Final report

1. Project details

Project title	Energieffektivt og selvstændigt hydraulisk drevkoncept
File no.	J.nr. 64018-0094
Name of the funding scheme	EUDP18-I Energieffektivt
Project managing company / institution	Aalborg University
CVR number (central business register)	29102384
Project partners	Bosch Rexroth A/S
Submission date	30 March 2023

Content

2. Summary

English version

The objective for this project was to develop a standalone hydraulic drive concept characterized by being highly energy efficient, scalable, durable as well as commercially attractive and in-line with industrial trends. The approach to this task took offset in the use of speed-variable simple external gear pumps to eliminate the majority of throttle losses compared to conventional technology, combined with simple controllable valves to enable drive functionalities. The drive functionality was to be realized through innovative control methods developed in the project, and to develop condition monitoring methods enabling monitoring measures of pump leakage of friction torque online, in line with industrial trends. The results obtained are several efficient drive concepts, including control methods very different from the ones conventionally used in hydraulic drives, allowing for motion and force control, bumpless transition between these control modes as well as smooth engagement of flow regeneration. Maximum drive efficiencies of up to 92% with and overall average efficiency of 85% for the entire operating area (all four quadrants) was achieved on the hydraulic side, and for the total drive from electric supply to hydraulic cylinder output power maximum drive efficiencies of up to 77% with an overall average efficiency of 51% has been achieved.

Danish version

Projektets objektiv var at udvikle et selvstændigt hydraulisk drevkoncept karakteriseret ved at være meget effektivt, skalerbart, holdbart og kommercielt attraktivt og I tråd med industrielle trends. Opgaven tog udgangspunkt I brugen af hastighedsvariable simple gearpumper for at eliminere hovedparten af drøvletabene sammenlignet med eksisterende teknologi, kombineret med simple styrbare ventiler for at skabe grundlag for drevfunktionaliteter. Drev-funktionaliteten skulle realiseres med gennem styring/reguleringsmetoder udviklet i projektet og monitoreringsfunktioner skulle udvikles for at kunne monitorere pumpelækage og friktion online, i tråd med industrielle trends. De opnåede resultater indbefatter adskillige drevkoncepter inklusive styrings-/reguleringsmetoder som er meget forskellige fra dem der konventionelt anvendes i hydrauliske drev, og som giver mulighed for bevægelses- og kraftregulering, glat overgang imellem disse reguleringsmodes samt glat aktivering af flow-regenerering. Maksimale drev-virkningsgrader op til 92% med en gennemsnitlig virkningsgrad på 85% for hele driftsområdet (alle fire kvadranter) blev opnået på den hydrauliske side, og for det totale drev fra elektrisk forsyning til hydraulisk cylinderudgangseffekt en maksimal drevvirkningsgrad på op til 77% med en gennemsnits-virkningsgrad på 51%.

3. Project objectives

3.1. Technology Developed & Demonstrated

The technology developed and demonstrated is related to the field of energy efficiency and within the subject area of hydraulic drive systems. The technology is highly electrified and rely on a “fluid gear” from rotating motion to linear motion. The technology therefore relies on a variable-speed electric motor and pumps to realize the linear motion or force of a hydraulic cylinder, enabling the possibility to reduce throttle losses substantially and thereby increase the energy efficiency.

3.2. Background & Premise for the Project

Hydraulic cylinder drives are used extensively in almost all industry sectors due to their high force and power densities, and include renewable energy systems, agricultural and construction machinery, marine and offshore systems, manufacturing systems etc. A major portion of these drives are comprised by single rod cylinder drives, conventionally controlled by means of inefficient flow control valves supplied by centralized voluminous hydraulic power units (HPU's). Despite their extensive usage, the main design principles and topologies of hydraulic cylinder drives have not improved notably since the 1950s, partly attributed to the relatively small research and R&D efforts compared to the related industry. As a result, common design principles remain based on empirical, static and sequential methods, and the nature of developments has mainly been evolutionary rather than innovative.

However, trends suggest efforts to avoid the inefficient throttle driven main flow and large fluid volumes of hydraulic power units. This is sought realized using pumps to control cylinders directly (**direct drive**) combined with small confined "onboard" flexible fluid volumes. Despite the potential for improved energy efficiency, pump controlled direct drives for differential cylinders have failed to break through on a broad scale, even though these are available as custom drive designs for specific applications. The reason for the missing breakthrough of this technology is likely because its competitor, conventional controllable valve(s) supplied by a centralized hydraulic power unit(s), is well proven with several decades of track record. Even though highly inefficient, the conventional technology has some beneficial characteristics which are; **four quadrant operation, high drive stiffness, high durability, reliable operation, high scalability, proper fluid cooling and filtration and relatively lower costs** (compared to pump controlled drive solutions).

Presumably the **premise** for a successful industry penetration is that pump controlled direct drive technology must provide the same characteristics as the conventional valve drive technology (mentioned above in **bold** text), while being more energy efficient, more compact and at a lower or matching cost.

3.3. Project Idea & Drive Architecture for Investigation

The idea of the project was the development of a drive concept in line with the premise outlined above, with the basic idea motivated by the drive concept depicted in Fig. 1.2. (A). Here the forward flow (flow into the cylinder) is realized directly with a pump, while the return flow (flow out of the cylinder) is throttled via simple 2/2 valves. If the valves are leakage-free this drive concept is self-locking, i.e. if the electric motor and the valves are not activated, the cylinder piston is locked. Furthermore, the separate forward and (common) return flow paths allow all the return flow to be cooled and filtered. Furthermore, if the fluid needs to be heated, the cooling function may be switched off, and the throttle losses will heat the fluid. The valve-controlled return flow allow to control the lower chamber pressure level, hence the drive stiffness which improves its application range. Furthermore, the drive architecture allows a certain level of fluid circulation, ideally without influencing the piston motion, and hence the ability to cool/heat the fluid in a process "parallel" to the piston motion. This feature is also potentially relevant with regards to ensuring proper lubrication of pump bearing(s).

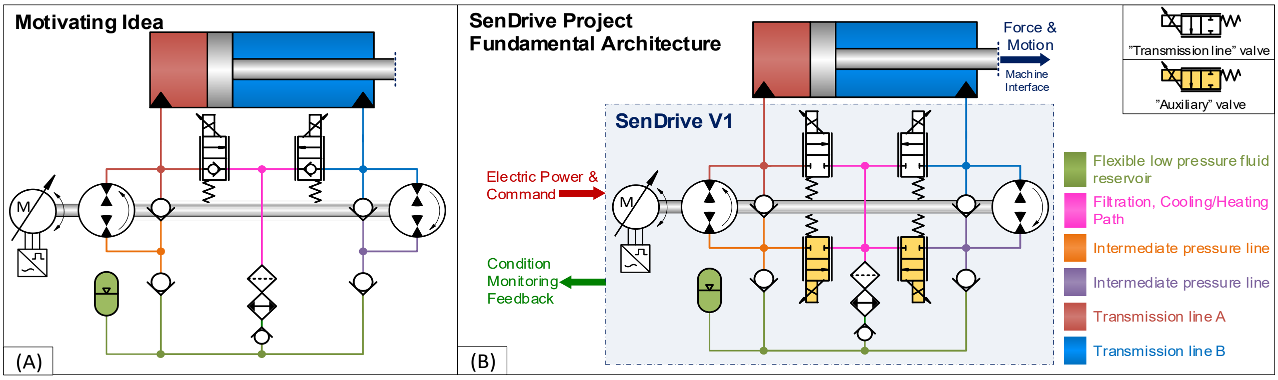

Fig. 1.2.: (A) Motivating drive concept. (B) Drive concept subject for investigation (SenDrive V1).

As the temperature and contamination level may be kept within the design range of the components, this suggest that the check valves, 2/2 valves, cylinder and accumulator can maintain their expected durability.

A main question regarding the success of such a drive concept is however, whether the pumps can be modified in a way that allow these to exhibit high pressure on the suction port without a case drain. In the event of the successful realization of such a drive, the constantly pressurized chambers allow for an immediate piston response whenever the pump shaft is rotated (provided the valves are controlled properly), while exhibiting no shaft torque (hence electrical losses) with zero pump shaft speed.

A drawback with this drive concept in Fig. 1.2. (A) is that no power can be recovered in aiding load cases. In such cases all the power transferred from the load to the drive is converted into heat via friction and throttling losses. This has led to a modification into the drive concept in Fig. 1.2. (B), with addition of two valves allowing to pass flow from the pump suction sides to the reservoir, hence allowing to regenerate energy (due to oppositely oriented pump torques, and the ability for load to drive the pump shaft letting the electric motor operate in generator mode). This drive is denoted *SenDrive V1* and forms the basic drive architecture subject for study in the project. The basic possibilities for realization of piston motion are shown in Fig. 1.3.

3.4. Project Objective

The objective of this project was to develop an energy efficient self-contained (standalone) direct cylinder drive concept that is significantly more efficient than conventional technology, generally applicable, and providing a more attractive alternative to conventional inefficient valve-cylinder drives as the foundation of hydraulic cylinder drive technology. The idea took offset in using standard off-the-shelf low-cost components but a high degree of controllable components in combination with innovative control structures in software to realize the necessary versatility and functionality, while aiming at cost competitiveness, high efficiency, and trends in terms of electrification and condition monitoring.

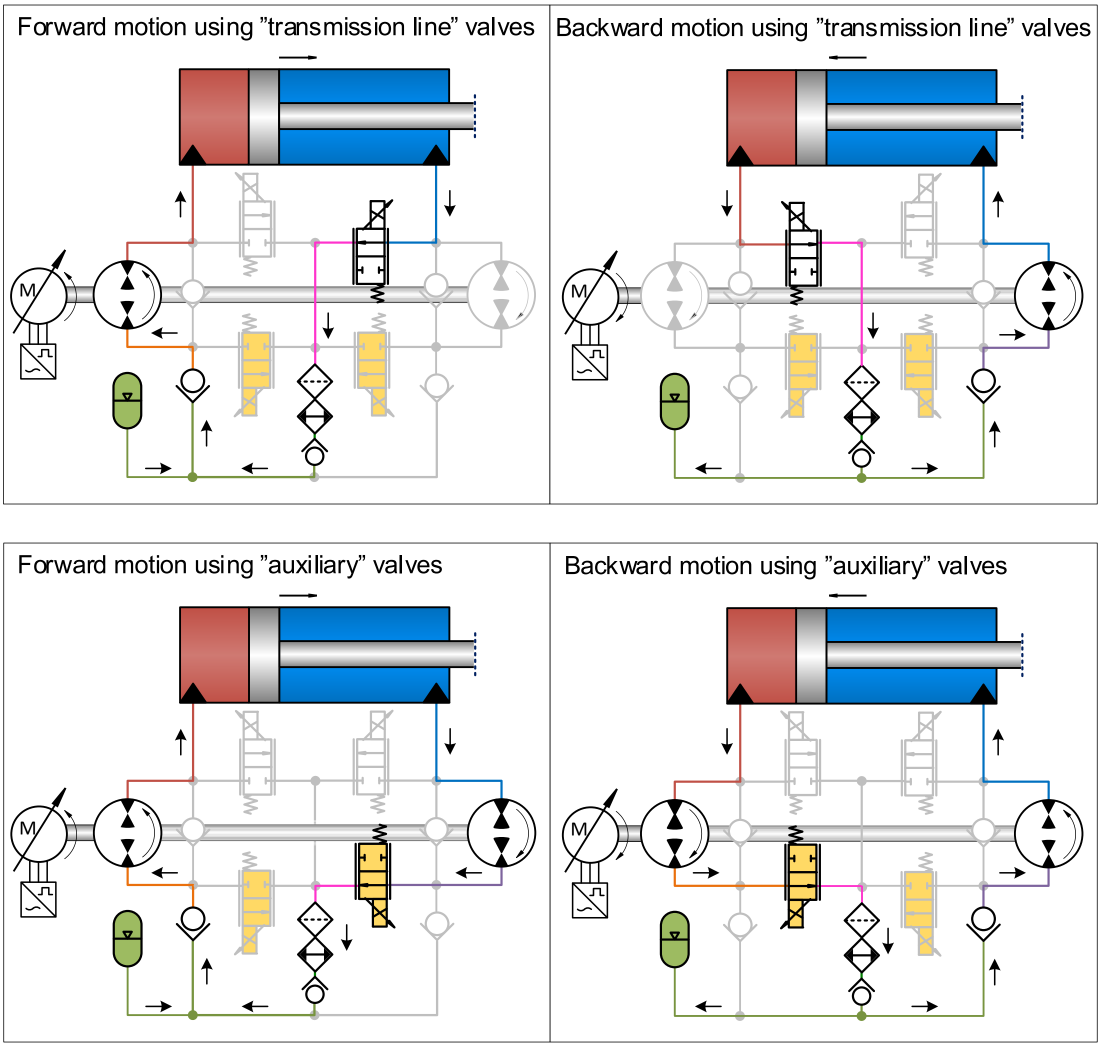
Forward motion using ”transmission line” valves
Backward motion using ”transmission line” valves
Forward motion using ”auxiliary” valves
Backward motion using ”auxiliary” valves

Fig. 1.3.: Schematics illustrating the drive function possibilities.

3.5. Criteria for the Project Work

In the work conducted, focus was always on *a high energy efficiency, scalability, durability, and commercial attractiveness*. Hence the project work always focused on the criteria below:

1. Utilization of standard non-high-end components to the highest possible extend.
2. Utilization of components available in large flow and pressure ranges (high level of scalability).
3. Ensuring that components were kept within their design ranges to the highest extend possible, and within recommended temperature and fluid contamination levels.
4. Aiming on control functionalities aiding to a high average energy efficiency, while achieving proper drive dynamics, robustness and simplicity in commissioning and usage (large application range).

4. Project implementation

4.1 Project Evolvement

The project evolved over three main stages, with these related to the initial drive development, first generation of drives (Generation I) and a second generation of drives (Generation II). These as well as control developments are described below.

4.1.1. Initial Drive Development

To acquire experience with the proposed drive architecture SenDrive V1 depicted in Fig. 1.2. (B) from an early point in the project, a 7.5 [kW] input power prototype drive was designed immediately after project start, with the components illustrated in Fig. 4.1. It was chosen to utilize Bosch Rexroth external gear pumps AZxx series due their simple design and low cost, while accepting to limit maximum pressures to 250-280 [bar] due to the aluminum housing. Furthermore, the M-SR type check valves and 2/2 way KKDSR1/KKDSR2 proportional valves with VT-SSPA plug-in amplification stages were chosen due to their relatively low cost.

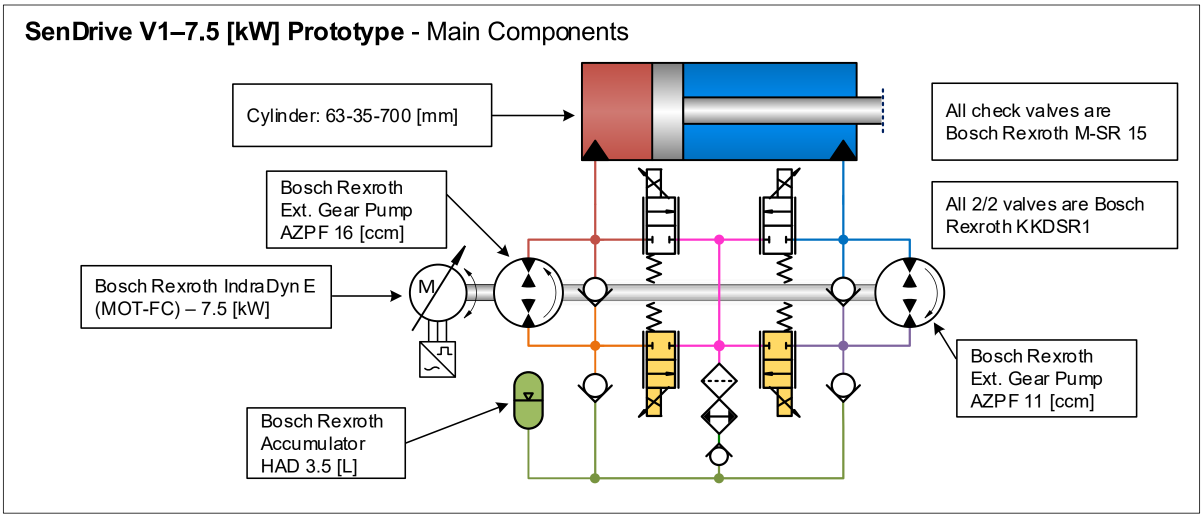

Fig. 4.1.: Main components of SenDrive V1 - 7.5 [kW] prototype.

The possibility to allow for pressurized pump suction sides was crucial for the realization of the SenDrive V1, and the limiting elements in this regard is the shaft sealings (inner and outer). Experimental tests revealed that the outer shaft sealing was extruded at approximately 10 [bar] pressure difference across the sealing. Hence an alternative sealing solution was needed. The resulting choice was the so-called Trelleborg Turcon Roto

Glyd Ring DXL due to its ability to withstand high pressure differences at reasonably high speeds (see Fig. 4.2. (A)). Even though limited at shaft speeds above 2100 [rpm], this should work if installed properly.

A specification for the associated modification of tandem pump for this sealing solution was made, encompassing one sealing for the shaft connection (to ambience), and two seals hydraulically separating the two pumps (see Fig. 4.2. (B)). In the end the cost of the required sealings, the customized three-part connector plate and two-part endplate required, would more than double compared to the original tandem pump.

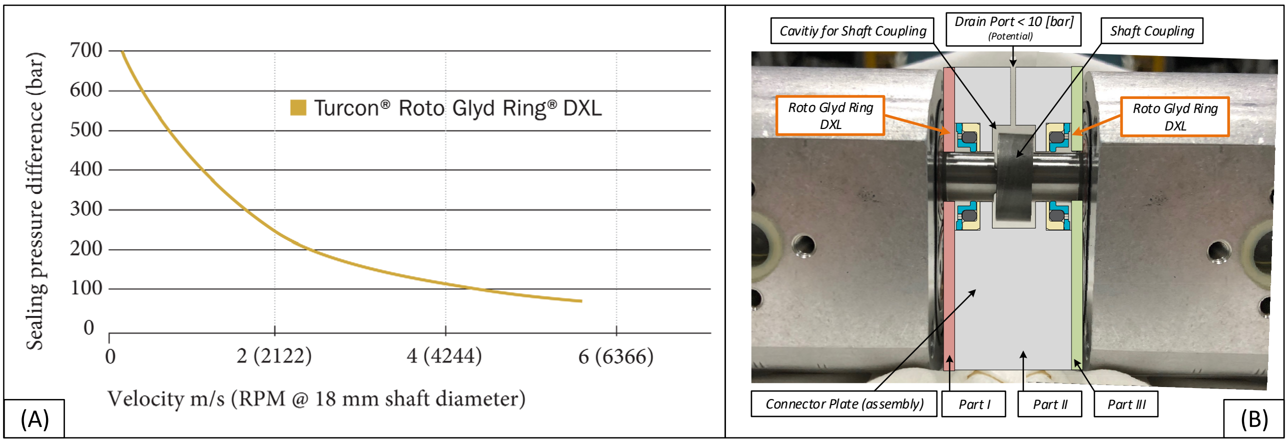

Fig. 4.2.: (A) Limitations for shaft seal. (B) Pump modification necessary to hydraulically separate the pumps.

4.1.2. First-Generation Drives (Generation I)

The project group assessed the above mentioned significantly increased cost compared to the basic (off-the-shelf) tandem pump and the missing track record of the sealing solution, to potentially compromising the outcome of the project both technically (durability / reliability) and commercially. For this reason, the SenDrive V1 architecture was discarded, and an alternative established, denoted SenDrive V2 (and later SenDrive V3). See Fig. 4.3. The main difference from SenDrive V1 is the flow rectification in front of the pumps.

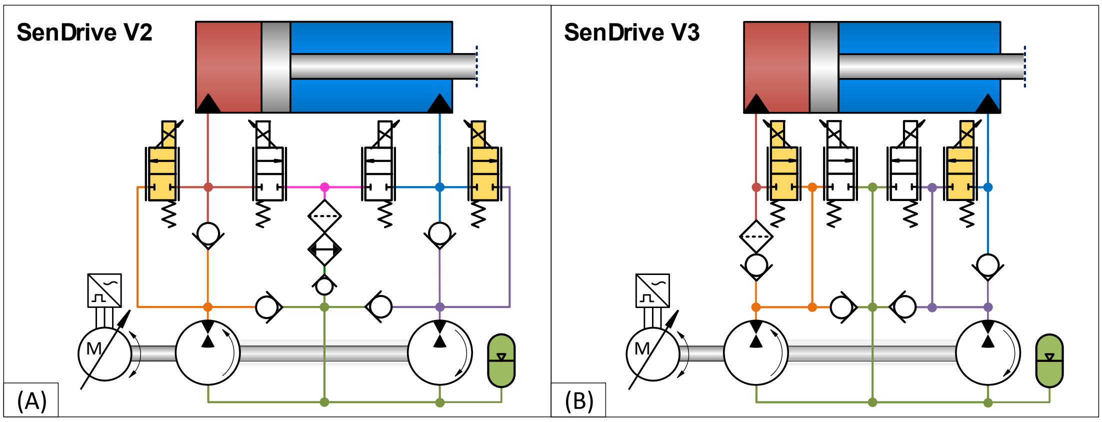

Fig. 4.3.: (A) Modified drive concept, SenDrive V2. (B) Further modified drive concept, SenDrive V3.

The forward flow paths remain separated, and a common return path allow for cooling/heating and fluid filtration. Furthermore, the auxiliary valves remain to allow for energy regeneration, whereas only the transmission line valve flows are cooled/heated and filtrated as opposed to all the return flow in the SenDrive V1 concept. Another challenge introduced with the SenDrive V2 concept, is the necessity to compress the chamber in front of the forward flow pump, prior to actuation of the cylinder piston. This introduces a lag when actuation of the piston is intended. This lag may be small dependent on the volume sizes (orange and purple volumes in Fig. 4.3. (A)) and may be further reduced via the drive controls.

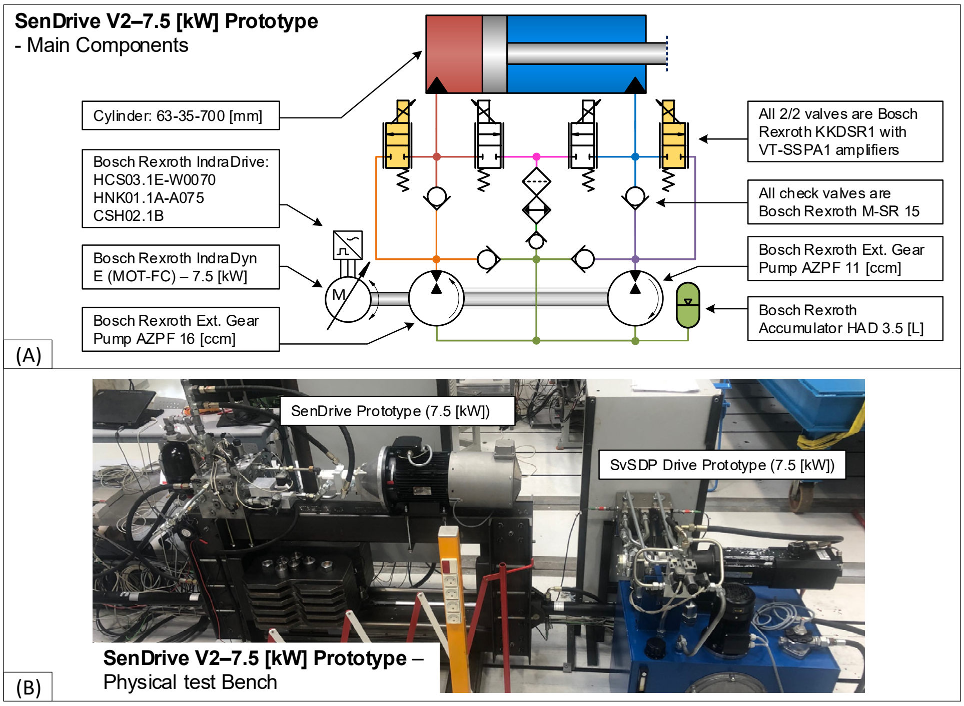

Fig. 4.4.: (A) Components used in SenDrive V2 prototype. (B) Physical test bench with SenDrive V2 prototype with the SvSDP drive prototype as load.

The SenDrive V2 was realized in 7.5 [kW] input power prototype to gain experience, validate models and initial control developments. The prototype was been installed at AAU, and is depicted in Fig. 4.4. The investigation into cooling functionalities (WP1 / P1.4.) considered in Section 4.4., have suggested that cooling may be realized directly on the hydraulic manifold. The success of such cooling functionalities allows to remove the common return flow path, realize filtration via a “high pressure approach” and to downsize two of the valves. The drive concept resulting from this modification is denoted SenDrive V3 and is illustrated in Fig. 4.3. (B). Ideally, the transmission line (white) valves only need to be active if leakage conditions and/or a difference in the area or displacement ratios causes situations where the flows cannot be extracted from the transmission lines, such that an unintended and excessive pressure build-up occur.

The control effort is however somewhat more complicated compared to SenDrive V1 and SenDrive V2, as the valves cannot extract fluid from the transmission lines separately. In the SenDrive V3 concept, the flow through two of the valves depend on the flow through the two other valves, respectively. However, the project group assessed these challenges to be manageable, and decided to focus efforts on SenDrive V3.

It is notable that the “original” SenDrive V3 drive concept depicted in Fig. 4.4. (A) and the one benefitting from pilot operated 2/2 valves in Fig. 4.4. (C), both are “quasi” self-locking due to valve leakage. These may be modified to “truly” self-locking drives as depicted in Fig. 4.4. (B) and (D), respectively. The proper operation of these strongly depend on the drive controls.

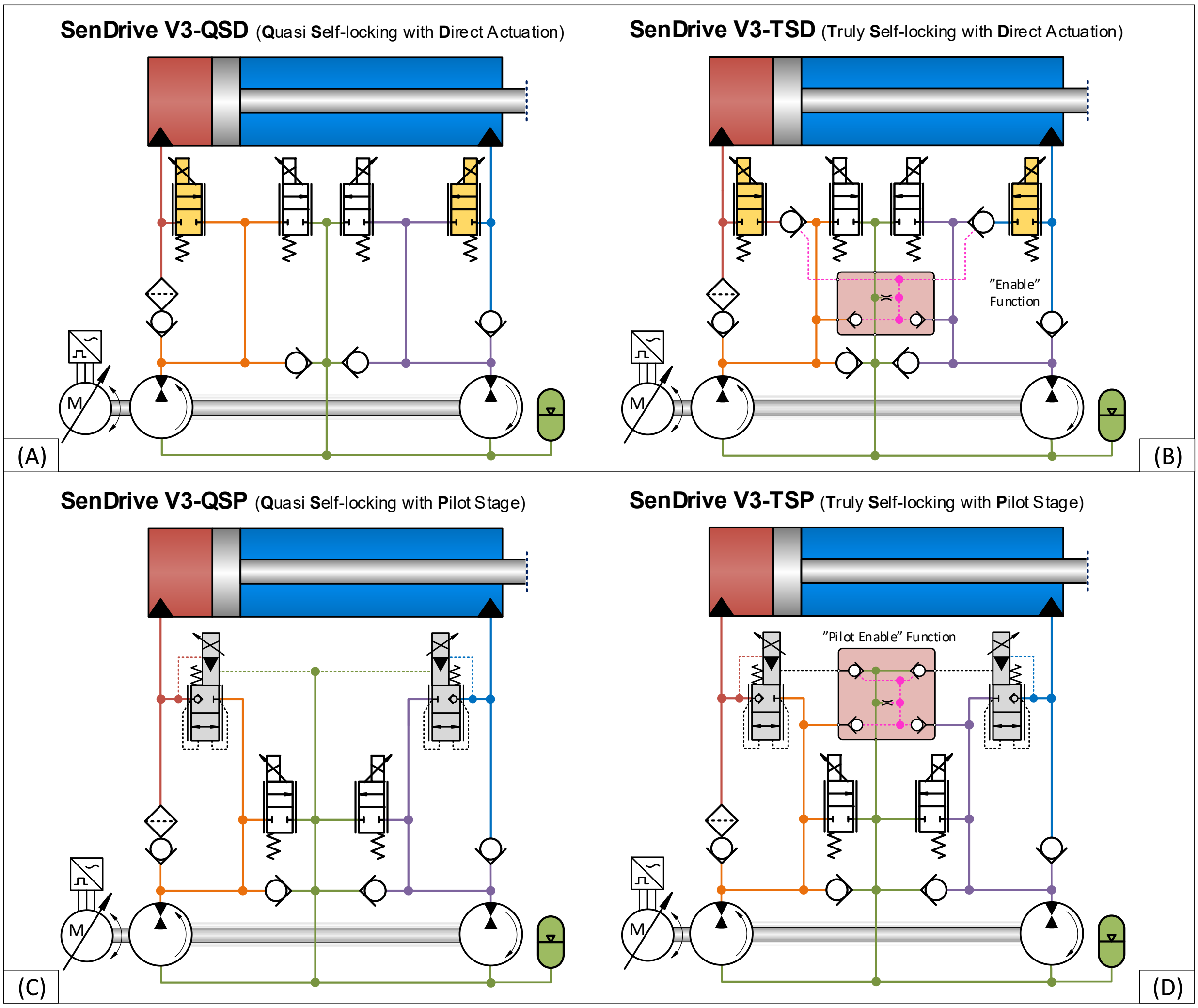

Fig. 4.4.: "Quasi" and "truly" self-locking variants of the SenDrive V3 concept, with direct- or pilot actuated valves.

4.1.3. Second-Generation Drives (Generation II)

As outlined above, the SenDrive V3 architecture allows to realize the cooling and filtering functionality without guiding the hydraulic fluid through a dedicated cooling/filtering path. Furthermore, in the SenDrive V3 architecture, the transmission line valves entirely control the return flow from the cylinder chambers, and the auxiliary valves only handles the potential effective flow mismatch in case of nonmatching cylinder area and displacement ratios, and hence the auxiliary valves may be downsized significantly compared to those of the SenDrive V2. However, considering larger drive power sizes it was found that the generally higher flows require several KKDSR1 valves in place of each valve in Fig. 4.1., as these are only available with a maximum flow of 58 [L/min], ultimately increase the valve costs significantly. Hence, a sensible choice of valves as alternative to the KKDSR1 valves fell on the 4/2-way 4WREE EA valve with onboard amplification stage. Realizing a 2/2 way function by connecting the ports, a substantial increase in the valve flow capacity is achieved, compared to the KKDSR (approximately 150 [L/min] @ ΔP = 10 [bar] with a 4WREE-10EA-75). Also, with this valve one achieves approximately twice the bandwidth as compared to the KKDSR1 valve (≈ 45 [Hz] compared to ≈ 22 [Hz]), a more "regular/predictable" flow as the 4WREE is not pressure compensated, and as the valve spool position is available from measurement. The latter feature is also useful for diagnosis purposes.

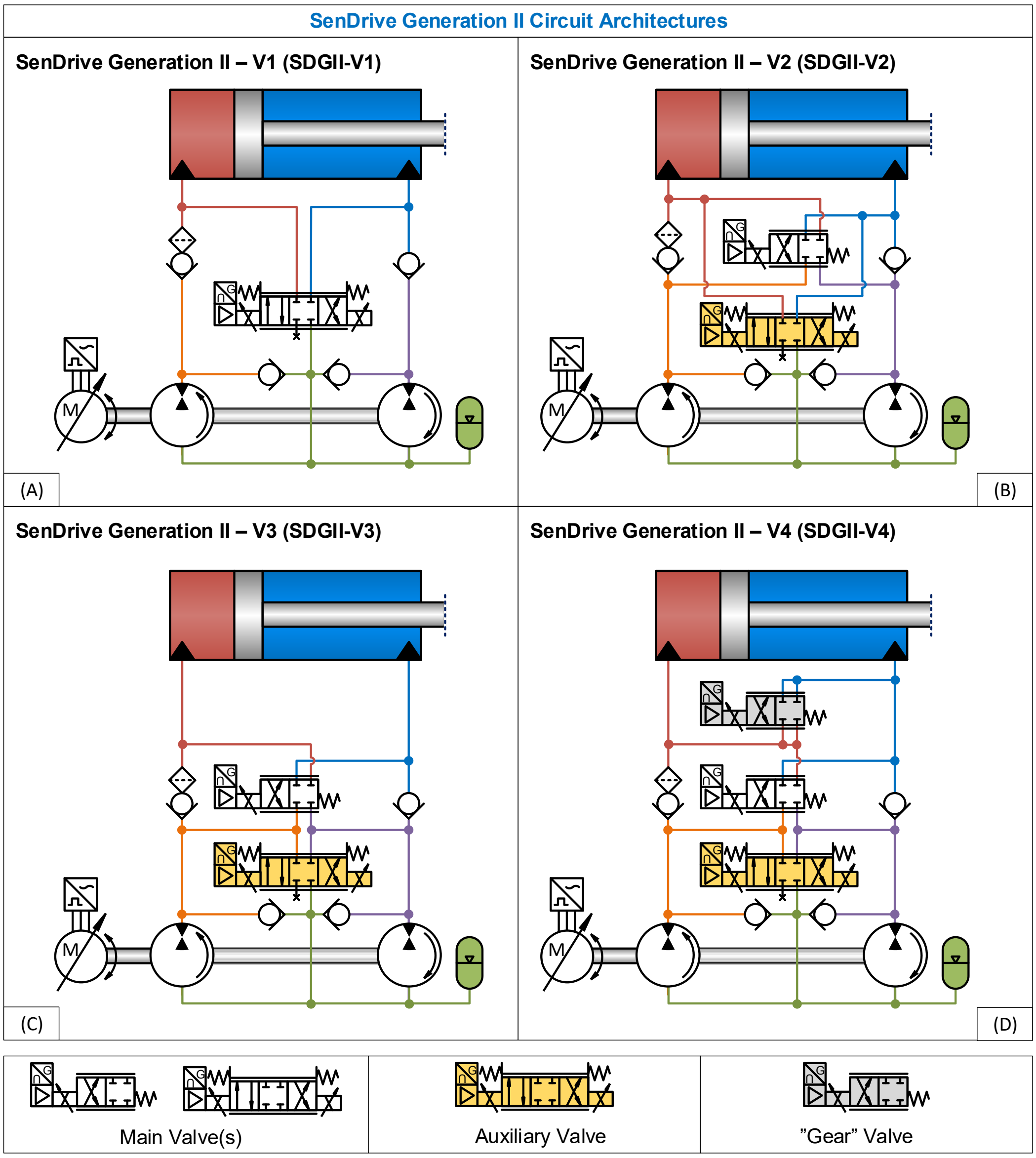

Fig. 4.5.: (A) SenDrive GII-V1 main function architecture. (B) SenDrive GII-V2 main function architecture. (C) SenDrive GII-V3 main function architecture. (D) SenDrive GII-V4 main function architecture.

As an alternative to the port connections mentioned above, one might also use a single valve for two flow paths, such that e.g. the SenDrive V3 functionality may be realized as depicted in Fig. 4.5 (C). With a higher bandwidth and spool position feedback, this seems to be the more feasible solution.

Based on the above considerations, a "new generation" of SenDrive architectures, denoted "SenDrive Generation II" were established. Four different architectures were established as depicted in Fig. 3.3. As may be seen, SenDrive V2 resembles SenDrive GII-V2 and SenDrive V3 resembles SenDrive GII-V3, to a high extend regarding their main functionality.

SenDrive GII-V1 is simple, but does not allow for energy regeneration, and will exhibit a "high" level of heat generation in load aiding quadrants. SenDrive GII-V2 and SenDrive GII-V3 does allow for energy regeneration, whereas leakage will be somewhat smaller for SenDrive GII-V3 compared to SenDrive GII-V2. SenDrive GII-V4 realizes the functionality of SenDrive GII-V3 plus a "gear" function, allowing to increase the speed of piston extension significantly when the rod side pressure is higher than the piston side pressure. This may especially be useful in press applications and similar. Also, due to the proportional flow control function, the “gear change” may be realized in a seamless/bump-less way, with proper control functionality. The auxiliary valves have the purpose similar to that of SenDrive V3, i.e., to handle a potential effective flow mismatch in case of nonmatching cylinder area and displacement ratios. Hence these valves may be chosen with a small nominal flow. Also, the presence of this valve allows for a certain level of fluid circulation, which may be relevant dependent on the potential pump wear resulting from low shaft speed-high torque loading of the pump journal bearings. To illustrate the functionality of the SenDrive GII-V3, a four-quadrant diagram is depicted in Fig. 4.6.

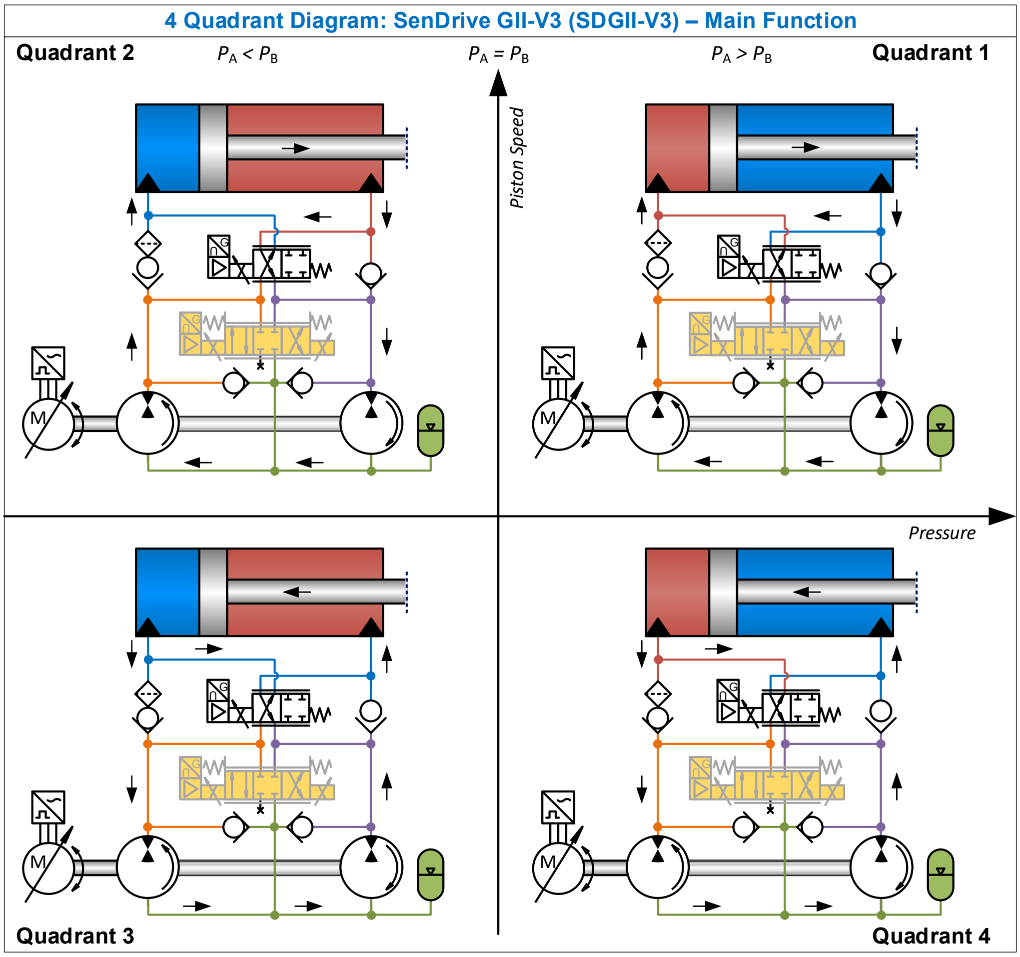

Fig. 4.6.: Four quadrant diagram for the main function of SenDrive GII-V3.

The Generation II drive architectures was found feasible in all relevant aspects, and for this reason a prototype was developed and realized, to validate the associated drive controls, and properties in general. The schematics of the prototype test bench is depicted in Fig. 4.7. The cylinder to be controlled by the SDGII-V4 prototype and its load is realized as tandem cylinder, essentially being two identical cylinders mounted back-to-back with these sharing a single piston rod. This configuration allows to limit test bench steel work significantly and avoids potential misalignment issues with the cylinders and guides etc. The main drawback of this test bench design is the low inertia loading of the cylinder piston not carrying additional mass.

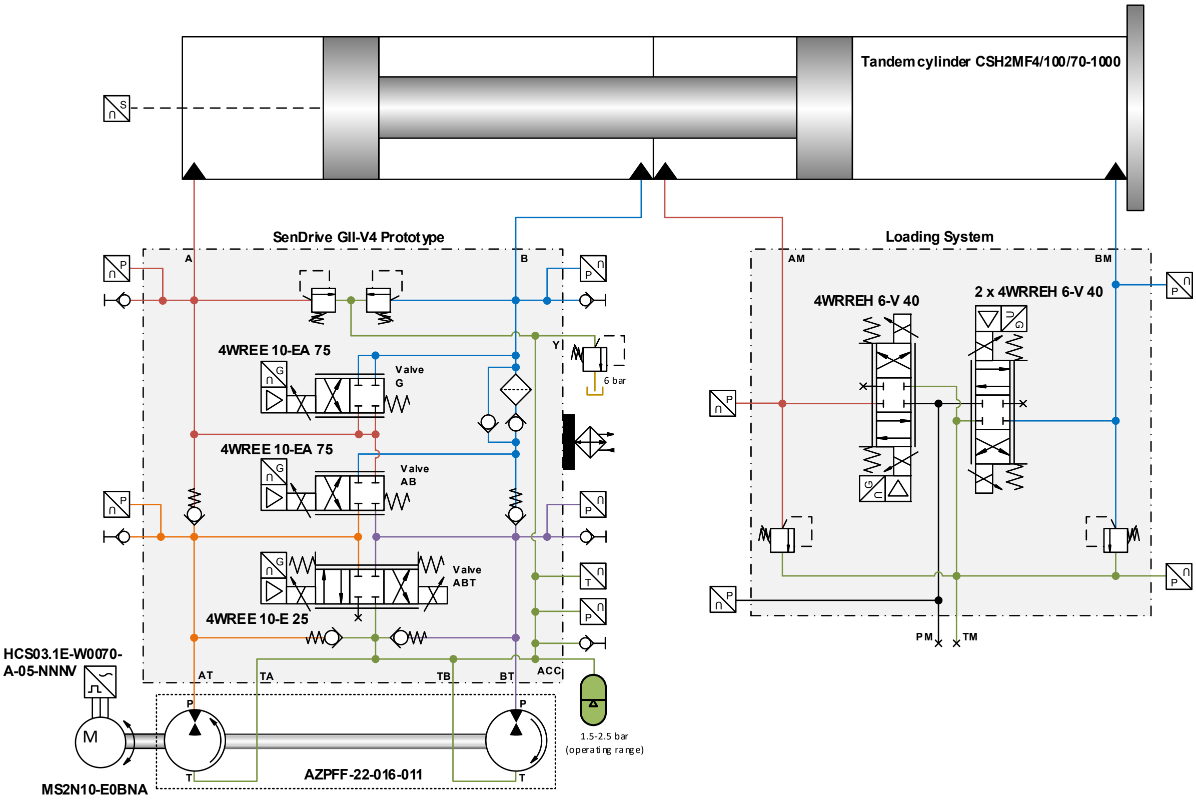

Fig. 4.7.: SenDrive GII-V4 test bench layout.

To limit the required engineering efforts and related costs when producing drives for customers, it was chosen to design and engineer a generalized manifold usable for SDGII-V3 and SDGII-V4 drives. To enable its utilization in various applications after project completion, the manifold has been engineered in "commercial grade" detail in collaboration with Bosch Rexroth GmbH, Linz, Austria.

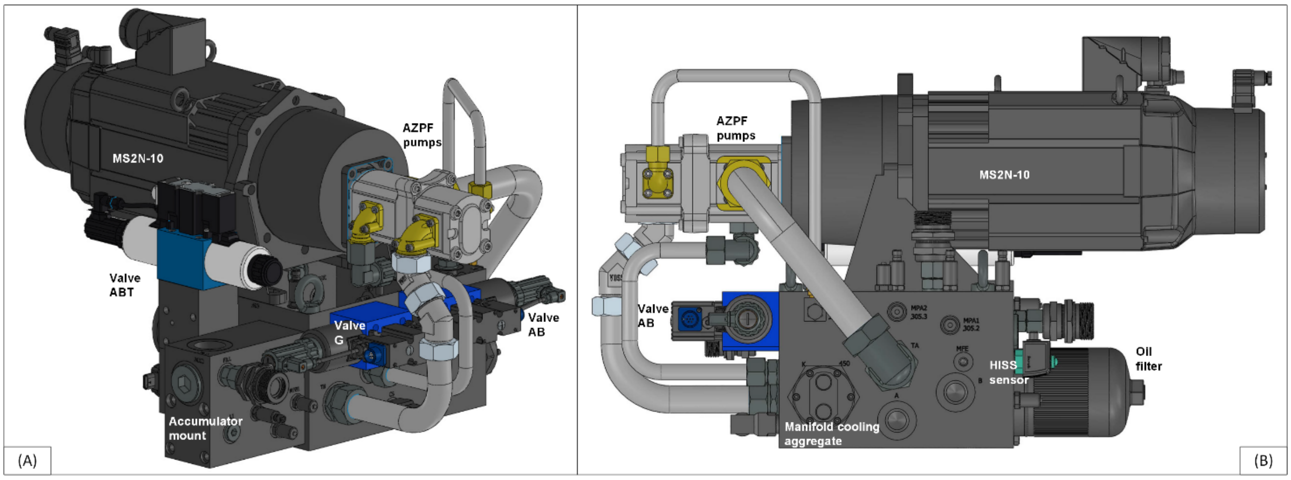

Fig. 4.8.: Physical configuration of the SenDrive GII-V4 prototype.

The drive design was based on well-known components regarding physical properties and control, considering the commercial aspects. To allow higher pressures at cyclic loads, also the A10FZO pump series was considered. The circuitry related to the gear valve (valve G in Fig. 4.8.) allows a higher flow than valve AB at the same pressure drop across the valve, hence gearing of the piston speed may be realized. In addition to the above a manifold mounted filter is used. Fluid cooling is realized directly on the manifold. IndraDrive components are used in combination with an MS2N permanent magnet machine. The actual control functionality is realized in an XM22. The physical configuration of the manifold is depicted in Fig. 4.8. The physical layout of the SDGII-V4 prototype test bench is depicted in Fig. 4.9.

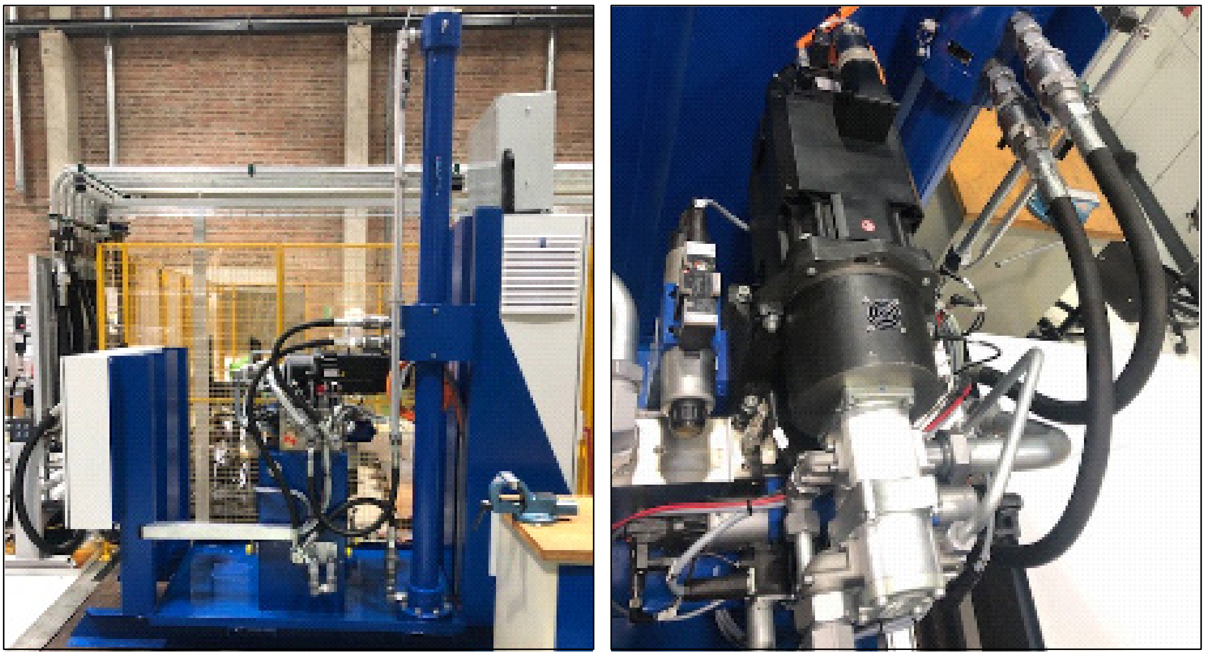

Fig. 4.9.: Physical layout of the SDGII-V4 prototype test bench.

Basic Second-Generation Drive Version & Pilot Application

Through the project it was found that the developed drive concept in many cases may be realized as a retrofit solution for existing applications. In many of these a hydraulic tank is already in place with off-line fluid cooling/heating/filtration. Furthermore, the work with control developments revealed that via the developed control structure and the high-bandwidth electric motor/drive, a high closed loop drive stiffness may be achieved when the hydraulic drive is placed close to the cylinder ("small" line volumes). For this reason, and to realize a drive at a lower cost, a "generation II Basic" was developed as depicted in Fig. 4.10. Finally, a prototype was developed for demonstration at a Bosch Rexroth customer for a press-like function in a block tile machine.

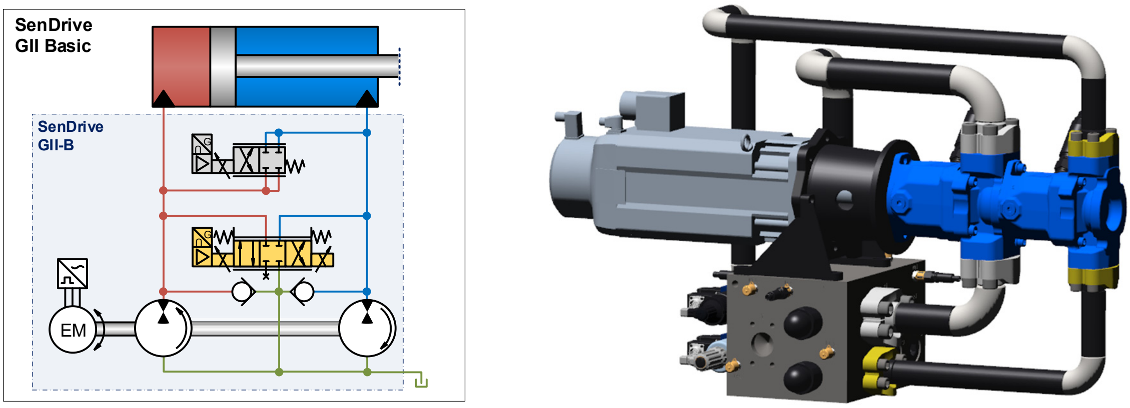

Fig. 4.10.: Generation II Basic drive architecture. Physical realization of Generation II Basic drive for pilot application.

4.1.4. Drive Controls

At an early stage in the development of the controls the potential of realizing secondary control features by virtue of the high bandwidth torque control mode of the motor was considered. This topic was intensively investigated due to the possibility to realize cylinder force control benefitting from the high electro-magnetic motor torque bandwidth in combination with shaft speed, position, and pressure feedback. The idea was to disregard the motor speed control loop and realize a torque/force coupling between the motor and actuator with a speed/flow reaction (secondary control), as opposed to conventional flow coupling with a pressure reaction (primary control). This concept was successfully developed for the tandem pump drive architecture, i.e., without flow rectification, illustrating that high force control bandwidths are achievable (see Appendices: "On Secondary Control Principles in Pump Controlled Electro-Hydraulic Linear Actuators"). However, the flow rectification realized by check valves essentially causes the drive architecture to be a variable structure system depending on the motion direction, and due to the "hard" pressure dependent flow restrictions, the application of the developed secondary control framework was unsuccessful. This may however show significant potential in pump-controlled cylinders where unrestricted bi-directional flows can be realized. In regard to the generation II drives, it was instead decided to realize a cylinder force control loop around the motor speed loop, i.e. a cascade type control, bearing in mind the limitation of the force control bandwidth induced by the speed control bandwidth. The force control loop is at the center of the drive control structure, allowing various outer loops for different functions, with their loop bandwidths defined by that of the force controller. Hence, controller parameterization may be generalized to a certain extend. The overall drive control function appears as in Fig. 4.11.

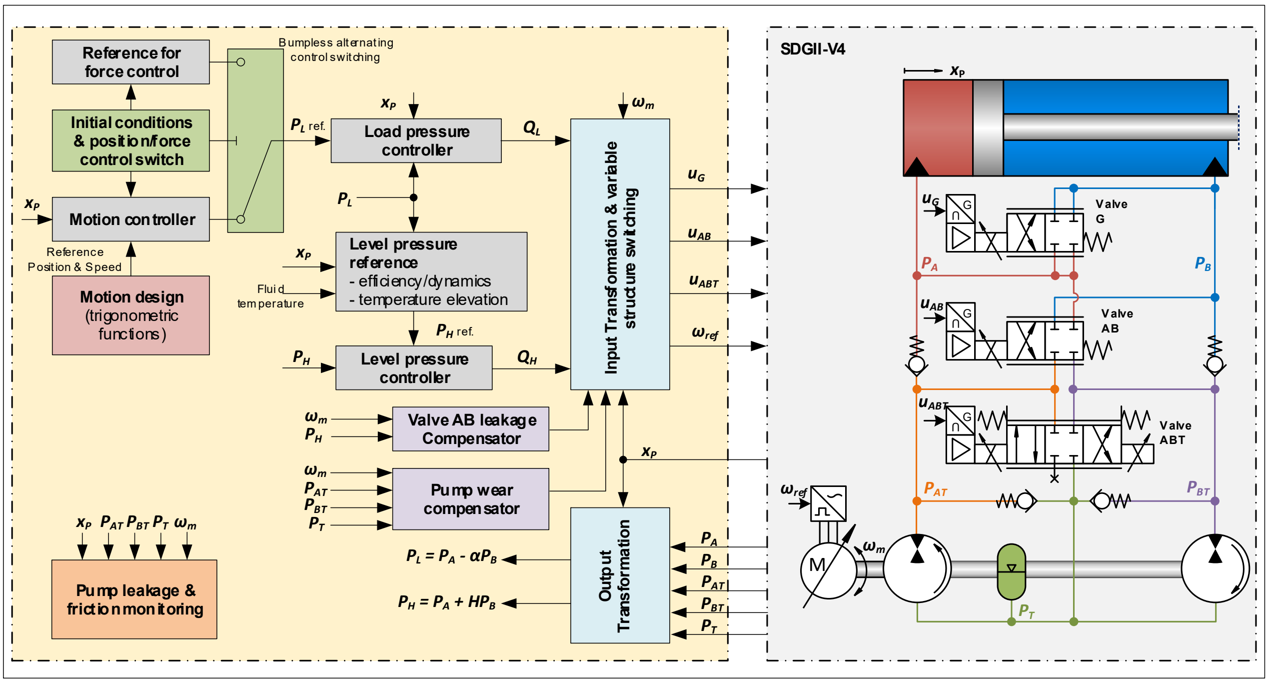

Fig. 4.11.: Overall drive control structure.

4.2 Risks Associated with the Project

The risks associated with the project was mainly assumed to be related to the durability of the pumps during low-speed operation and dynamic loading, and the impact of hold holding situations on the fluid properties in the absence of pump case drains.

The assessment of the pump durability related to the AZPF external gear pumps used, was conducted in a systematic experimental way, under combined static/dynamic load conditions. To do so, an additional test bench was developed and established as illustrated in Fig. 4.11.

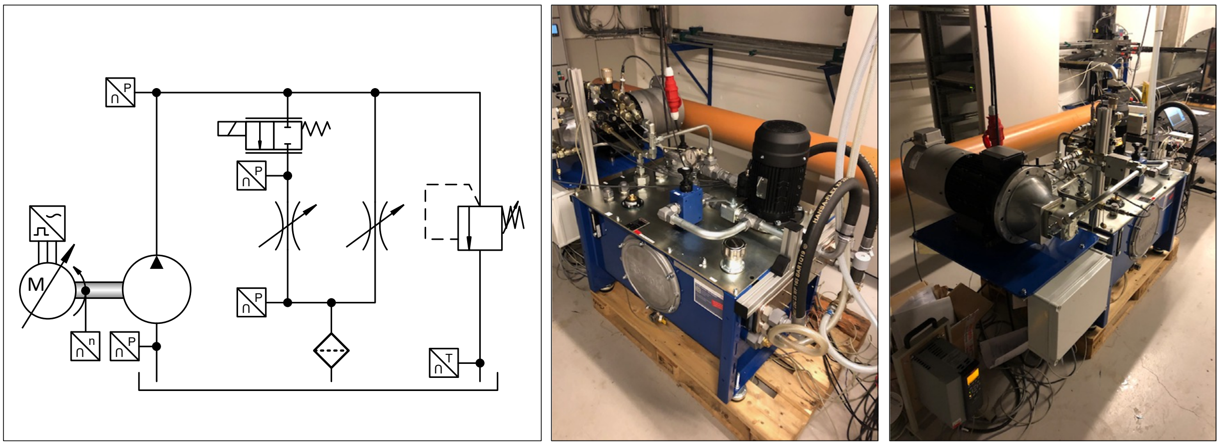

Fig. 4.11.: Schematics and pictures of pump test bench.

The pump test bench allows to specify a certain pump speed and load pressure, and to reduce/increase the load pressure abruptly via an on/off valve. The friction was estimated via the electric motor and hydraulic load torques, and the flow via datasheet information and pressure measurements. An algorithm structure estimated deviations in steady state average leakage and friction values from cycle to cycle. More than 2 mio. extreme load cycles were conducted, revealing that the AZPF pump is very robust as no consistent increase in leakage or friction could be measured.

The lack of fluid drains on the other hand, did cause the fluid to overheat during load holding situations. Through extensive laboratory lifetime tests on the Generation II drive prototype testbench it was found that the hydraulic fluid reached extreme temperatures during load holding situations, eventually resulted in deterioration the fluid properties. From this, the external gear pump was found infeasible, mainly due to lack of a fluid drain, and the previously mentioned A10FZO pump series was considered as an alternative. This pump has a drain line, allowing to flush the pump continuously and thereby eliminating the thermal problems.

4.3 Project Implementation, Challenges/Problems & Relation to Milestones

The project implementation went according to plan, however the corona pandemic slowed activities down for a period. Furthermore, several members of the project group have left their jobs for other opportunities, which have caused further delays in relation to the onboarding of new project members. For these reasons, among others, an extension of the project period for one year was applied for and granted by EUDP. One of the commercial milestones included installation of two pilot applications for demonstration in industrial environments, however the number of project hours, available budget and project period caused this milestone to be difficult to achieve, and hence this milestone was reduced to one pilot application (in agreement with EUDP). Subsequently, all milestones are reached as listed below, except for demonstration in an industrial environment and subsequent publication in a trade magazine, which have been partly reached. The demonstration in an industrial environment has partly been reached and will be finalized as soon as possible as described below in Section 5.2. Subsequently it is planned to publish the results to reach CM2 below.

Technical milestones:

• M1: Drive topology, design methodology and basic control design are finalized	reached
• M2: Test facilities have been commissioned and are operational	reached
• M3: The final drive-wide control structure has been completed and tested	reached
• M4: The final optimized drive concept completed	reached

Commercial milestones:

• CM1: Demonstration in an industrial environment	partly reached
• CM2: Publication of two articles in trade magazines on the final drive concept	pending

Throughout the project several drive designs were developed starting with a Generation I. This turned out to be limited in scalability due limited valve flows, and hence a Generation II was developed with alternative valve configurations, where especially two versions appear the more attractive ones. One of the two is a “basic” version of the other encompassing fewer components and simpler component integration. The control methods developed in the project proved to be very different from the ones conventionally used in hydraulic drives, allowing for motion and force control as well as bump less transition between the control modes. Furthermore, gearing of cylinder piston speeds through flow regeneration have been enabled via clever control of valves in combination with pump flows.

The risks associated with the project was mainly assumed to be related to the durability of the pumps, however extensive experimental evaluations proved these to be very robust as described above. The lack of fluid drains on the other hand, did cause the fluid to overheat during load holding situations, and hence the pumps were exchanged with pumps including such a drain.

5. Project results

5.1 Modified Objectives Relative to the Original Objective

The original technical objective of the project was achieved, however, the anticipated high drive stiffness turned out to be limited by the valve dynamics which was a “bottle neck” in regard to drive performance. However, control developments in the project allowed to discard the mentioned valves, while achieving a drive stiffness of the controlled system exceeding the one achievable with the valves. In the end several drive concepts were developed over two “generations”, resulting in a highly scalable version and a “basic” version of this with fewer components and simpler component integration, and very satisfactory performance attributed the developed control methods.

5.2 Technological Results

The drives resulting from the project provided in the best cases (Generation II Basic) maximum energy efficiencies up to 77%, and average efficiencies up to 51% for complete drive (electric supply to cylinder piston), measured in the Generation II testbench depicted in Fig. 4.7. and 4.8., when emulating the Generation II Basic drive (i.e. Valve AB fully open and Valve G and Valve ABT closed). In comparison, conventional valve-controlled drives exhibit max. efficiencies less than 50% and average efficiencies of up to 40%, but often on the area 25-35%. These data suggest an efficiency increase in this case of more than 40%, which is substantial. Furthermore, control precision of up to 0.65% relative to cylinder stroke was measured, which may be considered very precise, and which is attributed the developed control methods. Extrapolating the mentioned measured efficiencies, the efficiency map appears as depicted in Fig. 5.1.

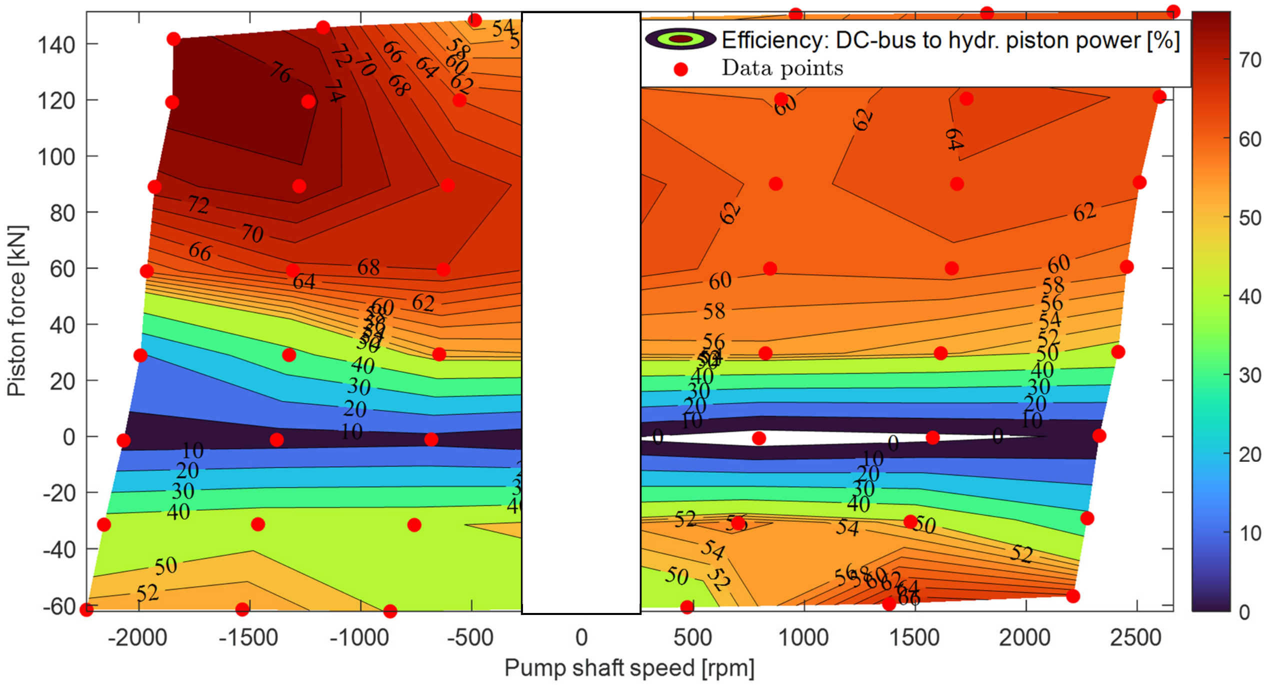

Fig. 5.1.: Efficiency of Generation II Basic drive.

5.3 Commercial Results

The commercial results were considered at two levels, being the ability to realize efficient and cost-effective drive structures based of low-cost components, as well as achieving two drives sold, build, installed and demonstrated in customer applications. The former was achieved to a high extend on a component level, as simple valves and external gear pumps were used, and especially as pump modifications were avoided as the final cost of these turned out to be high. However, it turned out that the component integration into a system was more costly than originally anticipated, and for this reason a generalized drive manifold was designed, applicable up to approximately 20-25 kW drives. Furthermore, to increase scalability and reduce the number of valves used, alternative low cost valves was considered. These features allow to reduce integration costs in future drives to be sold. Furthermore, it turned out that external gear pumps are robust and useful, but in load holding application the absence of a pump drain turned out to be critical (see Section 4), and in such cases axial piston tandem pumps may be used causing a cost increase. All in all, the commercial goal in terms low-cost component usage was achieved, but the system integration is more costly than originally expected.

Regarding the sales, realization, installation, and demonstration of two drives, this turned out to too ambitious for a new technology under development. For this reason, the original commercial milestones were modified to consider the demonstration in a single but demanding application, with a prototype build within the project (approved by EUDP). Due to clever realization of a testbench the associated costs were dramatically reduced, allowing to realize the industrial demonstration prototype without exceeding the project budget.

This prototype was based on the Generation II Basic drive version, and was installed in a block tile machine, enabling the utilization of all drive functionalities developed. Tests has been conducted on a customer machine and proved functional. The integration of the drive control hardware, communication between various components etc. turned out to be more extensive than anticipated, and status is that the project participants need to wait for the next customer machine to be produced before final commissioning can be conducted. After this has been conducted and the functionality validated, the machine will be placed at a tile manufacturer and operate in production for a period to prove the drive concept industrially. After successful demonstration here, the drive concept will be considered for other applications in order establish a broader industrial validation, for use in the commercial promotion of the drive concepts.

5.4 Target Group & Added User Value

The target group is mainly the manufacturing industry segment, and mainly for use in machinery applications. However, the strong trend of electrification of off-highway machinery and battery driven machines causes the developed technology to be relevant here, partly due to the electric power interface of the drives and partly due to the high energy efficiencies seen, enabling longer machine up times and/or reduced battery sizes and much reduced cooling requirements.

5.5 Dissemination of Results

The project results have been disseminated at various levels, both at conferences, in conference proceedings, in a journal, at Bosch Rexroth departments in Germany and at Bosch Rexroth customers. This also include four conference papers and a journal article. The publications are listed below with links available in the Appendix of Section 8:

1. 2019 – MDPI Energies: A Class of Energy Efficient Self-Contained Electro-Hydraulic Drives with Self-Locking Capability
2. 2019 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: Improving the Efficiency and Dynamic Properties of a Flow Control Unit in a Self-Locking Compact Electro-Hydraulic Cylinder Drive
3. 2020 – Proceedings of the 12th International Fluid Power Conference: Multi-Objective Control of a Self-Locking Compact Electro-Hydraulic Cylinder Drive
4. 2020 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: On Secondary Control Principles in Pump Controlled Electro-Hydraulic Linear Actuators
5. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: Prognostics in Custom-Build Electro-Hydraulic Variable-Speed Drive Applications

6. Utilisation of project results

6.1 Future Utilization of Technological Results

In the future, the technological results will be utilized at several levels, with these mainly being the generation II drives and further multi-axis drive developments with offset in the findings related to the control structure design approach.

- Standalone drives (Generation II) – The drive structures developed in this project, as well as the technical knowledge established in the development process, will be used in relation to new customer projects to aid the industry transition to more efficient machines. Even though functionalities commonly applied in conventional valve-controlled drives have been developed for technology developed in this project, and even further improved, great many different application types exist – hence, in order to broaden the application areas, specific control functionalities will be developed further when necessary.
- Drive design with offset in control structure design approach – as described above, the control structure design approach developed in the project has revealed a totally different approach of thinking variable-speed drives design. In fact, the idea of realizing multi-cylinder (multi-actuator) designs based

on control objectives and associated desired closed loop system dynamics came up through the project work. Conventionally, drive designs take offset in standalone drives and the ability to control these individually. The novel approach to multi-axis drives design, is to enable forces, speeds etc. via hardware, where the functionality realization is not intuitive, but realized via some desired closed loop dynamics. At this point it is believed that such a design approach enable the possibility to realize highly efficient drives, while at that same time reduce the number of components and associated system integration, and reduce the necessary power installation, making such solutions more commercial feasible.

The technological results and related spin-out developments will in the future be used by Bosch Rexroth and their customers, and further developments of the technology are already ongoing targeting cement manufacturing machinery and electrified off-highway machinery, as described below.

6.2 Future Utilization of Commercial Results

The commercial results will be utilized for various industry areas, and the technology is already subject to substantial additional development efforts as described below. The results will be commercialized by Bosch Rexroth directly, and by Bosch Rexroth customers indirectly.

The project has not yet led to increased turnover and exports, however, the control developments in the project has led to possibilities of realizing multi-cylinder drive types, previous not considered in both industry and academia (as mentioned above). Hence, with basis in the control structure developments in this project, two projects have been established targeting the further development of the technology area. One project is associated with energy efficient multi actuator drives for cement production machinery partly funded by Bosch Rexroth A/S, Aalborg University and EUDP with additional external funding by FLSmidth. The other project is related to the further development of energy efficient multi actuator drives for off-highway electrified machinery, funded by Bosch Rexroth AG.

In relation to these activities, Aalborg University has employed two PhD fellows and at Bosch Rexroth one newly employed engineer will be associated with the technology besides the employees already involved in this. Hence the future commercial results will be achieved through:

1. Pushing the developed technology into the market with offset in the existing demonstration as reference.
2. Further developments based on the finding of this project will be promoted in the market via references to demonstrations of cement and off-highway machinery, benefitting from expositions on trade fairs, SoMe etc.
3. The trend toward electrification and the associated necessary energy efficiency to be feasible, will be actively used as a lever to engage in customer collaborations related to application prototype demonstrations. This will expectedly support the sales process forward.

6.3 Competitive Situation in the Market

The competition for the technological area is limited, and mainly related to key industry players such as Parker Hannifin and Moog. However, in these cases developments have mainly been related to highly specialized applications such as aircraft flight controls or are low-power drive types. An example of such an electro-hydraulic actuator is shown in Fig. 6.1.

Fig. 6.1.: Example of electro-hydraulic actuator produced by Parker Hannefin[1]*. Outlet power: 560 W, max. force: 21.3 kN.*

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[1] https://ph.parker.com/dk/da/compact-electro-hydraulic-actuator

The technology of this project is targeting applications of 5 kW and above, and is mainly focused on industry applications in manufacturing processes etc. Relating to the cement machinery project mentioned above, further developing the technology, the industrial demonstration currently targets a two-cylinder drive with a total maximum output power of 80 kW.

6.4 Sales Barriers in the Market

The barriers are mainly related to cost levels, as these did not turn out as low as expected due to the number of components used, and especially the component integration. However, with the increasing focus on efficiency and electrification as well as the high energy efficiency levels achieved, this is not expected to be a major challenge in the future. Hence, with the technology being novel, it is believed that the efforts mentioned in Section 6.2., will allow the technology to break through in the market.

In addition, the further development activities described above are also focusing on reducing the number of components and the associated component integration, and through this aiming for reduced costs of realization, easing the commercialisation process.

6.5 Contribution of Project Results to the Realization of Energy Policy Objectives

The project results contribute substantially to realize energy policy objectives. The high energy efficiency compared to existing technology, energy recuperation abilities and electric power interfaces tabs into the energy policy areas of efficiency, electrification and e-mobility. The further development activities described above having basis in this project, will even more strongly contribute to realize these energy policy objectives.

7. Project conclusion and perspective

7.1 Conclusions Made in the Project & Next Steps for the Developed Technology

Main conclusions of the project are that highly efficient drives can indeed be realized from standard components, and rather sophisticated functionalities realized via innovative physically motivated control structures, if in-debt insights and understanding of dynamical systems is available, as well as the necessary creativity. Another conclusion is that such drives based on variable-speed pumps may be commercially feasible, if components and system integration efforts are reduced to the extend possible, by virtue of the mentioned creativity on a drives control level.

In this project several industrially feasible and highly energy efficient hydraulic drive concepts were developed and successfully proven experimentally and partly in industry (to be finalized as soon as possible). Major findings include the development of highly innovative control method enabling the drive functions and specific functions such as alternating position/force control and flow regeneration with smooth transition between the control modes. These developments have provided the basis for the establishment of two new projects to further develop the technology for multi cylinder drive systems for cement manufacturing and off-highway electrified machinery, and these constitute the next steps in terms of the further development of the technology. Regarding the developments of this project, next steps are to demonstrate the technology at more customers to provide stronger basis for a broader commercialization.

7.2 Perspectives of the Project in Relation to the Future Technological Development

It is believed that the project results as well as the results of two additional projects associated with the further development of the technology, will lead to even more technology development activities, and eventually provide a significant impact in industry and contribute to significant emission reductions in this field of industry.

8. Appendices

- Links to relevant publications.

6. 2019 – MDPI Energies: ***A Class of Energy Efficient Self-Contained Electro-Hydraulic Drives with Self-Locking Capability***
Link:https://www.mdpi.com/1996-1073/12/10/1866

7. 2019 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: ***Improving the Efficiency and Dynamic Properties of a Flow Control Unit in a Self-Locking Compact Electro-Hydraulic Cylinder Drive***
Link:https://asmedigitalcollection.asme.org/FPST/proceedings-abstract/FPMC2019/59339/V001T01A034/1071812?redirectedFrom=PDF

8. 2020 – Proceedings of the 12th International Fluid Power Conference: ***Multi-Objective Control of a Self-Locking Compact Electro-Hydraulic Cylinder Drive***
Link: https://tud.qucosa.de/api/qucosa%3A71094/attachment/ATT-0/?L=1

9. 2020 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: ***On Secondary Control Principles in Pump Controlled Electro-Hydraulic Linear Actuators***
Link:https://asmedigitalcollection.asme.org/FPST/search-results?page=1&q=ON%20SECONDARY%20CONTROL%20PRINCIPLES%20IN%20PUMP%20CONTROLLED%20ELECTRO-HYDRAULIC%20LINEAR%20ACTUATORS&fl_SiteID=1000093

10. 2022 – Proceedings of the ASME/Bath Symposium on Fluid Power and Motion Control: ***Prognostics in Custom-Build Electro-Hydraulic Variable-Speed Drive Applications***
Link:https://asmedigitalcollection.asme.org/FPST/search-results?page=1&q=PROGNOSTICS%20IN%20CUSTOM-BUILD%20ELECTRO-HYDRAULIC%20VARIABLE-SPEED%20DRIVE%20APPLICATIONS&fl_SiteID=1000093