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Dextreme MAX: A Digital Displacement® Excavator System for Energy Recovery and Reduced Losses

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Abstract.

We present Dextreme MAX, a hydraulic architecture applied to a 30-tonne electric excavator based on a Digital Displacement pump/motor with multiple independently controlled outlets. The system provides independent actuator supply, eliminates flow-sharing losses, and enables energy recovery / hydraulic transformation via a boom H-bridge valve. On standardized JCMAS cycles, the converted machine reduced DC energy use by 49% in grading and 31% in dig-and-dump, with negligible impact on cycle time; across a representative duty mix this corresponds to ≈35% lower battery power and >53% longer uptime. These gains primarily arise from reduced throttling; additional benefits come from boom-lowering energy recovery. Results indicate that MAX can reduce required battery capacity and cost while maintaining productivity, accelerating electrification of heavy machinery.

Keywords. Digital Displacement, Excavator, Energy recovery, Electrification, Hydraulic transformation.

1. INTRODUCTION

As climate targets tighten, the inefficiency of hydraulic off-highway machinery has become a pressing concern. Excavators, one of the largest and most energy-intensive off-highway segments, typically achieve only 20–30% hydraulic efficiency [1]. Whilst for ICEs this drives high fuel consumption and CO_2 emissions, for electric excavators, this inefficiency is especially costly: batteries must be sized for a full shift, and as the most expensive component, this makes electrification economically challenging. Conventional systems (Negative and Positive Flow Control, Load Sensing) suffer large throttling losses and lack energy recovery [2]. Numerous advanced concepts such as displacement control [3,4], independent metering valves (IMV) [5,6], multi-chamber cylinders [7], two-pressure-rail hybrids [8], and secondary controlled actuators [1] have shown 15–50% efficiency gains in research prototypes. Yet commercial adoption remains minimal due to cost, scalability, complexity, a radical overhaul of the system, and uncertain ROI.

Digital Displacement® (DD) technology offers a more evolutionary path: DD pumps combine high efficiency across the load range with multi-outlet capability [9]. Prior work on a 16-tonne excavator showed that a single "multi-outlet" DD pump could decouple boom/bucket from arm/swing functions, reducing throttling losses while retaining the original hydraulic layout. Reported results included productivity improvements of 10–15%

or fuel savings of 20–30% [10,11] in a diesel machine compared to the traditional NFC system with a tandem-swashplate unit. However, flow-sharing valve blocks as well as a lack of energy recovery still limited the further efficiency improvements.

This paper introduces Dextreme MAX, a novel architecture developed during a two-year project funded by the UK Department for Energy Security and Net Zero (DESNZ).

2. DEXTREME MAX SYSTEM DEVELOPMENT

The Dextreme MAX system aims at eliminating the flow-sharing central valve block by using a DD pump/motor with four independently controlled outlets to supply each actuator of the excavator, removing flow-sharing losses and enabling independent actuator control as well as energy recovery and hydraulic transformation. This new architecture builds on top of the SWAP and FLEX systems presented in [9,10].

2.1. Technology Background: The DD1x0D Digital Displacement Pump/Motor

The DD pump/motor is a radial piston unit based on electronically controlled poppet valves, enabling each cylinder to be switched on or off in real time according to crankshaft position [12] via a dedicated real-time controller, the DPC30. Flow is therefore modulated digitally at the cylinder level, with cylinders producing a full/partial pumping or motoring stroke or idling with negligible loss. This yields high efficiency across the full displacement range, combined with fast dynamics and precise flow control. The DD1x0 family is the first generation of large-format DD machines for prime movers in the 120–250 kW class, targeting 20–40 tonne excavators [13]. A key innovation is the combination of pump/motor capability with ten independently controlled outlets, each operating at its own pressure level. This allows independent multi-actuator supply and new modes of hydraulic transformation. In fact, the DD1x0D can operate as a transformer: some outlets motor while others pump or idle, enabling direct energy transfer between circuits at different pressures (Figure 2.1).

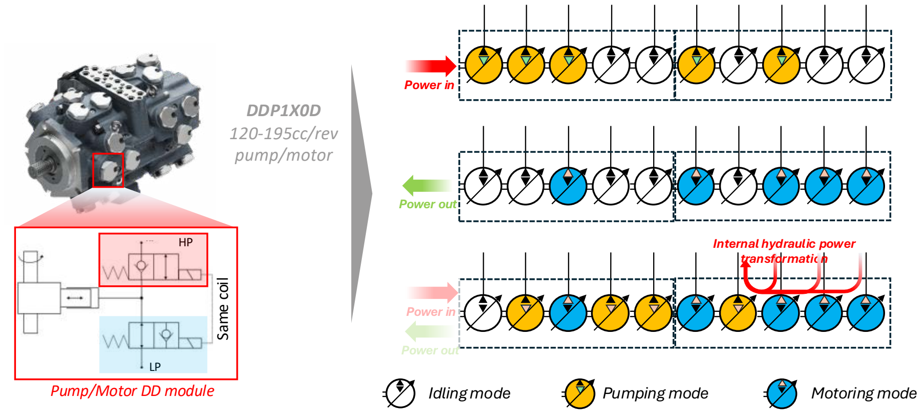


Figure 2.1. The DD1x0D Pump/Motor combines pump/motor/transformer functionality with ten independent outlets

Overrunning energy, such as from boom lowering, can be returned to the drivetrain or transformed to support other actuators. Component tests of the DD1x0 have shown pumping and motoring efficiencies above 94.5% in the main excavator operating range (150–250 bar, 1400–1800 rpm), with peak motoring efficiency of 96.7%. These results confirm the DD1x0's potential for very high efficiency together with system-level functions like energy recovery and transformation unavailable with conventional pumps [13].

2.2. The DX300 Dextreme MAX System: concept and implementation

The MAX system was demonstrated for the first time on a 30-tonne battery-electric excavator, selected to meet the objectives of the UK Red Diesel Replacement Phase 2 (RDR2) programme [14], which aims to accelerate decarbonisation of off-highway machinery. The project sought to prove that higher hydraulic efficiency can reduce required battery capacity, cutting cost and charging demand while maintaining productivity. Although validated on an electric platform, the same principles directly apply to diesel machines, where lower hydraulic losses reduce fuel use and emissions.

A DEVELON DX300LC-7 crawler excavator was chosen as the test platform. Originally diesel-powered with a two-service NFC hydraulic system, it was obtained in an electric configuration from STAAD B.V., which replaces the engine with an electric drivetrain and battery system (Table 2.1). The model offered representative scale, short delivery time, and strong technical support, enabling integration of the MAX concept to a Technology Readiness Level 7 prototype (TRL7 [15]).

Table 2.1. Electric Drivetrain Specifications

Parameter	**Value**	**Notes / Components**
System HV voltage	670-790 VDC	Battery supply voltage
Nominal motor speed	1900 rpm	
Maximum motor speed	2200 rpm	
Continuous motor power	145 kW	Limited at machine level (motor rated 174 kW)
Motor	Danfoss PMI375-T800-1800	Permanent magnet synchronous motor
Inverter	Danfoss EC-1200-450-L240A	DC–AC phase inverter
Motor controller (VCU)	Danfoss MC050-010	Vehicle control unit
Installed Battery Capacity	3x140kWh	1 fixed + 2 swappable

The Dextreme MAX hydraulic architecture comprises four primary services – boom, arm, bucket, and swing – each supplied independently by the DD1x0D. The unit features ten controllable outlets that can be dynamically grouped through a digital distributor reallocating capacity to the actuator requesting it [9]. A schematic comparison between the baseline and MAX configurations is shown in Figure 2.2.

For this prototype, full decoupling of all four services was not implemented due to project time limits and the need to retain the original main control valve (MCV) without altering its core functions. Energy-flow analysis showed that keeping the MCV for the arm and bucket circuits introduced acceptable losses: during high arm-in demands (> 50 % operator input), the "arm 2" and bucket spools continue to share flow through the coupled MCV arrangement.

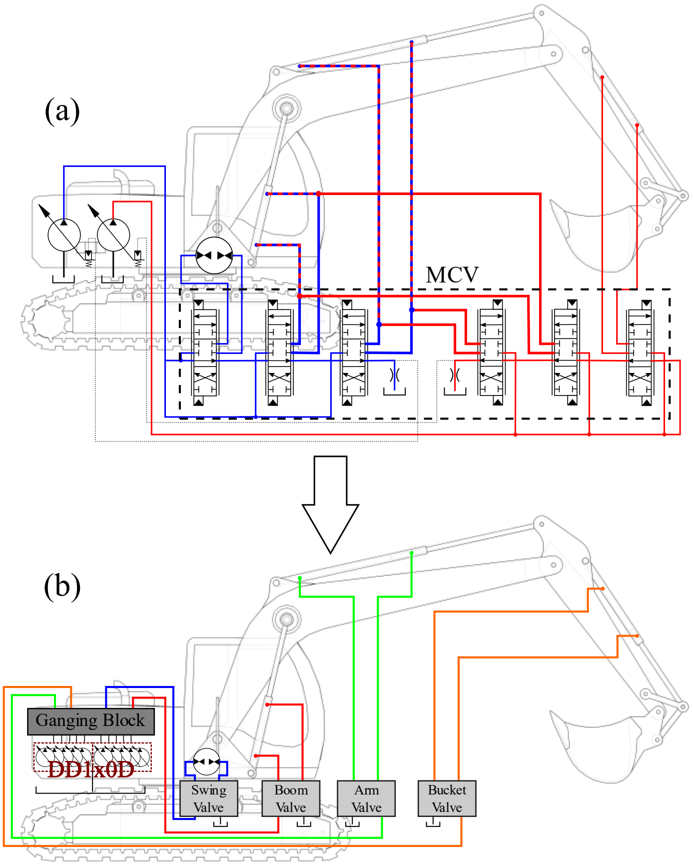


Figure 2.2. Layouts of the original NFC system (a) and the Dextreme MAX system (b).

Based on previous studies [7,8], the boom and swing were identified as the main candidates for energy recovery, as they dominate potential and kinetic energy exchange during excavator cycles. The boom typically offers several times higher recovery potential than other actuators and about two to four times that of the swing. Consequently, both functions received dedicated valve services in the MAX demonstrator. Because the DD1x0D operates in an open circuit, practical swing-energy recovery could not be implemented within the project timeframe. Instead, the swing used an independent metering valve to remove flow-sharing and metering losses, while only the boom employed a full H-bridge for regeneration and pressure amplification. Table 2.2 summarizes the configuration of the baseline NFC and MAX systems. To maximize the possibility of energy recovery and simultaneous actuators operation, a DD180D (2x180cc/rev) has been selected, replacing the original 140cc/rev swashplate tandem unit. In addition to the DD180D, two supporting subsystems were added:

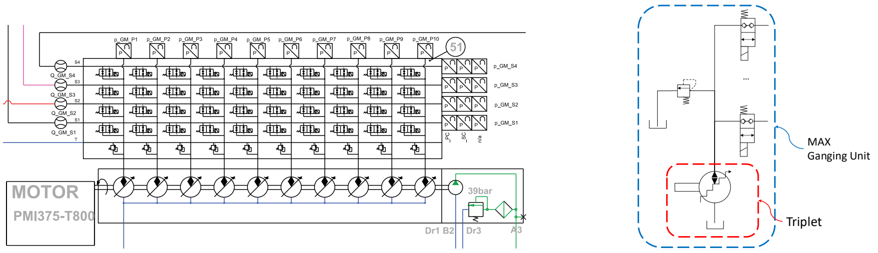
- Ganging block – a digital distributor enabling dynamic grouping of pump outlets
- Boom and swing valve – a dedicated arrangement providing advanced control of these actuators

Table 2.2. Service/actuators configurations comparing the original NFC and Dextreme MAX systems

Service ID	**Original**	**MAX configuration**
Service 1	-	Swing
Service 2 (2)	Bucket / Boom 1 / Arm 2	Bucket / Arm 2
Service 3 (1)	Swing / Boom 2 / Arm 1	Arm1
Service 4	-	Boom

2.2.1. *The Ganging Block*

This valve block, referred to here as the ganging block, connects each service to each DD outlet ("triplet" – three pistons each), enabling the allocation of large capacity to individual services when required. A set of digitally controlled valves is introduced to distribute the flow supplied or absorbed by the DD1x0D among the working actuators. The hydraulic schematic of the ganging block is shown in Figure 2.3.



(a) (b)

Figure 2.3. (a) Schematic of the ganging manifold; (b) MAX ganging unit consisting of a DD1x0 Triplet and four 2/2 valves, and a PRV connected in parallel.

The valves selected for the ganging block are 2-way 2-position, high pressure bi-directional, pilot operated, poppet type screw-in cartridge valve (Danfoss SBV11-12-C). Each valve is normally closed (no free-flow direction) and allows bidirectional flow when energized. In addition, the manifold integrates ten safety relief valves, one per pump outlet.

2.2.2. *Boom valve - the H-bridge*

Because the DD1x0D is an open-circuit pump/motor, additional valve functionality was required for full bidirectional control of the linear actuators. A dedicated H-bridge valve was therefore developed to manage independent meter-in and meter-out flows, providing anti-cavitation, pressure amplification, and energy recovery during overrunning motions. Building on previous work on independent metering and secondary control [1,16], the design aimed to minimize throttling losses while enabling controlled energy exchange. In the Dextreme MAX system, the H-bridge supports the following key functions:

1. Four-quadrant operation – provide full control of actuator motion across all load and velocity directions, ensuring symmetric functionality in extension and

retraction. For the boom, quadrant I corresponds to resistive extension (lifting) and quadrant II to overrunning lowering.

2. Anti-cavitation (quadrants II and IV) – supply make-up flow to prevent cavitation when the actuator is driven by overrunning loads
3. Flow regeneration (quadrant II) – transfer flow from the head side to the rod side during overrunning lowering.
4. Pressure amplification / differential mode (quadrant II) – apply controlled pressure on the rod-side to raise effective load pressure while reducing flow demand. For the DD1x0D, this maintains constant power transfer with less processed flow, reducing conveyance losses and freeing capacity for other actuators.
5. Normal metering-out (quadrants II and IV) – allow conventional throttling when energy recovery or transformation is not possible.

Together, these modes provide the flexibility, safety, and fallback behaviour required for practical excavator operation.

Several H-bridge topologies were evaluated. A four-cartridge concept ([16]) and Valvistor-type elements were excluded due to flow-capacity limitations and development time constraints. To ensure availability and reliability, the final design employed Danfoss PVG components, as shown schematically in Figure 2.4.

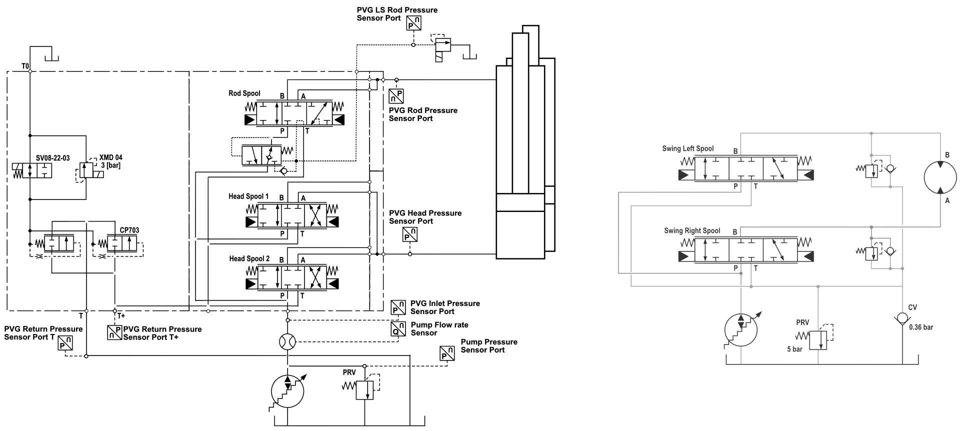


Figure 2.4. Simplified schematic of the Boom H-Bridge and Swing valve

The implemented boom H-bridge employs three PVB valves (2 × PVB128 and 1 × PVB256) to meet the requirements for four-quadrant operation, anti-cavitation, regeneration, pressure amplification, and safe metering-out while handling the excavator's peak flows. The circuit connects pump to head (P–A), pump to rod (P–B), head to tank (A–T), and rod to tank (B–T), enabling full control of both chambers. For stable rod-side pressure regulation, the PVB256 compensator was modified so that the main spool remains fully open while an actively piloted compensator in the rod branch maintains chamber pressure. A pilot relief valve (PRV) defines the pressure reference dynamically, providing faster and more stable control than direct control of the PVG spool. This approach is consistent with [17], which showed the efficiency and safety benefits of active pressure regulation. The resulting PVG-based layout delivers the required four-quadrant performance using standard, commercially available hardware, ensuring timely and practical system integration.

2.2.3. Swing valve

The swing service valve was implemented using the same independent-metering PVG concept adopted for the boom, but with a simplified layout consisting of two PVB128 as shown in Figure 2.4. All PVB blocks for boom and swing were physically integrated into a single large PVG assembly, interconnected through a custom hydraulic integrated circuit (HIC) block. This approach allowed the services to be grouped in a compact package while providing the necessary functionality for the MAX system.

2.3. Control Logic

The introduction of four independent services in the Dextreme MAX system required a complete redesign of the control strategy compared with previous SWAP and FLEX implementations. The controller must manage flow allocation, displacement distribution, pressure regulation, torque sharing, and boom-specific recovery logic, while ensuring seamless operator control and compatibility with the machine's electric prime mover. Figure 2.5 summarizes the control architecture, highlighting the interaction between displacement control, pressure controllers, torque management, and H-bridge logic.

2.3.1. Flow Allocation and Elastic Pump Distribution

Similar to positive flow control (PFC) systems the joystick pilot pressures are mapped through look-up tables to generate service flow demands. The DD pump/motor provides multiple discrete outlets ("triplets"), which must be assigned dynamically to the active services. In general, the system tries to satisfy the capacity request of each actuator. When the demand exceeds the total pump capacity, proportional displacement allocation is enforced. The 2/2 valves in the ganging block are switched on and off accordingly. As each service is handled separately by the pump controller, the flow is adjusted by controlling the displacement fraction of the instantaneous allocated capacity of the service.

2.3.2. Pressure Limiting

The MAX controller allows for pressure control for all services. A PI controller regulates pump displacement accordingly to limit losses over relief valve, which is common control practice when accelerating the swing function. The pressure setpoint can be changed dynamically based on the operating conditions: for example, because the MAX architecture decouples the boom and swing into separate services, the flow-sharing characteristic of the baseline system during lift-and-rotate operation is lost. To re-establish the expected interaction between these functions, a flow-sharing emulating algorithm is introduced. In this case, the pressure of the swing is limited to the boom service pressure, thereby reproducing the coordination observed in conventional architectures while preserving the independence of the MAX layout.

2.3.3. Torque Control

The torque controller determines the aggregate pump torque request and interfaces with the prime mover. Only the positive torque contributions of each service are considered when calculating total demand; negative torques from motoring services are excluded to avoid disturbing the expected flow distribution. An anti-lift-off strategy is applied to reduce motoring demand when the shaft speed exceeds a defined threshold, preventing overspeed. In addition, motoring is disabled entirely when calculated negative power falls below the minimum limit specified by the electric motor control unit. Under these circumstances the H-Bridge metering functionality maintains productivity by ensuring requested boom down speed. These safeguards ensure compatibility between hydraulic energy recovery and the electric drivetrain.

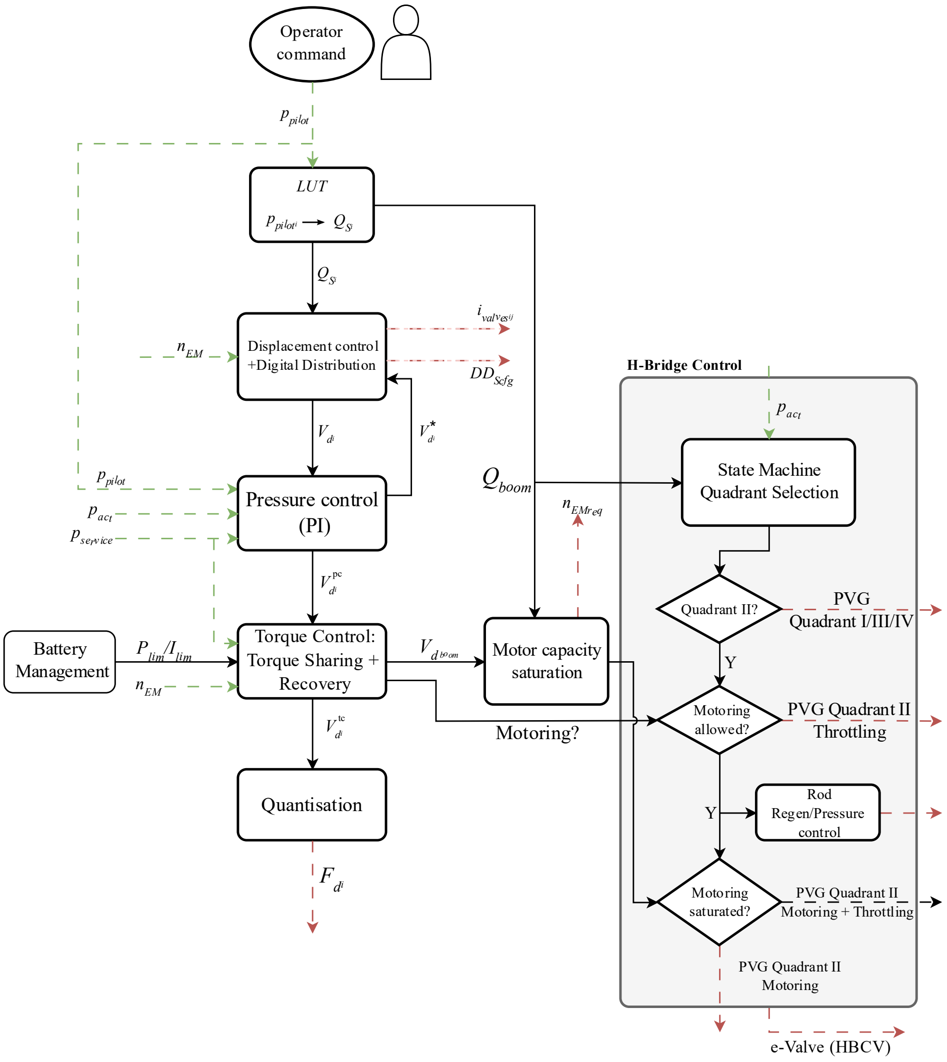


Figure 2.5. Control structure for the Dextreme MAX system

2.3.4. Boom Control Logic

Boom control is critical to the overall efficiency of the MAX system. The boom controller is structured around four quadrants of actuator operation:

- Quadrant I – Resistive extension (lifting).
- Quadrant II – Overrunning retraction (lowering).
- Quadrant III – Resistive retraction.
- Quadrant IV – Overrunning extension.

During resistive operation (Quadrants I and III), the pump supplies the head or rod chamber in a conventional manner. The head spool remains fully open, and motion is regulated entirely through displacement control of the DD180D, with smooth behaviour enabled by its fast dynamic response. Overrunning retraction (Quadrant II, i.e. boom lowering) presents the greatest control challenge. The key issue is managing cavitation risk in the rod chamber while handling surplus flow from the head side. This is addressed through differential actuation, in which part of the head flow is routed to the rod side. In this mode, the rod chamber pressure is actively regulated: either by partial opening of the rod spool or, preferably, by a piloted pressure compensator in the rod branch. The compensator, controlled via an external PRV, provides faster and more stable response. Rod pressure set-points vary with load: a higher-pressure setting is used for light bucket loads to maximize energy recovery, while lower pressure is set for heavy loads to avoid excessive head pressurization or when motoring is not possible. During motoring, because the machine has finite capacity, any excess head flow beyond the motoring limit is throttled to tank. While this introduces some loss, it ensures safe boom lowering and maintains productivity.

2.4. Control System Implementation

2.4.1. Data acquisition

To evaluate the performance of the prototype system, a comprehensive data acquisition (DAQ) alongside the control setup was installed on the excavator. The objective of this setup was to capture all relevant parameters from the working hydraulics – such as arm, boom, bucket, swing, and track systems – as well as from the DD pump outlets. The measurement system consisted of five DEWE-43 data acquisition units from Dewesoft, enabling synchronized high-speed recording across all channels covering hydraulic, mechanical, and electrical domains, allowing a detailed analysis of machine performance, energy flow, and control behaviour. The instrumentation covered the following main sensor groups:

- Hydraulic pressure sensors – installed at each DD pump outlet (service ports), actuator chambers, main control valve, and pilot lines to monitor system pressures and load conditions.
- Flow meters – flow meters on each DD outlet to measure service flow rates and calculate hydraulic power. A screw flowmeter was installed on the Boom Service for better accuracy at high flows during motoring.
- Position sensors – string potentiometers on the boom, arm, and bucket cylinders, and an IMU for the swing for displacement and motion tracking.
- Electrical power sensor – a high current and voltage transducer monitors DC supply from the battery to the inverter.

2.4.2. System controllers

The control system architecture (Figure 2.6) was designed to provide real-time control of the DD system, electric powertrain, and auxiliary subsystems. The setup combines a SpeedGoat Mobile real-time target machine (M3) with two Danfoss XL104-0000.

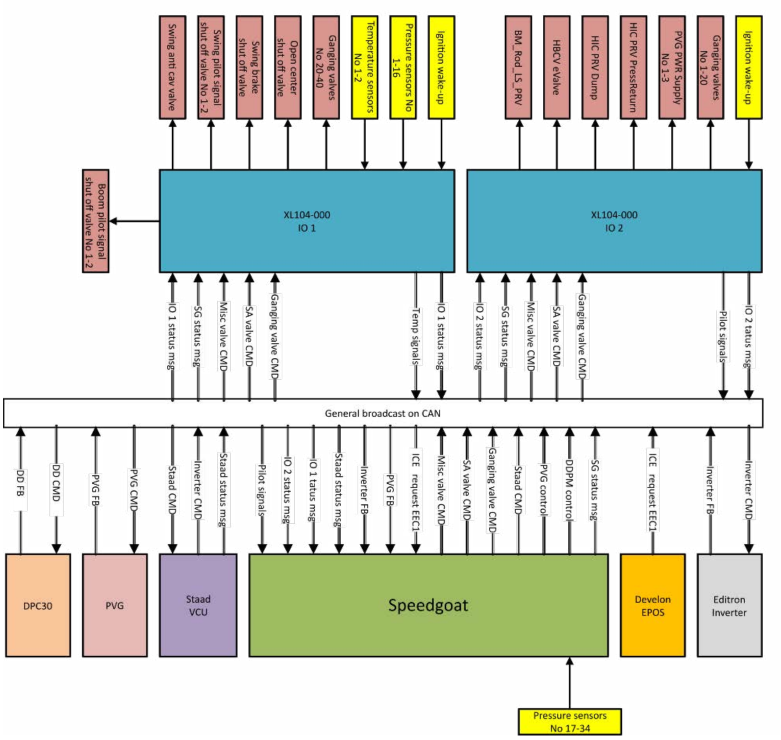


Figure 2.6. Control system architecture showing the SpeedGoat real-time target as the main controller and two Danfoss XL104-0000 units as distributed I/O.

The SpeedGoat unit is equipped with two IO133 modules for analog and digital I/O and one IO602 CAN interface module. It serves as the main real-time controller, executing the system's supervisory control, coordination of subsystems, advanced algorithms such as motoring and digital distribution, power limiting, and fault handling. The control logic was developed entirely in MATLAB / Simulink, and SpeedGoat was chosen for its capability for rapid prototyping. A corresponding Simscape model of the excavator was used to develop and verify the algorithms in real-time before deployment.

Two Danfoss XL104-0000 controllers act as distributed I/O nodes that interface directly with the hydraulic valves, pilot signals, and pressure sensors. These units provide the required output power to drive the proportional and on/off valves that exceed the current-handling capacity of the SpeedGoat I/O modules. They also serve as functional safety controllers, implementing local safety logic and redundancy for critical valve operations. All components communicate via CAN HS and J1939 protocol including the Danfoss Editron inverter, Develon EPOS, and STAAD VCU, which exchange commands and feedback signals over different CAN networks.

3. TESTING

The RDR2 program required a field trial to demonstrate TRL 7 and controlled testing to compare system performance before and after conversion. To quantify performance, a comprehensive characterisation of the original configuration was undertaken. The tests were designed to capture single-function behaviour, function-prioritisation performance, and simulated duty-cycle operation. Three types of simulated duty-cycle tests were performed:

1. JCMAS air grading (Equivalent of ISO11152-2) (Figure 3.1a)
2. JCMAS air dig and dump (Equivalent of ISO11152-2) (Figure 3.1b)
3. Real dig and dump with gravel (Figure 3.1c)

All tests were designed for repeatability and could be executed both before and after conversion. Operators were instructed to work as quickly as possible, as this typically yields the most consistent results.

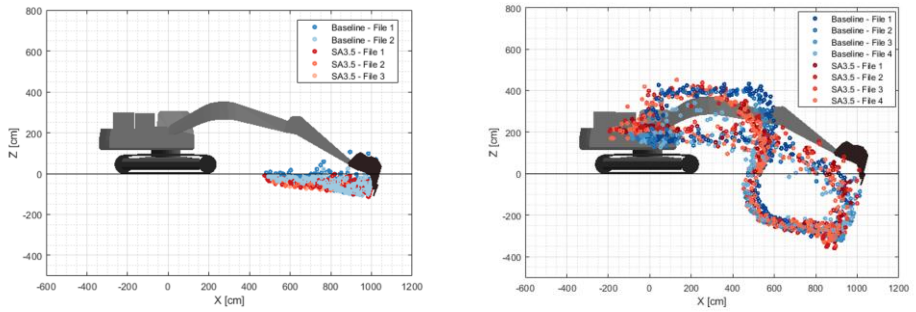

(a) (b) (c)

Figure 3.1. (a) JCMAS Air-Grading, (b) Air-Dig and Dump, (c) Real Dig and Dump

Baseline testing of the conventional system was conducted at the Danfoss Application Development Centre (ADC) in Nordborg. To meet project timelines, the post-conversion tests were repeated at a dedicated site near Edinburgh, providing a consistent basis for quantitative comparison and enabling safe operation in MAX mode. Because calibrated gravel was unavailable, real dig-and-dump tests could not be repeated; however, the JCMAS air cycles offered a controlled and repeatable means of assessing Dextreme MAX system efficiency relative to the Nordborg baseline.

Ensuring consistency across test cycles was challenging, as the baseline tests were conducted by a different operator at a separate site nearly a year earlier. The bucket-tracking tool was used to verify motion repeatability, and outlier cycles were excluded from the energy analysis using plotting tools. A sample comparison of bucket paths for the JCMAS tests is shown in Figure 3.2.

Cycle time influenced repeatability since the DDP180D pump's 30 % larger displacement enabled faster operation than the baseline unit. To align cycle durations, motor speed setpoints were adjusted for the converted machine tests, with active control of the EM speed during boom down to maximize energy recovery.



(a) (b)

	BOOM [M]	ARM [M]	BUCKET [M]	SWING [°]	
BASELINE	0.68	0.86	0.74	88	DnD
DEX. MAX	0.72	0.86	0.7	95	
ERROR %	**+5.8%**	**0%**	**-5.4%**	**+8%**	
BASELINE	0.33	1.23	-	-	Grading
DEX. MAX	0.30	1.23	-	-	
ERROR %	**-9.1%**	**0%**	-	-	

Figure 3.2. Comparison of bucket traces for JCMAS test – (a) Grading, (b) DnD; table with error percentage between average actuators extensions across tests.

3.1. Test results

Several tests were conducted for both the baseline and the converted machine using sets of 10 cycles per test for both grading and dig and dump. To ensure a fair comparison, the actuators' extensions have been evaluated, and clear outliers have been discarded. The errors in the actuators extensions (rotation) are between 9% and 0%. In case of the grading, the MAX system boom extension is 9% lower than the baseline, but the absolute value is 0.03m which is difficult to control in a fast and dynamic cycle. Average of the selected cycles results are presented in Table 3.1 and Table 3.2 for air grading and dig-and-dump operations, respectively.

Table 3.1. Air Grading results

Configuration	Cycle Time (s)	DC Power (kW)	DC Energy (kJ)
Baseline	6.78	120.5	817.0
MAX	7.29	56.9	414.8
% difference	+7.5%	-52.8%	**-49.2%**

Table 3.2. Air Dig and Dump (DnD) results

Configuration	Cycle Time (s)	DC Power (kW)	DC Energy (kJ)
Baseline	14.44	99.9	1442.6
MAX	14.59	68.2	995.0
% difference	+1%	-31.7%	**-31%**

General field operation of excavators implies a mix of grading, dig and dump and idling. Each OEM uses a different mix of those with dig and dump being the largest portion of the mix. For electric machines, we can exclude the idle portion as the electric motor can easily be stopped and started when needed. Assuming a duty cycle of 30% air grading and 70% air digging, the MAX system would reduce battery power consumption by 35% without significantly compromising work rate. This would result in 53% longer operating hours.

3.2. Data analysis

Table 3.3 summarizes the energy balance in a series of JCMAS DnD cycles between the baseline and MAX configurations, highlighting where the efficiency improvements originate. Losses associated with the inverter/motor, DD pump, baseline pump, and the AUX systems are estimated using numerical loss models; actuator mechanical losses are embedded in the reported actuator net energy. The different contributions are calculated using a mix of measured data and simulation models hence the small difference with the reported DC energy in Table 3.2.

Table 3.3. Breakdown of the system losses and contribution of energy savings

Energy [kJ]	Baseline	MAX	Δ	% of savings contribution
DC	1449.7	1021.6	**428.0**	
Pump Losses	167.3	85.2	82.1	19.2%
AUX	61.9	33.6	28.3	6.6%
EM Losses	71.5	50.6	20.9	4.9%
Actuator Net	481.8	457.8	24.0	5.6%
Meter In Loss	307.7	142.5	165.2	38.6%
Meter Out Loss	207.4	272.3	-64.9	-15.2%
Open Center Loss	93.9	38.6	55.3	12.9%
Relief Valve	58.1	40.7	17.4	4.1%
Recovered Energy	0.0	-99.7	99.7	23.3%

The total energy savings are primarily attributed to reductions in pump losses, metering losses, and the introduction of energy recovery. Pump losses decrease by 82.1 kJ (19.2 % of total savings), reflecting the improved part-load efficiency of the DD pump. A significant 220.5 kJ reduction in combined open-center/meter-in losses (51.5%) confirms the effectiveness of independent flow-matching control in minimizing metering losses during multi-actuator operation. The recovery system contributes an additional 99.7kJ (23.3 %), corresponding to energy regenerated during boom lowering. Meter-out losses are not improved and are slightly increased. This is primarily due to the higher flow levels through the arm and bucket circuits, while the same conventional valves were retained.

Overall, approximately half of the total energy savings result directly from reduced hydraulic throttling, with the remaining half achieved through energy recovery and pump efficiency improvements. Figure 3.3 shows a detail breakdown of energy for an Air Dig and Dump cycle of the Dextreme MAX system. It is clear that a significant portion of the energy is still lost in meter out for bucket and arm. This is due to the usage of the original MCV for those actuators. These losses can be addressed with a different valve design in a system developed from scratch. Additionally, a significant part of the boom potential energy is lost through metering: this was due to an error in the control logic parameters preventing a complete opening of the boom load holding valve during boom down operation, wasting more than 30kW of potential power during peak flows. Unfortunately, the issue was discovered after the tests were completed and it will be fixed in the future.

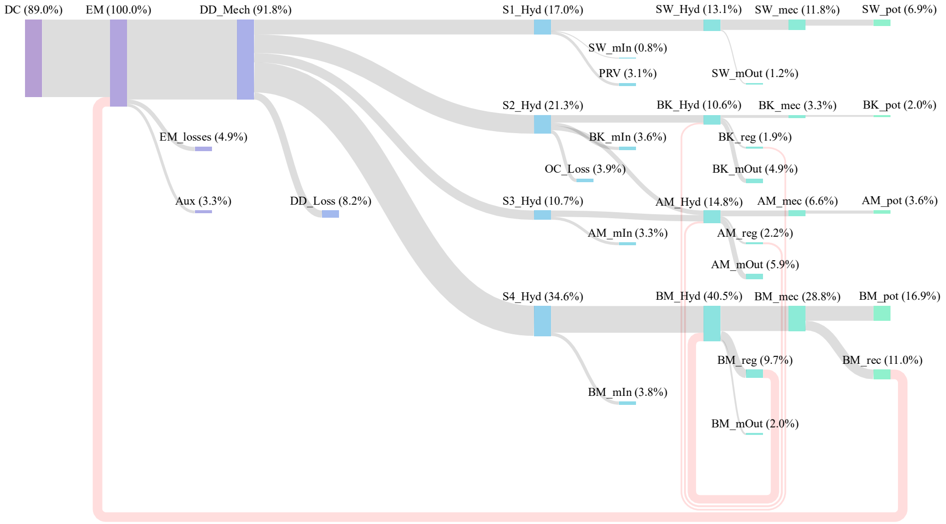


Figure 3.3. Sankey chart of the energy flow for the MAX system in a JCMAS DnD cycle.

4. CONCLUSION AND FUTURE WORK

The Dextreme MAX prototype successfully demonstrated that a fully digital, multi-service electro-hydraulic architecture can significantly improve the efficiency of a 30-tonne electric excavator without compromising performance. Tests conducted on standardized duty cycles showed energy consumption reductions of 31–49%, corresponding to a 35% decrease in electric energy demand for typical operations. A large part of the energy savings stemmed from reduced throttling losses due to independent actuator control, while approximately one-quarter resulted from energy recovery during boom lowering. While the results confirm the potential of DD technology for large excavators, time constraints, some control and hardware limitations hindered full system optimization. Specifically, incomplete opening of the boom Hose Burst Control Valve prevented full energy recovery, and the current control logic can be refined to improve transient performance and motoring efficiency.

Future work will therefore focus on:

- Enhancing control performance and addressing the identified valve control issue to enable complete boom energy recovery.
- Conducting real dig-and-dump testing once the machine returns to the Danfoss Application Development Centre (ADC) for validation under representative working conditions.
- Investigate and extend the concept to include an electrified swing drive (e-swing), which represents an obvious next step given the electric platform; this addition is expected to further reduce losses and enable additional energy recuperation.

ACKNOWLEDGEMENT

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NOMENCLATURE

F_d	Fraction of Displacement [0-1]
n	Shaft speed
p	Pressure
P	Power
pc, tc	Pressure control/torque control
Q	Flow
S_i	Service [i=1-4]
V_{di}	Service capacity cc/rev [i=1-4]

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Paul Marshall graduated from the University of Strathclyde in 2016 with a master's degree in mechanical engineering. Since then, he has worked on developing and testing prototype off-highway vehicles using Digital Displacement hydraulic systems for Artemis Intelligent Power and Danfoss Scotland. As a Senior Systems Engineer, he is currently working alongside OEM partners, providing technical leadership on projects aiming to improve the system efficiency of excavators through the application of Digital Displacement pumps and novel hydraulic systems.

Casper Olesen received his M.Sc. degree in Electro-Mechanical System Design from Aalborg University, Denmark, in 2011. He is currently a Senior Systems Engineer at Danfoss Power Solutions, Denmark. His work focuses on the development and analysis of system architectures integrating hydraulic and electrical components, with an emphasis on improving overall performance, comfort and efficiency.

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