COMPARISON STUDY OF FULLY INDIVIDUALIZED SYSTEM ARCHITECTURES FOR ELECTRIFIED MINI-EXCAVATORS: DISPLACEMENT CONTROL (DC) VS ELECTRO-HYDRAULIC ACTUATION (EHA)

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ABSTRACT

Energy consumption and overall installed power are key parameters for evaluating different technology for the hydraulic actuation system of electrified off-road vehicles. This paper presents a study on these parameters considering the case of all the functions of a 5-ton mini-excavator. The hydraulic system architectures considered for this study are the current commercial solution (load sensing system) and two alternative high-efficiency primary controlled architectures that minimize energy loss: the Displacement Control (DC) system that uses a single electric prime mover and a variable displacement pump for each actuator, and an Electro-Hydraulic Actuator (EHA) system that uses an electric prime mover and a fixed displacement pump for each actuator. For this study, a basic sizing for the two alternative systems is performed based on available commercial components. Both the proposed systems and the conventional LS system are simulated in Simcenter Amesim to determine the energy distribution over a digging duty cycle. The baseline system is also validated based on experimental measurements. The results show a 50% reduction in energy consumption for both the individualized systems, but the overall displacement of the pump units increases by a factor of 3.75. Furthermore, the installed power for the EHA system is 8 times higher than the baseline. Although the study does not suggest a specific architecture for the reference application, the results can assist decision making processes for selecting sub-function primary controlled actuation in future electrified mini-excavators.

Keywords: Electrification, Excavator, Displacement Control, Electro-Hydraulic Actuation, Installed Power

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1. INTRODUCTION

The rising demand for battery operated off-road vehicles (ORVs) that can avoid local pollutant emissions is pushing towards the proposal of actuation architectures that can maximize energy efficiency, so that overall energy consumption and battery up-time can be maximized. Advantages of hydraulic actuation, including high-power to weight ratio, resistance to shocks as well as load holding features [1,2] makes fluid power technology particularly suitable for off-road applications such as excavator, independently from the prime mover technology. However, typical metering control concepts used in commercial machines, such as Load Sensing (LS) systems, suffer from high throttle loss and inability to recover energy during overrunning load conditions [3]. Zimmerman et al. [4] showed how in a 5-ton LS mini-excavator operating a digging cycle, only 31% of the pump shaft energy is provided to the actuator. Therefore, there is an opportunity to adopt more energy-efficient architectures, that could be applied over a wide range of ORVs. There are several solutions proposed by research institutes or companies that could achieve this goal, with different cost/efficiency levels. Among these, significant are the solutions proposed by Pellegri et al. [5], based on the promising concept of digital displacement pump, outlining a potential fuel savings of 43% compared to a baseline 16-ton excavator; or the common-pressure rail strategy proposed by Heybroek et al. [6] on a 30-ton excavator, improving the fuel efficiency in the 34-50% range. A comprehensive list of solutions is presented in the review paper [1]. Certainly, among the most efficient architectures, there are the pure primary controlled ones that avoid throttle loss and allow energy recuperation during overrunning load [3]. As laid out by Weber et al [7], primary control can be implemented using different function-individualization strategies: (i) the use of a common prime mover with separate pumps for each actuator (commonly referred to as Displacement Control – DC); and (ii) the use of separate motor-pump units for each actuator respectively (commonly referred to as Electro-Hydraulic Actuator – EHA). There are some key differences between the two systems, predominantly in the areas of power distribution method, flexibility, compactness, and installed capacity of components. Both architectures have been extensively studied at the authors' center: DC allowed to save 40% fuel in [8] in a 5-ton excavator (further improvement was achieved later through hybridization); EHA permitted to reach efficiencies of up to 80% on the boom-bucket system of a compact loader [9].

There is a common misconception that simply applying electro-hydraulic actuators (EHA) or electro-mechanical actuators (which have comparable efficiency to EHA [10]), is in general the best solution for future sustainable electrified machines [11]. One important aspect of implementing a fully individualized system in an electrified ORV relates to the installed power of the electric components machine. However, most of the past studies like the abovementioned ones put focus only on energy consumption, which cannot serve as the only parameter to determine the optimal architecture for the actuation system. Moreover, these studies focus on the individualization of the most relevant functions without considering the secondary functions such as tracks, blade, etc. This paper aims at studying both aspects of energy efficiency and installed power that come with the implementation of either a DC or an EHA architecture for all the hydraulic functions in an excavator, to highlight the possible limitations of the fully-individualization approach. For this purpose, the paper considers the case of a 5-ton excavator, and determines the sizing of the system considering the extreme case of all the vehicle functions individualized. The energy efficiency of two individualized solutions is evaluated in simulations and compared against the baseline LS system considering a 90º digging cycle where measurements were available. The required pump shaft power is used to estimate the required installed power of the electric drives for each one of the considered architectures. The overall results on efficiency gains vs installed power are finally discussed.

The authors acknowledge that the full application of the DC and EHA architecture to all functions represents an extreme scenario. Their application can be cost effective only on selected functions, such as in Casoli et al [12] where the individualization concept was considered only on the boom, arm and bucket functions of an excavator, or Padovani et al. [13], where the focus was put only at the boom. Another approach for increasing cost-effectiveness is the pump-switching layout, as proposed by Busquets et al. [14], who combined the DC architecture with a pump-switching layout, which allowed controlling all the eight functions of an excavator with only four multi-quadrant pumps. Still, the considerations made in the paper are useful for the decision-making process of sub-functions individualization in an ORV. Moreover, in the context of ORV electrification, there is an argument for using electro-mechanical drives for the rotary actuators. But for the scope of this research, and for providing consistent installed power comparison between baseline and individualized systems, the rotary functions, namely the swing and tracks, are considered as hydraulic actuators.

2. REFERENCE EXCAVATOR SYSTEM

The hydraulic system of a 5 ton, 47 hp excavator (Bobcat E50) is chosen as the reference case. As is typical in many compact excavators, the system layout is based on a multi-actuator load-sensing (LS) post compensated architectures. The hydraulic functions of the vehicle include the standard digging functions: boom, arm, bucket, swing, and the secondary functions: tracks, blade, offset and auxiliary ports, used for backfilling holes and machine positioning. The hydraulic circuit is shown with a simplified schematic in Figure 1. The post compensated design allows to incorporate the so-called 'flow sharing' feature, which reduces the flow to the actuators during events of pump flow saturation to allow simultaneous operation of the working functions [3]. This feature allows minimizing the pump displacement and therefore the prime mover torque (for the reference case an engine).

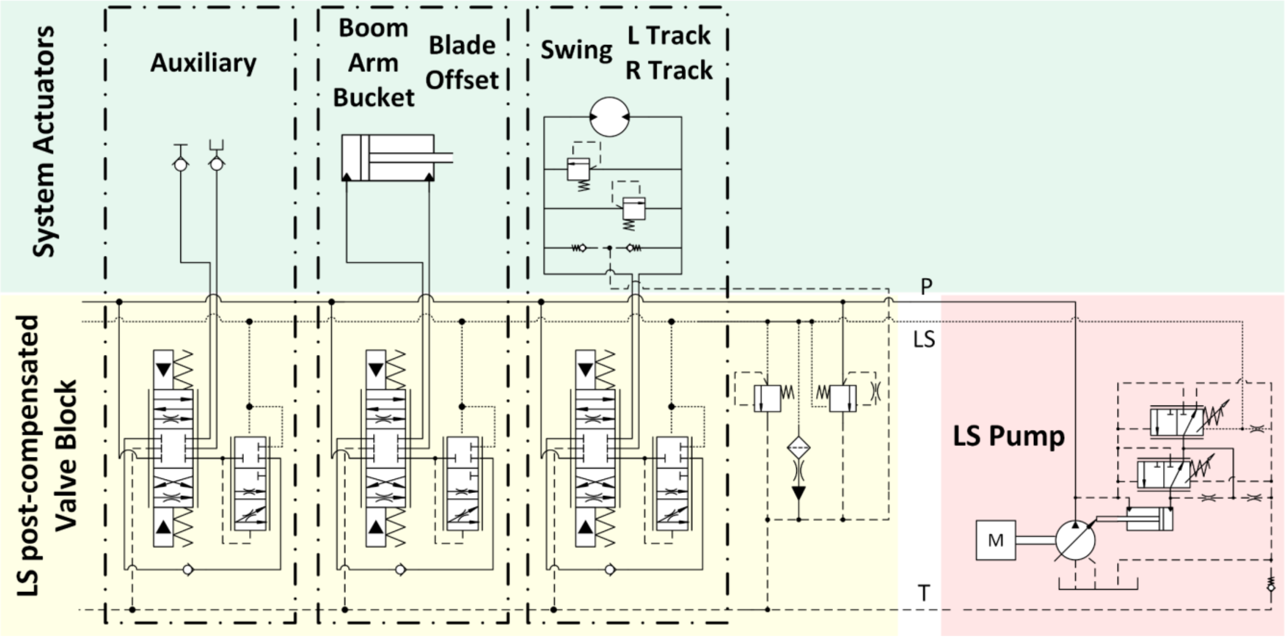

Figure 1: Simplified Hydraulic Circuit of Reference Excavator

3. FULLY INDIVIDUALIZED ARCHITECTURES

The pump-controlled hydraulic systems considered in this study consist of a closed-circuit architecture with the prime mover driving either a variable (DC) or a fixed (EHA) displacement pump. A charge circuit is used to compensates the flow difference resulting from differential areas for linear actuators, pump volumetric losses, and other leakages. Pilot-operated check valves (POCV) are used for connections between the charge and main circuit. Furthermore, load-holding (LH) valves, either mechanical or solenoid operated, can be used to avoid sudden lowering of the actuators [15].

3.1. Displacement-controlled (DC) System

The circuit of the DC architecture for the excavator system is shown in Figure 2. The most notable feature is the use of separate variable-displacement pumps for each of the nine actuators and their connection to a single electric drive system, which is driven at a constant speed. The low-pressure lines of all the actuators are connected to the charge circuit, which includes a charge pump, accumulator, low-pressure relief valve and a cooling system for the fluid. The accumulator in this case is sized large enough to account for the differential flow of the cylinders, which means that the charge pump is sized to only account for the other losses in the system. This leads to lower parasitic losses and a higher overall efficiency of the system. The relieving pressure for the charge circuit is set considering requirements for the swash plate regulation system for the pumps and the pressure drops across the POCVs.

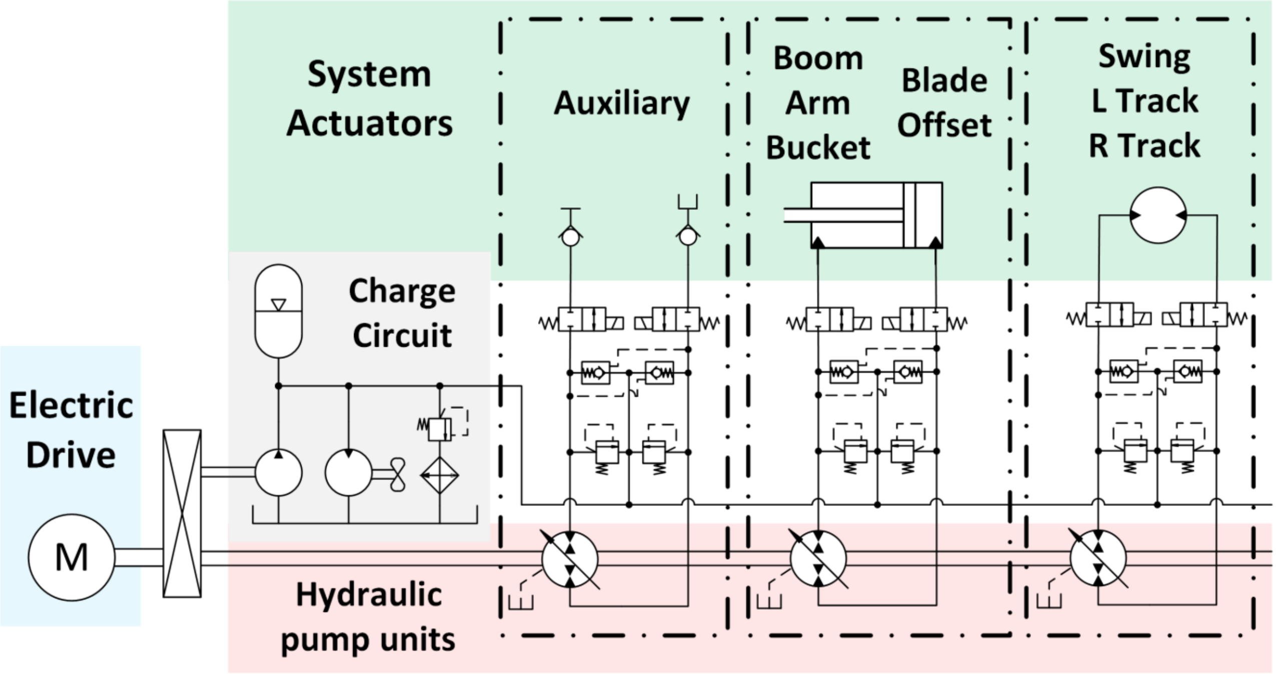

Figure 2: Hydraulic Circuit of Fully Individualized Displacement Controlled (DC) Excavator

3.2. Electro-Hydraulic Actuation (EHA) System

Figure 3 represents the hydraulic circuit of the EHA architecture for the excavator system. Here, the actuators are connected to individual fixed-displacement pumps, each powered by a separate electric drive. The term “EHA” is often used to indicate self-contained and compact electro-hydraulic linear functions [7], although the components of an EHA system can also be spatially distributed for a more convenient implementation that does not require changes in the mechanical structure of the ORV. This architecture is employed for the linear actuators of the system, as shown in Figure 3, where the charge circuit is connected to the pump drain port and an accumulator. The pressure level of the accumulator is therefore, restricted by the allowable drain line pressure for the pump. Furthermore, the self-contained design is able to incorporate a cooling system in the charge circuit [16]. In contrast, the charge circuit for the rotary actuators is equipped with a common charge pump and relieving valve as shown in Figure 3. This design, even with additional parasitic losses and an extra electric drive, is selected considering the flushing requirements of the hydraulic motors. Fixed displacement units, like inexpensive external gear units, can be utilized for the EHA system implementation. Such units commonly have a minimum continuous speed of operation. For this reason, the addition of the by-pass valve (BPV), as presented in [9] is used to handle the low-speed operation of each actuator.

3.3. Comparison between LS and Individualized (DC/EHA) Architectures

The LS system uses the metering concept for controlling the actuator velocity, which leads to significant throttling losses during simultaneous operation. Figure 4 (a) shows an illustrative simultaneous actuation of two functions, the boom and arm, for the LS architecture. The power plot describes the distribution of energy when both actuators are commanded to operate at 50% of their respective maximum rated velocities. From the plot, it can be seen that the pump pressure is always governed by the highest load actuator. The meter-in loss corresponds to throttling of the pump flow in the metering valve, which signifies the margin maintained by the LS pump. The lower load actuator, in this case, the arm, has an additional loss of pressure energy corresponding to the compensator operation. Lastly, the meter-out throttling loss are a result of the restriction in the return line of the valve to tank. A note here is that the return flow to tank is less than the pump flow due to the differential area of the cylinder. The mentioned losses add up to a significant amount of the total hydraulic energy, which greatly reduces the efficiency of the system. For individualized (DC/EHA) architectures in a similar operation, the power plots are shown in Figure 4 (b). Since these systems have independent drive units, the pump pressures follow the load pressures on their respective actuators and do not involve any load interference. Furthermore, the throttle-less action of the systems leads to minimal loss of energy, with the ability to recover potential energy, a feature not available in LS systems. However, the POCV, LH valves, BPV (with EHA only), and the charge pump result in a small amount of lost energy in the system.

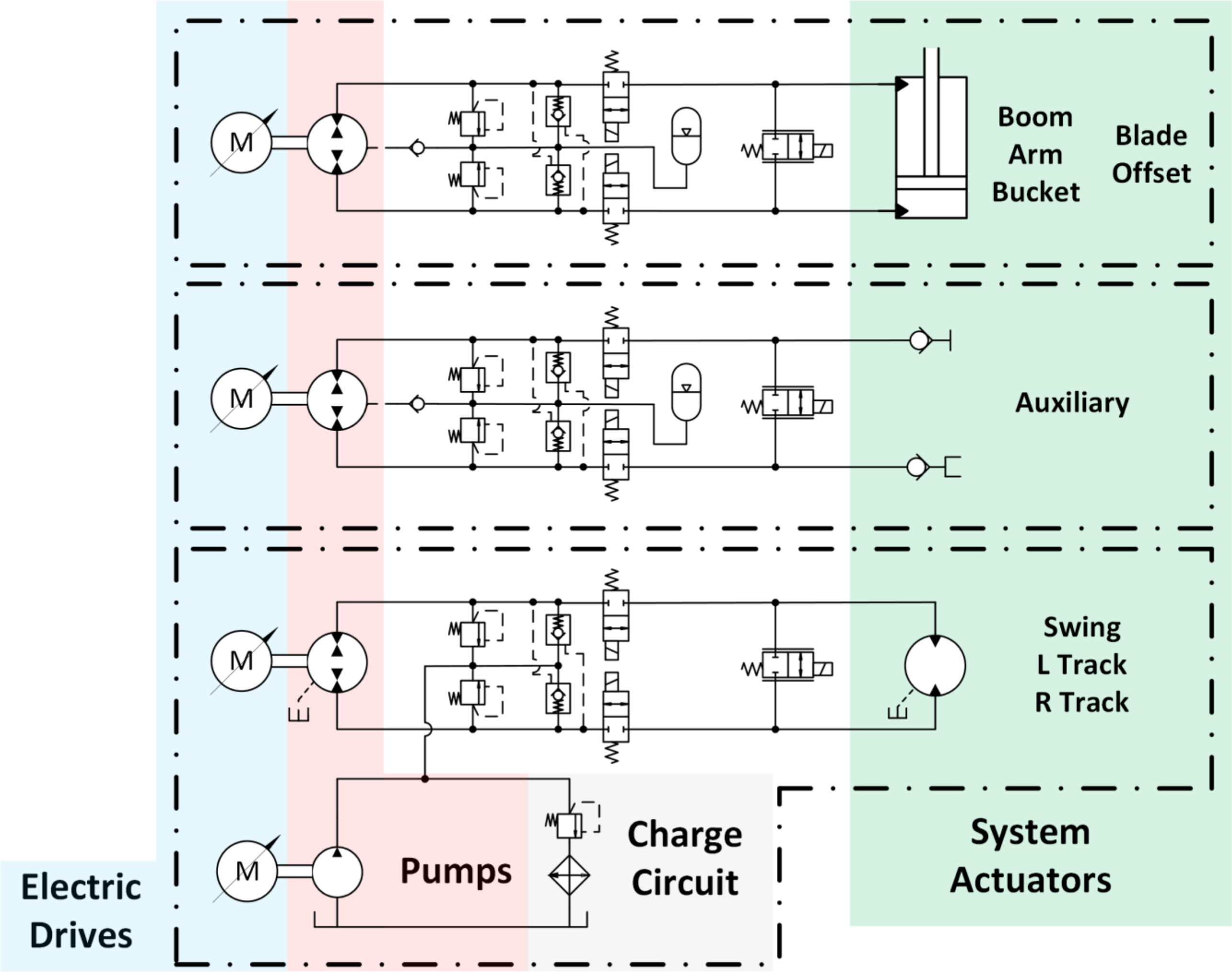

Figure 3: Hydraulic Circuit of Fully Individualized Electro-Hydraulic Actuated (EHA) Excavator

An advantage with the LS architecture is that by studying the operating duty cycles of the machine, the pump can be sized to provide a fraction of the actuators maximum flow during simultaneous actuation. Therefore, to achieve the maximum velocity of an actuator, the simultaneous operation of other actuators can be limited. In other words, flow saturation is imposed on the system to downsize the prime mover and reduce the installed power on the machine. This can be seen in the power plot in Figure 4 (a), where the pump maximum flow is sized close to the required flow to the two actuators at 50% velocity. In contrast, the pump units in the DC/EHA systems have to be sized individually for the required maximum flow of their corresponding actuators. This results in a significant increase in the installed capacity of pumps for such systems as shown in Figure 4 (b).

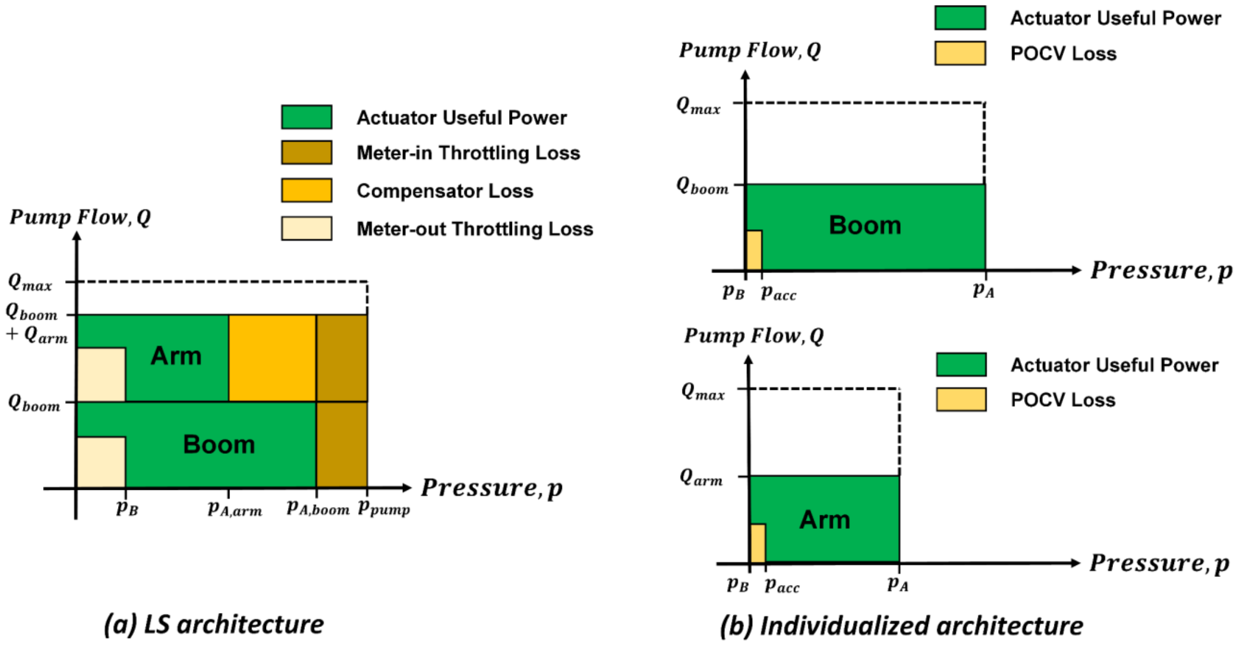

Figure 4: Hydraulic Power Distribution for LS (a) and Individualized DC/EHA (b) architectures, with two actuators operated at 50% of maximum rated velocity (resistive extension mode)

4. SYSTEM SIZING AND SIMULATION MODEL

For the proposed DC and EHA systems, the pumps corresponding to the various functions are selected according to the requirements of the reference machine. Moreover, to allow providing realistic results, each pump is chosen among commericially available units. Swash-plate type axial piston machines designed for closed circuit applications and external gear machines capable of four-quadrant operation are chosen for the DC and EHA systems respectively. From the reference machine, the maximum required speed during extension/retraction (for linear actuators) or maximum angular velocity (for rotary actuators) and the limiting load conditions governed the selection of the pump displacement for each actuator. An important consideration of the pump sizing is that with the current commercial technology, electric motors are capable of driving pump-motor units at much higher speeds than conventional engines, and therefore, the individual pump displacements for the DC/EHA systems can be reduced considerably compared to the baseline LS system. Table 1 lists the pump specifications for each actuator for both the proposed systems. Compared to the baseline LS system, the sum of individual pump displacements for both the DC and EHA systems is about 3.75 times higher. The valves in the systems, namely the POCV, LH, BPV and relief valves, are also sized based on the flow and pressure requirements of the actuators using commercial components. In the DC system, the charge circuit relief pressure is set to 25 bar with a 10-litre bladder-type accumulator and an 8 cc/rev charge pump. The EHA system charge circuit (for the rotary actuators) uses a 5 cc/rev pump with a relief setting of 10 bar. The lower relief setting is selected due to the absence of a swash-plate regulation system in this system. For the linear actuators with the self-contained EHA systems, 5-litre accumulators are used and their pre-charge pressures are set such that the maximum pressure does not exceed 5 bar in the charge circuit, due to the constraint of the allowable drain line pressure for commercial external gear machines.

The sizing for the electric drives in the individualized systems depends on the study of the duty cycles, with simultaneous actuation of functions under specific load conditions affecting the rated power of the installed electric drives (motors). The digging cycle is considered as the most aggressive cycle for the excavator involving the swing, boom, arm and bucket functions, during which the secondary functions are not operated. Certain considerations can be made for this cycle for systems employing a common prime mover for all actuators, in this case, the LS and DC systems. In the case of the reference excavator, the LS system employs a torque limiter to set a constraint on the maximum torque acting on the variable displacement pump. This method is utilized to limit the installed power of the electric drive for the DC system, while considering the digging duty cycle for the participating functions and the maximum operating limits of the secondary functions. In contrast, for the EHA system, the separate electric drives for the actuators need to be sized for their corresponding operating load limits. The torque limiter is useful in setting the constraint for the maximum torque on electric drives, but the limiting load conditions for each actuator can be used to select the actual rated torque and therefore, power for the corresponding electric drives.

Table 1: Individual Pump Unit Specifications for DC and EHA excavators

	Displacement-Control (DC)			Electro-Hydraulic Actuation (EHA)			
Actuator	Pump Displacement [cc/rev]	Maximum continuous speed [rpm]	Maximum continuous pressure [bar]	Pump Displacement [cc/rev]	Maximum continuous speed [rpm]	Minimum continuous speed [rpm]	Maximum continuous pressure [bar]
Boom	25	3400	300	26.7	3000	350	300
Arm	30	3400	300	29.06	3000	350	300
Bucket	25	3400	300	21.99	3000	350	280
Swing	18	4000	300	14.53	3500	350	290
Offset	30	3400	300	29.06	3000	350	260
Blade	35	3400	300	34.56	3000	350	300
Auxiliary	25	3400	300	26.7	3000	350	260
Right Track	25	3400	300	26.7	3000	350	300
Left Track	25	3400	300	26.7	3000	350	300

Lumped parameter models for the baseline LS architecture, the DC and EHA architecture were implemented in Simcenter Amesim for the analysis of the energy consumption. The selected approach allows simulating the performance of each architecture considering both steady-state and dynamic component characteristics. To this end, following elements were taken into consideration:

- Volumetric and hydromechanical efficiency maps for both fixed displacement pumps (gear pumps) and variable displacement pumps (swash plate pumps)
- Realistic line lengths/diameter, using values derived from the baseline reference vehicle. Reasonable line lengths are necessary to properly consider capacitance and resistance effects.
- Steady-state characteristic curves for the valves (i.e. flow vs pressure drop at different openings) from off-the shelve components
- Dynamic behaviors in terms of valve opening/closing, stroke/destroke time for the pumps.
- Unitary efficiency (ideal) electric drives and mechanical transmission in the DC and EHA systems. This simplification is also made to make the results agnostic with respect to the technology of the electric system.

As model inputs, the actuator force/torque from baseline measurements is applied to the hydraulic actuators instead of a mechanical model of the excavator bodies. Finally, an “operator model” is designed to ensure tracking the actuator displacement measurements for each one of the three system models. The modelling of the three architectures only involved the digging functions of the excavator, boom, arm, bucket and swing, since the 90° digging duty cycle has been selected for the energy analysis in this research. To assess the validity of the simulation approach, the LS system model with the four functions was previously validated using measurements from the reference machine for the digging cycle. The energy losses in the system are computed using the approach described by Zimmerman et al. [4].

5. RESULTS

5.1. Excavator Working Cycle

A typical 90° digging cycle, which involves the swing, boom, arm, bucket functions, for the reference excavator is selected for simulation and energy analysis of the three systems. The cycle involves the filling of dirt in the bucket, rotation of about 90°, dumping the load onto a pile, and returning to the starting position. A representative snapshot of the cycle for 21 seconds of operation is shown in Figure 5, which shows the normalized position (left) and the experimentally measured hydraulic force of the actuators (right) in the reference LS system.

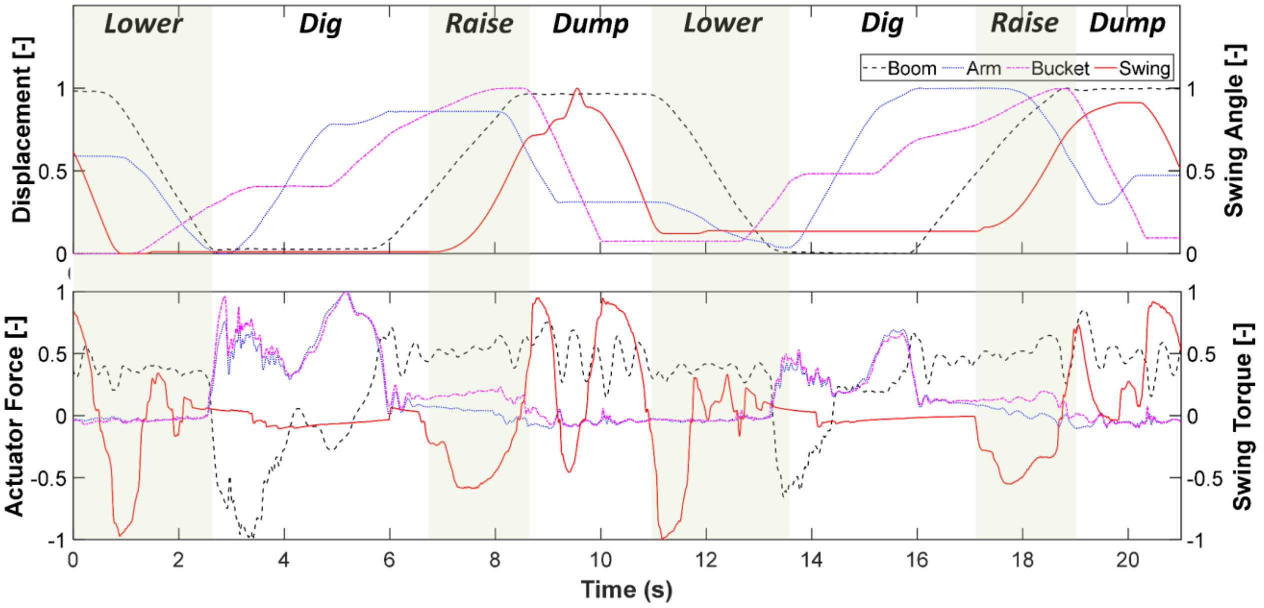

Figure 5: Actuator Displacements (top) and Hydraulic Forces (bottom) during a 90° digging duty cycle

5.2. Energy Analysis

Using the simulation results of the LS, DC and EHA systems with the digging cycle, the distribution of energy at the pump shaft is presented in this section. The losses in the three systems are classified as described in section 3.3. Firstly, the energy distribution for the LS system is shown in Figure 6. Since the simulation results are taken from pressure measurements at the actuator chambers, the actuator work done includes the transient and friction losses. Furthermore, the net actuator work includes the positive and negative (recoverable) work done by the actuator. This means that the negative work, not recovered by the LS system, is considered as part of the meter-out throttling loss. The energy distribution in Figure 6 shows that the useful or net work done by the LS system is 25% of the total pump shaft energy, and about 38% of the energy is lost in the valve block. The recoverable or negative work accounts for about 11% of the total energy. It is also shown that the swing and boom actuator work are only about 5% and 3% respectively, because they form a large portion of the total recoverable (negative) energy, which is lost due to throttling.

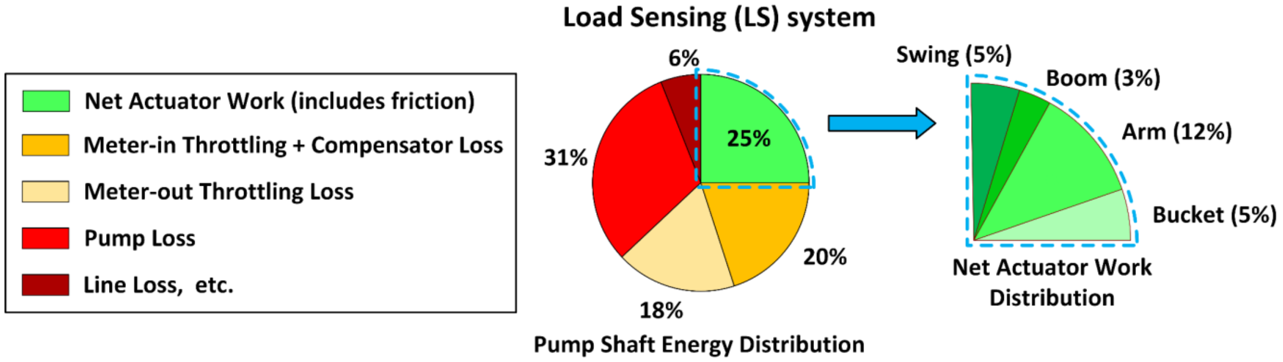

Figure 6: Energy Distribution for LS excavator during the 90° digging cycle

For the individualized architectures, the throttling and compensator losses are eliminated due to the use of independent pumps and the negative work is able to be recovered through mechanical or electrical energy recovery. The energy distribution for the DC and EHA systems are shown in Figures 7 and 8 respectively. The energy distribution of the pump shaft(s) shows an efficiency of 61% and 64.5% for the DC and EHA systems respectively. For the DC system, the energy consumption excluding the charge circuit losses can be split for the working actuators, whereas the complete distribution for the EHA system can be split because of independent charge systems. The relatively low efficiency of the boom actuator results from the pump losses occurring during motoring mode, when the work done is negative. The line loss distribution is the result of the actuator placement, with the swing placed closest to the pump and bucket the farthest. For the EHA system, the by-pass valve (BPV) induces some throttling in the system at low-speed actuation.

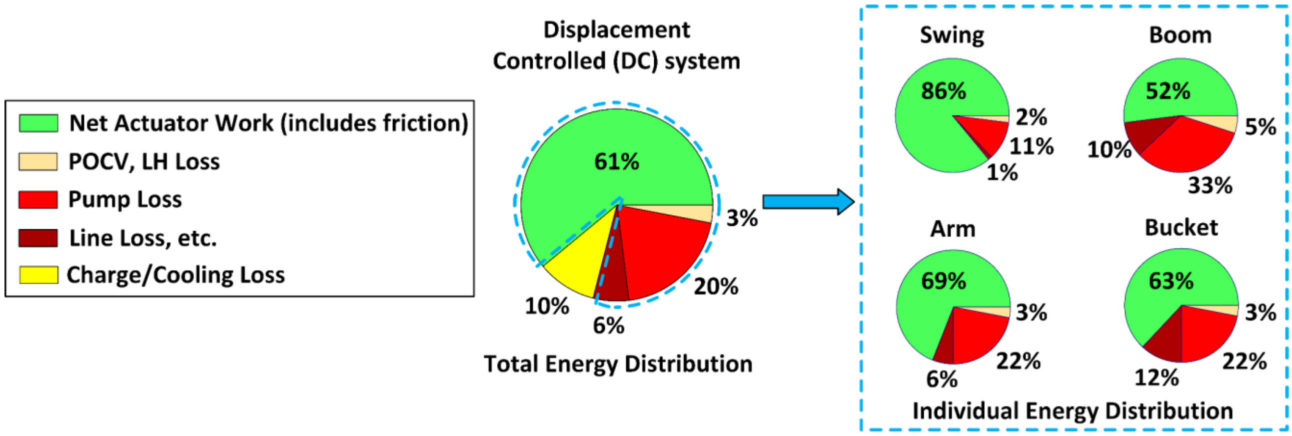

Figure 7: Energy Distribution for DC excavator during the 90° digging cycle

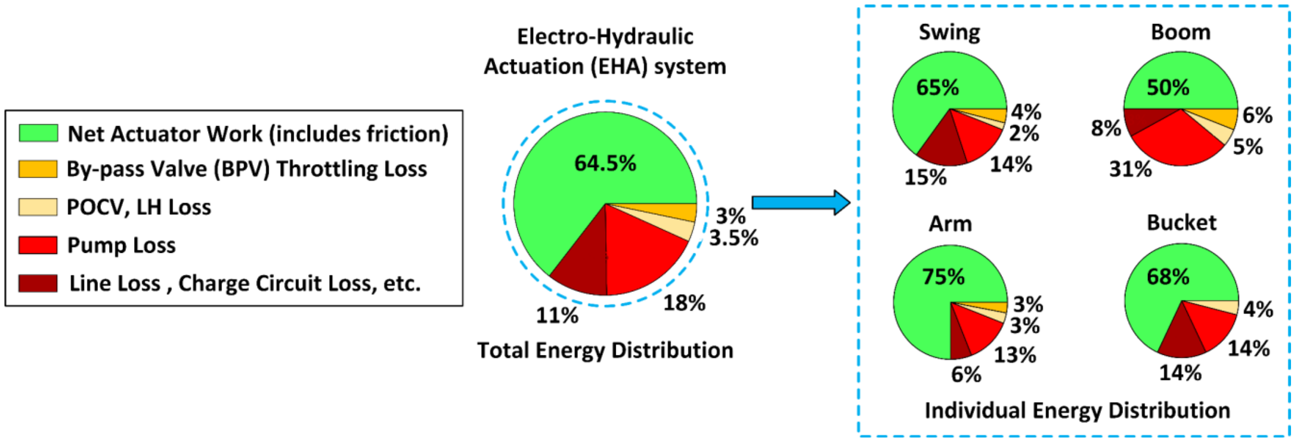

Figure 8: Energy Distribution for EHA excavator during the 90° digging cycle

5.3. Installed Power Analysis

Based on the simulation results, the power requirements for the electrified LS, DC and EHA systems for the digging cycle can be obtained. The operating points of the pump shaft(s) for the LS and individualized architectures is shown in Figure 9, where the LS and DC systems have a common shaft for the variable pumps, whereas the EHA system has independent pump shafts driven by separate electric motors. The figure shows that the operating torque range is lower than the LS system, which is due to lower energy consumption and higher speed capabilities of electric motors, and therefore, a lower displacement of the pumps for the same flow requirements. In contrast, for the EHA system with fixed displacement pumps, the shaft torque only depends on the pressure differential and is therefore, in general higher than the DC system as can be seen for the swing and arm actuators. Also, during negative (overrunning) work in, for example, the boom in simultaneous operation with the arm doing positive work, the energy recovery is mechanical in the DC system and therefore, reduces the torque on the electric drive. On the other hand, the form of recoverable energy is always electrical for the EHA system, which results in further conversion losses and no reduction in shaft torque.

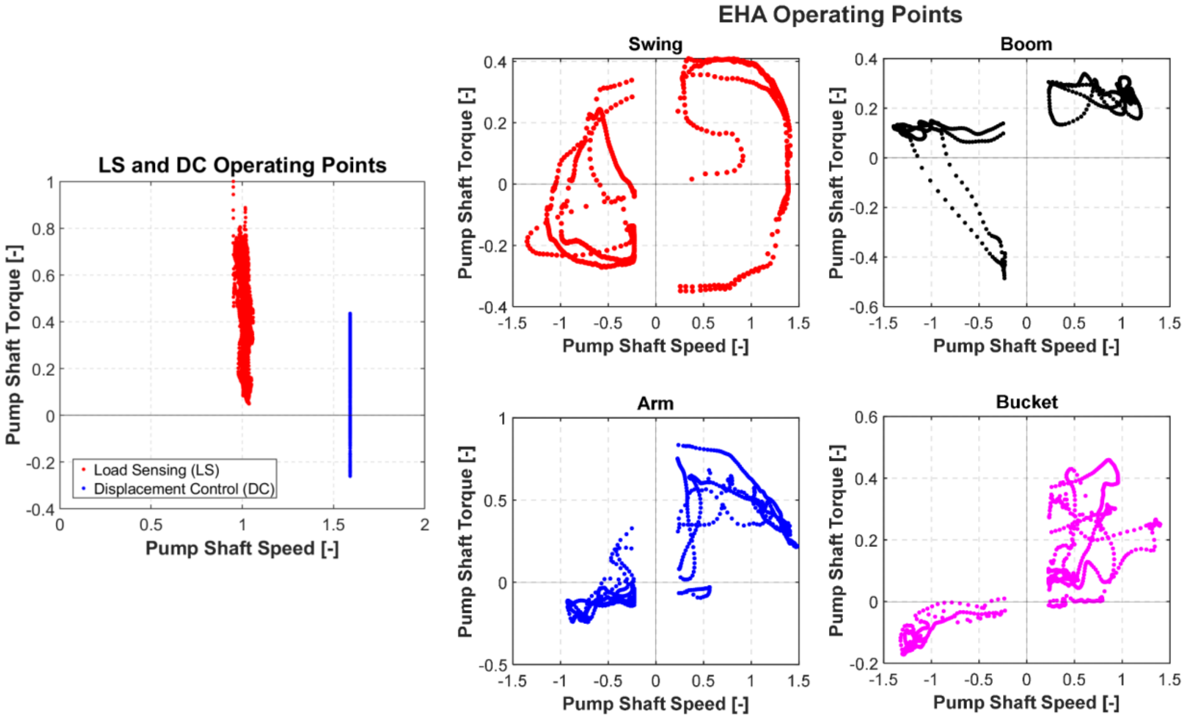

Figure 9: Operating Points (Normalized) for Pump Shaft(s) Power in LS, DC and EHA excavator during the 90º digging cycle

Based on the analysis of the duty cycles, the appropriate electric drives for the DC and EHA systems can be selected to provide adequate power during different phases of the cycles. In the scope of this study, only the digging cycle is considered for this purpose. Instead, the electric drives sizes for the secondary functions are chosen based on specific assumptions and knowledge of the reference machine. Based on the assumptions in section 4, the theoretical installed power of the electric drives relative to the reference LS system is listed in Table 2. Even though the DC system consumes less power during the digging cycle compared to the LS system, the installed power needs to be adequate for limiting operating conditions of single- or multi-actuator operation. The fact that a torque limiter is present in the reference machine to limit the maximum power of the LS system is used to limit the maximum torque for the DC system, so that the power of the electric drive is equal to the reference system. For the EHA system, since the actuators have separate electric drives, the installed power for the digging functions is 2.87 times higher than the LS installed power based on the simulation results shown in Figure 9. For the remaining actuators, their limiting operating conditions and maximum torque limit of the LS system are utilized to obtain the power of the electric drives. The use of LS torque limit instead of power limit like the DC system is because the torque for fixed displacement pumps depends only on pressure differential. Therefore, the total installed power of the EHA excavator is 8.26 times the LS installed power. This shows that even if the energy consumption during digging for the two individualized excavator systems is similar, the EHA system requires a significantly higher installed power and number of electric drives compared to the DC system, which requires the same installed power as the LS system. However, the advantage of using EHA drives stems from the compactness of integrated systems and modular designs.

Table 2: Relative Theoritical Installed Power of the Electric Drives

System	Maximum Torque [-]	Maximum Speed [-]	Power [-]
LS	1	1	1
DC	0.625	1.6	1
EHA – Swing	0.43	1.37	0.54
EHA – Boom	0.5	1.37	0.69
EHA – Arm	0.8	1.37	1.1
EHA – Bucket	0.43	1.37	0.54
EHA – Blade	1	1.37	1.4
EHA – Offset	0.69	1.37	0.95
EHA – Auxiliary	0.64	1.37	0.88
EHA – Right Track	0.79	1.37	1.08
EHA – Left Track	0.79	1.37	1.08
EHA – Charge Pump	0.003	1.37	0.004
EHA – Total			8.264

6. CONCLUSION AND OUTLOOK

This paper presented a comprehensive study to assess the pros and cons, in terms of energy consumption and the installed power, of fully individualized hydraulic systems in an electrified mini-excavator. The reference case of an electrified load sensing (LS) system, as in the baseline vehicle, is considered against two fully individualized hydraulic architectures based on the Displacement Control (DC) and the Electro-Hydraulic Actuation (EHA) concept. While the DC system uses variable displacement pumps for each actuator with a common electric drive, the EHA system uses fixed displacement pumps with separate electric drives for each actuator. A breakdown of the energy losses in the LS, DC and EHA was given and appropriate sizing for the components was conducted in the proposed systems. Simulation models for the hydraulic systems of the architectures were built in Simcenter Amesim and a 90° digging cycle was simulated to analyse the energy consumption of the three systems. The digging cycle had four working actuators, swing, boom, arm and bucket, and a breakdown of the system power losses showed that the pump shaft energy efficiency increased by about 59% and 61% compared to the reference LS system for the DC and EHA systems respectively. However, the installed capacity of the pumps for both the systems increased significantly. In the DC system, the power of the electric drive installed was comparable to the reference LS system. In contrast, for the EHA system, with the increase in the number of electric drives, the total installed power of the units increased to about 8.3 times the LS installed prime mover power. In conclusion, this study shows that the full individualization of centralized hydraulic circuits of excavators can notably reduce the energy consumption for both DC and EHA concept, but at the cost of significantly higher installed power of the components. While both DC and EHA increase the overall pump capacity, the EHA concept also increases the installed power of the prime movers by 8 times. Hence, a trade-off exists between the energy efficiency and the level of individualization for electrified hydraulic architectures.

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NOMENCLATURE

BPV	By-Pass Valve	
DC	Displacement Control	
EHA	Electro-Hydraulic Actuation	
ICE	Internal Combustion Engine	
LH	Load Holding Valve	
LS	Load Sensing	
ORV	Off-Road Vehicles	
POCV	Pilot Operated Check Valve	
p_A	Pressure in cylinder piston-side chamber (A)	[bar]
p_{acc}	Pressure in the accumulator	[bar]
p_B	Pressure in cylinder rod-side chamber (B)	[bar]
p_{pump}	Pressure at pump delivery port	[bar]
Q_{max}	Maximum flow rate of the pump	[L/min]

REFERENCES

[1] Quan Z, Ge L, Wei Z, Li YW, Quan L (2021) A Survey of Powertrain Technologies for Energy-Efficient Heavy-Duty Machinery. Proceedings of the IEEE 109:279–308

[2] Hagen D, Padovani D, Choux M (2020) Guidelines to Select Between Self-Contained Electro-Hydraulic and Electro-Mechanical Cylinders. 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), 547-554

[3] Vacca A, Franzoni G (2021) Hydraulic Fluid Power: Fundamentals, Applications, and Circuit Design. Hoboken, NJ: Wiley

[4] Zimmerman J, Pelosi M, Williamson C, Ivantysynova M (2007) Energy Consumption of an LS Excavator Hydraulic System. Proceedings of the ASME 2007 International Mechanical Engineering Congress and Exposition. Vol. 4, 117-126

[5] Pellegri M, Green M, Macpherson J, MacKay C, Caldwell N (2020) Applying a multi-service digital displacement® pump to an excavator to reduce valve losses. 12th International Fluid Power Conference 59-68

[6] Heybroek K, Sahlman M (2018) A hydraulic hybrid excavator based on multi-chamber cylinders and secondary control–design and experimental validation. International Journal of Fluid Power, 19(2), 91–105

[7] Weber J, Beck B, Fischer E, Ivantysyn R, Kolks G, Kunkis M, Lohse H, Lübbert J, Michel S, Schneider M, Shabi L, Sitte A, Weber J (2016) Novel System Architectures by Individual Drives.

10th International Fluid Power Conference 29-62

[8] Zimmerman J, Busquets E, Ivantysynova M (2011) 40% Fuel Savings by Displacement Control Leads to Lower Working Temperatures - A Simulation Study and Measurements. Proceedings of the 52nd National Conference on Fluid Power, Vol.1, 693-701

[9] Qu S, Fassbender D, Vacca A, Busquets E (2021) A high-efficient solution for electro-hydraulic actuators with energy regeneration capability. Energy, Elsevier, 216(C)

[10] Haack S, Flaig A (2022) Sustainable Hydraulics for Industrial and Mobile Application. Presented at the 13th International Fluid Power Conference, Aachen, Germany

[11] Pischinger S (2022) Future CO_2-Neutral Propulsion and their Impact on Fluid Technical Systems. Presented at the 13th International Fluid Power Conference, Aachen, Germany

[12] Casoli P, Scolari F, Minav T, Rundo M (2020) Comparative energy analysis of a load sensing system and a zonal hydraulics for a 9-tonne excavator. Actuators 9, 2: 39

[13] Padovani D, Fresia P, Rundo M, Altare G (2022) Downsizing the electric machines of energy-efficient electro-hydraulic drives for mobile hydraulics. Journal of Physics: Conference Series, 2385 012028

[14] Busquets E, Ivantysynova M (2015) A Multi-Actuator Displacement-Controlled System with Pump Switching - A Study of the Architecture and Actuator-Level Control. JFPS International Journal of Fluid Power System 8(2) 66-75

[15] Figge F, Schmitz K (2023) Simulative Comparison Approach of Electro-Hydrostatic Actuator Circuits in Excavators. Proceedings of the BATH/ASME 2023 Symposium on Fluid Power and Motion Control FPMC2023-111798

[16] Padovani D, Ketelsen S, Hagen D, Schmidt L (2019) A self-contained electro-hydraulic cylinder with passive load-holding capability. Energies 12, 2: 292