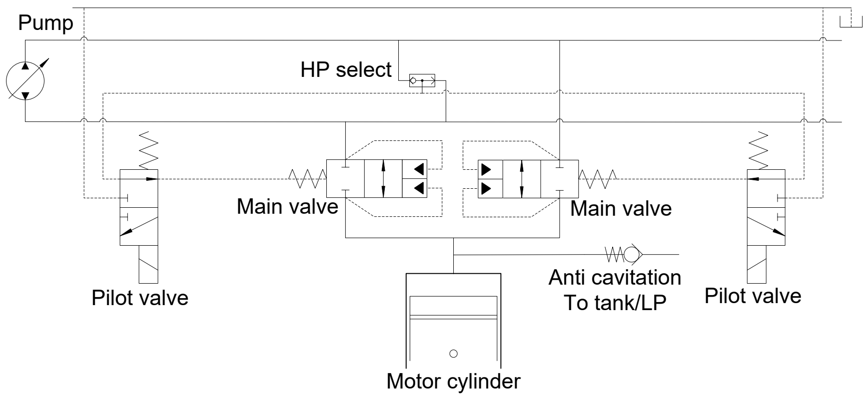

Fig. 3: Example of symmetric hydraulic circuit diagram of the valve system for one cylinder

The pilot valve shifts the pressure on the pilot area A3 of the poppet valve between pilot pressure and tank pressure. A main valve closes when there is high pressure on A3 and opens when there is low pressure on A3. The pilot pressure is selected from the higher pressure of the two pump ports via the HP select, i.e. pilot supply pressure is not higher than pump pressure and varies with pump pressure. An anti-cavitation valve may be built into the system and connected to low pressure or tank.

2 IMPLEMENTED SOLUTION

Fig. 4 shows a slightly simplified diagram of the implemented solution. The valve is set up for motors working with dedicated high- and low-pressure sides. Powerless condition of the high-pressure pilot valve is to close the main valve and powerless condition of the lower pressure pilot valve is to open the main valve. The result is that the motor freewheel with all cylinders connected to low pressure if electrical power is lost. The anti-cavitation valve is connected to low pressure and is optional.

Fig. 5 is a CAD model of the physical valve block containing the functions in the diagram for one cylinder. The valve block is dimensioned for a continuous motor flow of 170 lpm pr. cylinder with an average valve pressure loss of less than 4 bar.

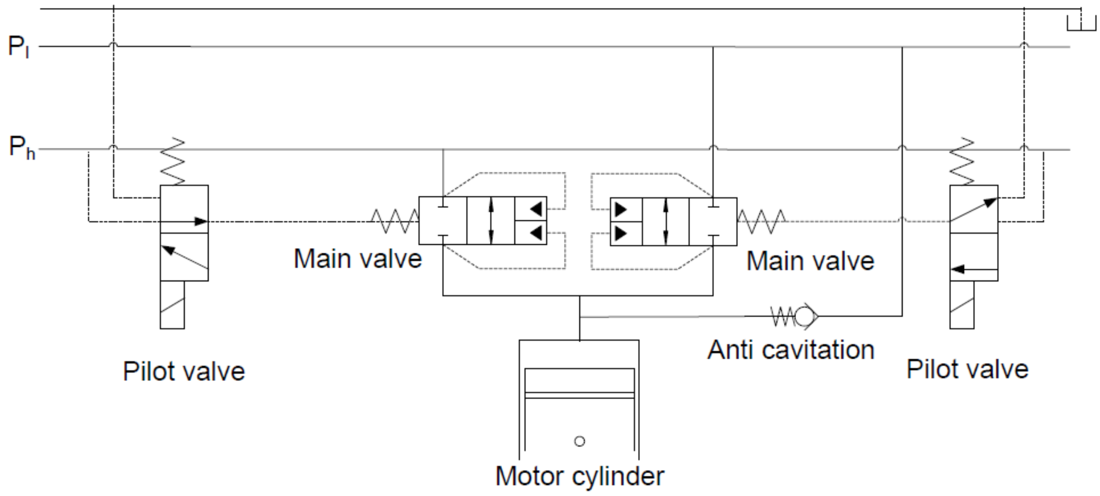

Fig. 4: Diinef digital distributor valve diagram. Anti-cavitation valve is optional

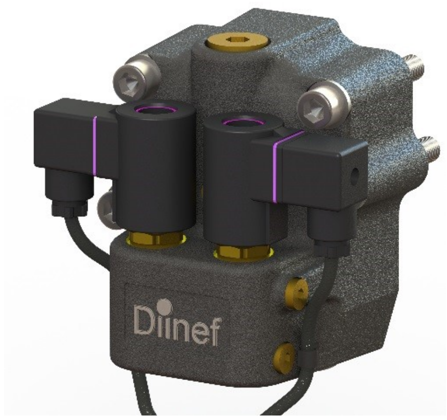

Fig. 5: Diinef digital distributor valve block, CAD model

3 VALVE ACTIVATION TIMING

The term valve activation timing or just "valve timing" is used for the process of activating the main valves in such a manner that the wanted motor response occurs. As discussed in section 1.1 one advantage of balanced actuation is a good timing of valve opening when it comes to equalizing pressures on both sides of the valves before opening. With forced actuation, the benefits of good timing are similar, but the control system does not get any help from pressure differences, and accordingly optimal timing is more demanding to achieve.

In systems with many cylinders it is an advantage and possible to operate most of the cylinders in a full stroke mode with optimal timing most of the time, whereas a minor fraction of the cylinders may be switched at other points of their stroke. The full stroke mode with optimal timing will be discussed below, based on simulation results from [2] and recent measurements.

3.1 Test set-up

The test object is a 5 cylinder motor with 3.3 l/rev displacement, i.e. each cylinder has 0.67 l displacement. The motor internals are proven designs by Imenco Bauer Hydraulics, but the motor housing is changed to interface to the valve system. Each cylinder is connected to a valve block similar to the one explained in section 2. The motor is equipped with sensors for high pressure, low pressure, one cylinder pressure and shaft position. For improved understanding, pilot pressures for one valve block have been measured as well.

The load on the motor is a same-size traditional motor operating as pump. The only inertia is that of the motors and the mechanical coupling. Response time of the sensors is less than 1 ms and sampling frequency of the control system is 10 kHz, allowing for digital filtering experiments. The test setup is shown in Fig. 6.

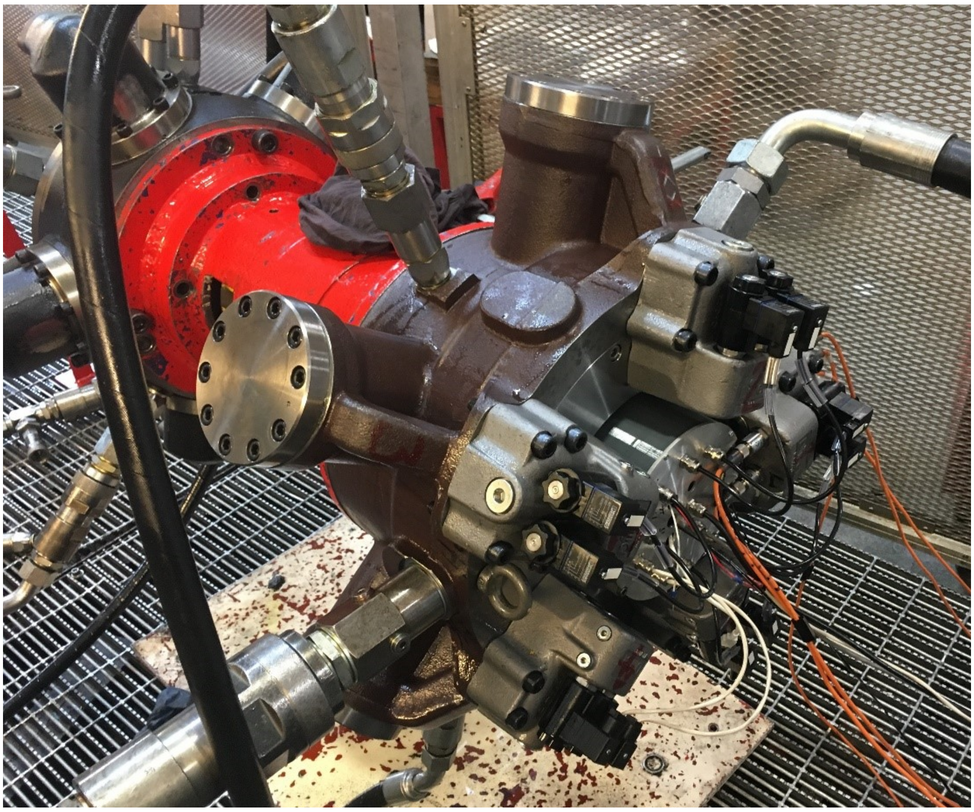

Fig. 6: Test set-up for loading and rotating the digital motor

3.2 Chain of events

Fig. 7 taken from [2] illustrates the chain of events required to close the high-pressure main valve in a motor stroke to depressurise the cylinder chamber before the low-pressure valve opens. In this case the goal is to have full motor stroke, i.e. to close the valve as near as possible to bottom dead centre of the cylinder while the cylinder pressure reaches exactly the same pressure as on low pressure side before opening the low-pressure valve.

The process of closing the high-pressure valve can be divided into 8 events. The first four events happen in the control system and the last four in the hydro-mechanical domain.

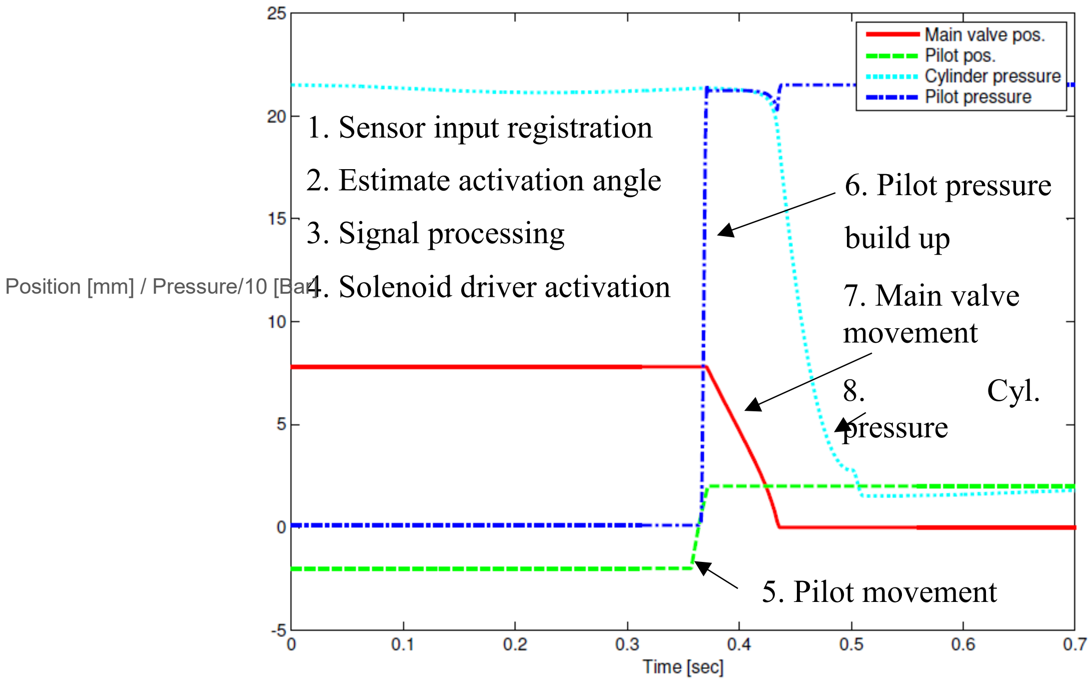

Fig. 7: Illustration of the chain of events needed to close the HP main stage valve. Values are based on early valve dimensions

3.3 Control system events 1-4

Explanation is with reference to [2] and Fig. 7. The motor controller continuously measures shaft position, pressures and temperature (event 1). Based on this information, it is estimated at which angle the high-pressure pilot valve has to be activated/deactivated (event 2). The controller I/O sends activation signals to the solenoid driver at the right time (event 3) and the driver switches on or off the pilot valve (event 4). In the test system, power to the solenoid is switched on due to the implemented no-power condition.

3.4 Hydromechanical events 5-8

Explanation is with reference to [2]. The pilot valve movement (event 5) causes the pressure inside the pilot chamber to build up (event 6) and the main valve starts closing (event 7). When the main valve is almost closed the pressure in the cylinder drops (event 8).

3.5 Simulation results

Fig. 8 and 9 [2] show simulation results related to shaft angle for a cylinder operating as a motor at 20 rpm and 90 rpm. The cylinder displacement is 1.8 l and the valve system is dimensioned for operation up to 90 rpm. The system high pressure is 210 bar and the low pressure is 10 bar. The graph of the cylinder pressure in Fig. 8 shows late closure of the high-pressure valve in the expansion stroke as cylinder pressure has not reached low pressure when the low-pressure valve opens, and when the low pressure valve opens cylinder pressure drops immediately. In Fig. 9 the same operation has optimal timing, i.e. cylinder has been decompressed after closure of the high-pressure valve so that cylinder pressure is equal to low pressure when low-pressure valve is closed.

Comparing cylinder pressure in Fig. 8 and Fig. 9 it is seen, that at 20 rpm in Fig. 8 there is hardly any pressure loss across valves (cylinder pressure is almost constant except when switching between high-pressure and low-pressure) while at 90 rpm it begins to vary with cylinder movement, i.e. there is a pressure loss depending on the flow through the valves. These pressures are reflected in the torque curves as well.

The torque curves show that torque from the cylinder varies with shaft angle and pressure. To be noticed is a slight negative dip on the torque curve around TDC (360°). The reason is the compression of the oil that happens just before TDC and increase the torque working against the rotation.

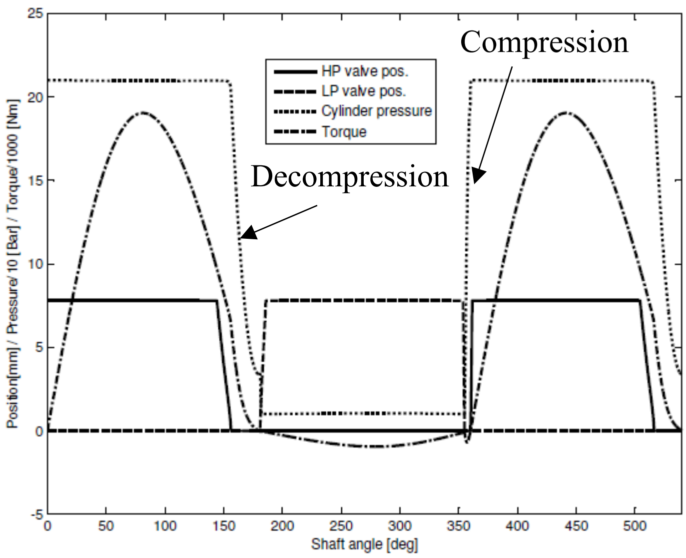

Fig. 8: Simulation of motor operation with a delta pressure of 200 bar and 20 rpm with a 1.8 l cylinder. TDC is at 0°/360°

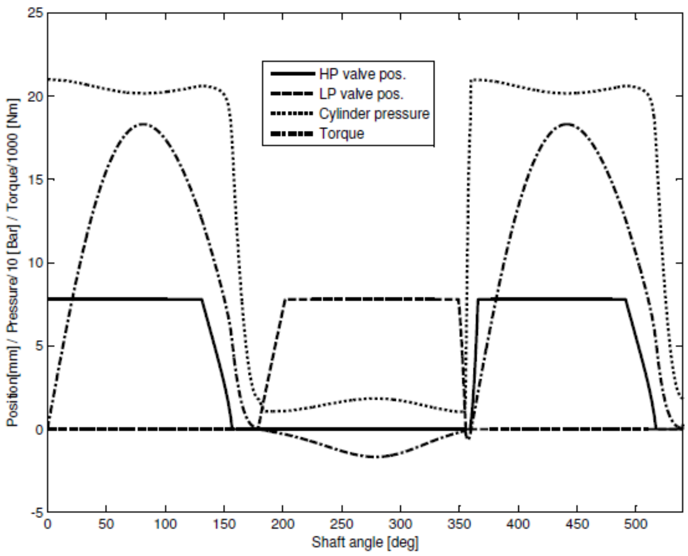

Fig. 9: Simulation of motor operation with a delta pressure of at 200 bar and 90 rpm with a 1.8 l cylinder. TDC is at 0°/360°

3.6 Motor test results

Fig. 10-11 show examples of measurement data from the 5 cylinder 3.3 l/rev digital motor. Explanation to the legend: P_h *Act.* is control signal to solenoid driver for the high-pressure pilot valve, P_l *Act.* is activation signal to the solenoid driver on the low-pressure pilot valve, *Cyl pres.* is cylinder pressure, P_h *Pilot* is pilot pressure on the high-pressure main valve, P_l *Pilot* is pilot pressure on the low-pressure main valve, *Shaft pos.* is shaft position.

When a valve is shifted, the corresponding pilot pressure changes in two steps. First step is the pressure where the main valve is moving, second step is the stable pressure that the pilot valve connects the pilot chamber to. This way it is possible to estimate shifting time.

Fig 10: at 0.6 s the controller sends signal to shift (close) the low pressure valve. The valve closes just before the piston reaches TDC, and accordingly the oil is compressed. At approximately 0.64 s the controller sends signal to switch (open) the high-pressure valve. The high-pressure valve starts opening at TDC. From the cylinder pressure an uneven progress is seen, the closing of the low pressure valve happens later than what is needed to compress oil to full pressure. The remaining increase happens when the high pressure valve opens.

In Fig. 11 the same sequence is seen between 0.8 s and 0.9 s but here the compression is more precise, and the cylinder pressure almost reaches high pressure before the high-pressure valve is opened. Fig 12 is a zoom of Fig. 11. It confirms that compression is close to ideal, missing less than 10 bar. What also becomes visible is that cylinder pressure decreases slightly before the high pressure valve is opened. This is due to the piston moving downwards and expanding the cylinder chamber slightly.

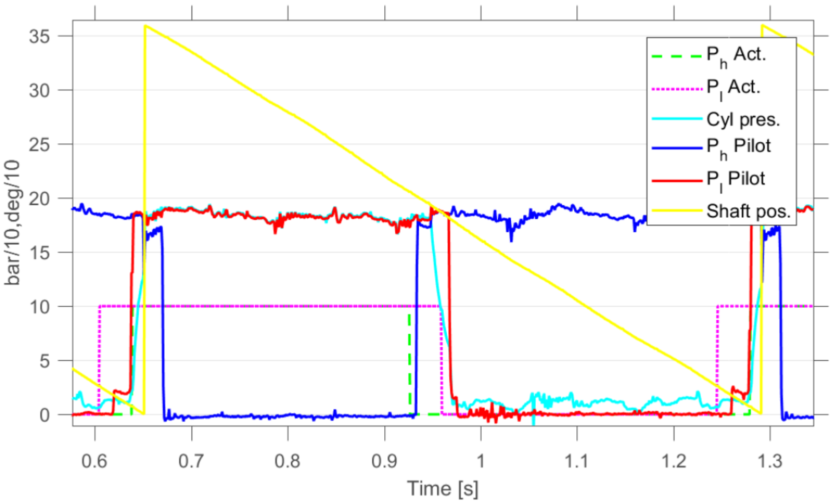

Fig. 10: Operating conditions, mean values: High pressure: 186 bar, low pressure: 15 bar, speed: 94 rpm

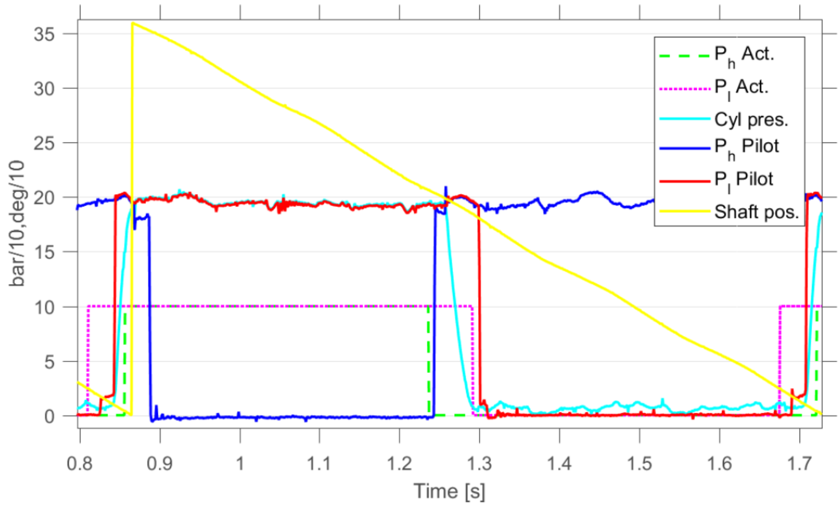

Fig. 11: Operating conditions, mean values: High pressure: 198 bar, low pressure: 10 bar, speed: 69 rpm

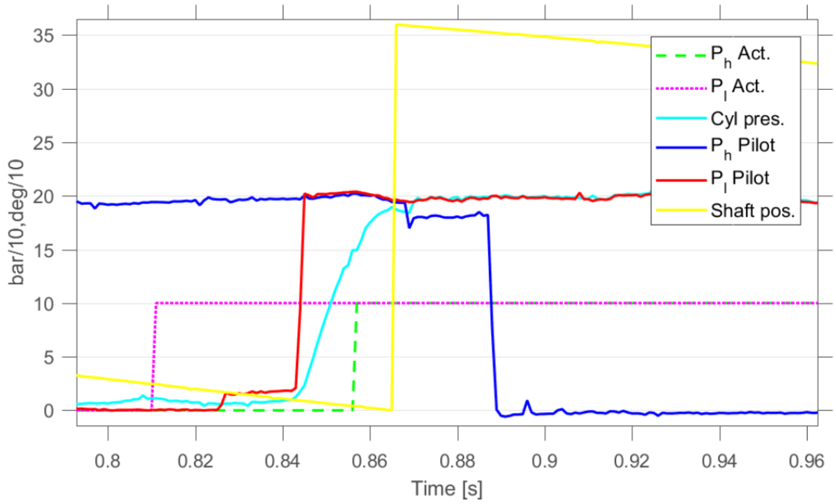

Fig. 12: Operating conditions, mean values: High pressure: 198 bar, low pressure: 10 bar, speed: 69 rpm

As is obvious, valves need to shift prior to TDC or BDC. When rotating in the opposite direction, optimal shifting takes place at shaft angles mirrored to the other side of TDC or BDC.

3.7 Overpressure protection

Overpressure protection is integral in the design of the high pressure main valve. From Fig. 2 it is seen that if high pressure is put on A2 and A3, then if the cylinder pressure rises above high pressure the net force only need to overcome spring force to open the valve.

3.8 Anti-cavitation

To prevent cavitation a check valve may be connected between the cylinder chamber and either low pressure or tank.

4 CONTROLLABILITY

A few of the control- and estimation options are briefly described in this section without further proof or illustration.

4.1 Lock and start

If all valves in a motor are closed, a load torque will cause a torque equilibrium from pressurized cylinders that balances the load. In case movement of the motor against the load is intended, cylinders that generate torque in the direction or the intended movement can be connected to high pressure one by one, and cylinders generating torque against the intended movement can be connected to low pressure.

4.2 Idle

If all high-pressure valves are closed and all low-pressure valves are open, the motor will rotate with pressure losses from oil reciprocating through low pressure valves only, and with only the friction generated from low pressure in the motor.

4.3 Torque estimate

By knowing shaft position and thereby each cylinder position and which cylinders are connected to low pressure and which are connected to high pressure, an estimate of the generated torque can be given.

4.4 Stop of motor

The motor can be stopped simply by closing all valves. This should be done from low speed only, depending on the size of the attached inertia.

4.5 Full-stroke displacement control

Displacement can be varied by setting some cylinders to idle. With more cylinders in a motor, there are more cylinder combinations that provide low-ripple displacement.

A five cylinder motor has two low ripple displacements, 0 and 5 cylinders. A 10 cylinder motor has three low ripple displacements, 0, 5 and 10 cylinders.

An 18 cylinder motor can be operated with 0, 6, 9, 12 and 18 cylinders, all with very low ripple. If a little more ripple is acceptable, also 15 and 4.5 are possible.

If more motors are mechanically connected, a larger number of cylinders become available, and secondary control becomes possible, the quality of which increase with and increasing number of cylinders.

5 COMMERCIAL DIGITAL HTLS MOTOR

5.1 Valve blocks

The valve system is modularized with one valve block for each cylinder, embedding all valve functionality. The valves fit Imenco Bauer Hydraulics motor program from 5 to 18 cylinders with displacements from 2.6 to 32.6 l/rev. The blocks are bolted to the housing of the motor and connects to oil supply galleries and cylinder connections.

The valve capacity of 170 lpm motor flow means that rated flow for a digital 5 cylinder motor is $5 \cdot 170$ lpm = 850 lpm, and for an 18 cylinder motor it is 3060 lpm. As a comparison, traditional motors from Imenco Bauer Hydraulics have capacities of approximately 500 lpm for 5 cylinder motors and 1000 lpm for 18 cylinder motors. In addition, the pressure losses of the traditional valves are 10-15 bar at rated flows, whereas the average pressure loss of the digital valve system is 4 bar at rated flow.

5.2 Digital Bauer HMB5

In May 2017, the first digital HTLS motor was unveiled officially [5]. The motor is an Imenco Bauer Hydraulics HMB5 digital motor, Fig. 13.

It is a self-contained digital motor with embedded sensors, electronics and software. The digital distributor valve system consists of a valve block for each cylinder, control electronics mounted in the centre of the motor, power cables to the solenoid valves, pressure sensors, temperature sensor and shaft encoder.

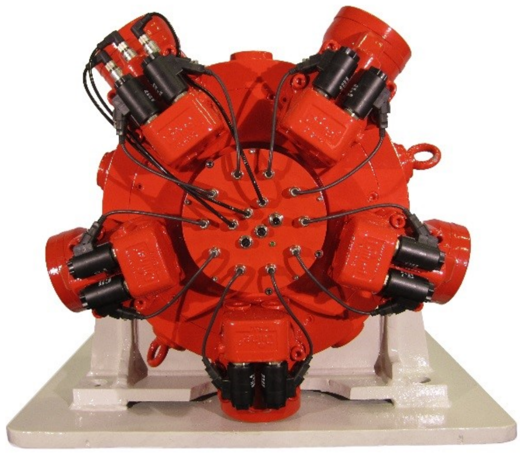

Fig. 13: Imenco Bauer Hydraulics HMB5 digital hydraulic motor

Inside the motor housing the motor mechanics are the same as for conventional motors, meaning that the digital motor is based upon a proven, robust motor design.

The control box is supplied by 48V DC and is controlled via an Ethernet Powerlink network. This network also allows the connection of several motors in master-slave configurations, where all cylinders in the connected motors are controlled individually by the master motor so that controllability effectively is the same as for a multi-cylinder motor. The system is designed for rough maritime usage and is IP67 protected.

5.3 Digital Bauer HMK18 design

A design study on using the same valve block to distribute oil flow in Imenco Bauer Hydraulics HMK frame shows a motor with peak power of close to 1.4MW, 3000 lpm flow capacity, 130000 Nm peak torque, 90 rpm rated speed and a multitude of control options. Overall dimensions are Ø980 mm, length of approximately 700 mm from the mounting flange to the rear end of the motor and a weight of 2100-2300 kg. An illustration is shown in Fig. 14.

Fig. 14: Imenco Bauer Hydraulics HMK18 digital hydraulic motor

6 CONCLUSION

The presented digital distributor valve promises to increase efficiency, speed, power and controllability over the traditional motor, in the end yielding simpler and more cost effective designs with more features. Timing of the valve operation is one critical area of these motors that has been dealt with. A production design of a digital HTLS motor is presented showing a viable design for a mass-produced system.

7 NOMENCLATURE

CCW	Counter-clock wise
CW	Clock wise
HP	High Pressure
HTLS	High Torque Low Speed
LP	Low Pressure
BDC	Bottom Dead Centre
TDC	Top Dead Centre

8 REFERENCES

[1] Artemis Intelligent Power LTD, “Technology”, http://www.artemisip.com/technology/

[2] Chapple, P., Lindholdt P.N., Larsen, H.B., “An approach to digital distributor valves in low speed pumps and motors”, Proceedings of the Bath/ASME symposium on fluid power and motion control, FPMC 2014, Sep 10-12, 2014, Bath, United Kingdom

[3] Payne, G. S., Kiprakis, A. E., Ehsan, M., Rampen, W. H. S., Chick, J. P. and Wallace, A. R., 2007, “Efficiency and Dynamic Performance of Digital DisplacementTM Hydraulic Transmission in Tidal Current Energy Converters,” Journal of Power and Energy, Proc. IMechE, Vol. 221, Part A, pp. 207-218

[4] Wadesly L., 2011, “Optimal System Solutions Enabled by Digital Pumps”, http://www.artemisip.com/sites/default/files/docs/2011-03-23%20Optimal%20system%20solutions%20enabaled%20by%20digital%20pumps.pdf

[5] Norshipping, 2017, “Press release: Diinef technology enables launch of world’s first digital hydraulic motor with Imenco Bauer Hydraulics”,

http://nor-shipping.com/press-release-diinef-technology-enables-launch-worlds-first-digital-hydraulic-motor-imenco-bauer-hydraulics/