Centralized Pressure Control and Displacement Quantization with Digital Displacement Pumps

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Abstract

Danfoss Power Solutions has developed a centralized pressure control solution for multi-pump hydraulic power units in the industrial market. This system architecture has been developed around the use of the Digital Displacement Pump® (DDP) which is highly efficient over a wide range of operating conditions and has typically shown a >30% decrease in electrical input energy over similar systems using axial piston pumps.

MTS Systems expanded this centralized control to work in a harmonized fashion with other pumping technologies housed within unique motor-pump modules; some containing DDP and others containing conventional axial piston pumps. This arrangement provided several benefits and empirically demonstrated the DDP module efficiency over the axial piston pump module in supplying fluid power to dynamic downstream force and motion systems that replicate real-world automotive drive files and test track profiles.

Special consideration was required when implementing DDP in a system with multiple pumps' (maximum of 6) outlet flow combined in parallel. Allowing each individual pump controller to operate in pressure control mode caused compounding complexity in tuning, and noisy, unstable flow pulsations. As a solution, a centralized pressure control scheme was implemented in which a system level microcontroller evaluated user inputs, pressure signals from a transducer, executed logic, and output displacement commands to each pump controller as required to meet the system demand. What makes this control scheme unique is that in a multi-pump system, one pump has a continuously variable displacement fraction with any value from 0 to 100%. The other pump displacements were controlled in a quantized manner with stepped values of displacement (for example: 0%, 25%, 75%, 100%). Hose resonant frequencies were also avoided in this manner.

Testing and implementation of this control scheme has proven to be effective in reducing system tuning complexity and undesirable flow pulsations in the system. Measured results indicate that the average pressure ripple power was reduced by 28% to 94% and the average pressure ripple band power by 61% to 98% (pump module dependent).

Successful implementation of the centralized control allowed MTS to demonstrate through an energy efficiency study that HPUs equipped with DDP consume up to 37.5% less energy than those with swashplate pumps for a given test cycle.

Keywords. Digital Displacement, Hydraulic Power Units, Centralized Pressure Control.

1. INTRODUCTION

1.1. Motivation

Energy conservation to reduce CO2 emissions becomes increasingly prominent for industrial equipment. Last year, the EU adopted European Sustainability Reporting Standards, which require publicly traded EU companies to disclose CO2 emissions in their annual reports, beginning in fiscal year 2024.

The economic benefits of energy efficiency are also compelling, particularly in European countries where the price of electrical power has increased dramatically in recent years. The United States government finds that pumps represent 27% of the electricity used by industrial systems [1]. Energy is the largest cost of ownership of an industrial pump system, representing 50% to 90% of total life cycle costs, depending on the technology.

1.2. Background

Digital Displacement Pump (DDP) technology was invented at the University of Edinburgh [2]. The basic DD principle is activating cylinders individually with an electronic controller, varying the pump displacement volume by on/off control rather than by reducing the piston stroke. This method enables high energy efficiency and fast, precise flow control. Innovation in Scotland led to numerous successful demonstrations of digital fluid power for renewable energy, industrial machinery, on-highway and off-highway vehicles, and more. Danfoss Power Solutions acquired Artemis Intelligent Power and its DDP portfolio in 2021. Danfoss brought DDP to market with the DDP096 pump [3], and Danfoss continues to introduce new DD components and systems. Digital pumps and motors also have been a research topic at multiple universities over the last 20 years, and new contributions to the field are published continuously. A full bibliography of the state of the art would be too large for this paper. The interested reader can find extensive references in [4] and a few interesting examples of more recent works in [5] through [8].

Hydraulic Power Units (HPU) are a mainstay of many industrial installations. HPUs convert electrical power to fluid power with one or more hydraulic pumps driven by electric motors. HPUs include associated components such as a reservoir, filters, control valves, accumulators, sensors, controllers, and so on. A typical HPU has AC induction motors driving variable displacement, pressure-compensated piston pumps. Large installations with multiple pumps in parallel may have trouble with pressure control stability if each pump is individually pressure-compensated. Consequently, a multi-pump HPU may synchronize pump commands with a single hydro-mechanical pressure control and a common pilot line connected to all pumps.

If an HPU has periods of low power demand, motors with variable frequency drives are an energy-efficient alternative by adjusting motor speed to reduce standby power loss. However, it is important to note that VFD efficiency decreases with decreasing motor load and the decline in efficiency is more pronounced with drives of smaller horsepower ratings [9]. Additionally, a VFD system requires slightly more energy when the motor is running at rated speed and load due to higher losses within the drive.

MTS Systems is a leading global supplier of test and simulation systems. This testing relates to applying precision forces and motions to help understand the physical properties of structures, components, materials, and the accuracy of model-based designs. The HPU is the backroom fluid power producer that feeds fluid power through a network of pipes and valves to the front room test operations. The actuator system in the front room imparts forces and motions into the test article, such as a vehicle or structure. MTS SilentFlo™ HPU are designed to be used with servocontrolled, electro-hydraulic systems. MTS HPU are scalable with multiple pump/motor modules arranged in single, 3-module and 6-module arrays. The pump/motor modules are submerged in the hydraulic reservoir to save space and reduce noise.

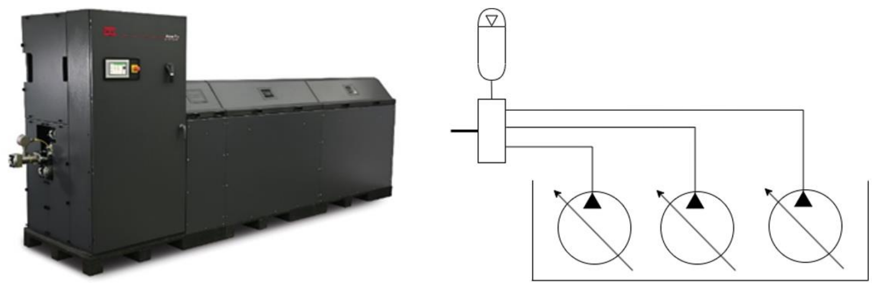


Figure 1: MTS SilentFlo™ HPU

Total energy efficiency of a test system is rather low. Efficiencies at each stage of power transmission from electrical to fluid to mechanical domains are multiplied together to realize the overall efficiency of the physical test system. For example, if each power conversion step is 90% efficient, then the overall efficiency = 90% x 90% x 90% = 73%. Efficiencies based on conventional technologies in these three phases of transmission need to consider the full operating range from idling to full power consumption. Total system efficiency in the range of 30% to 60% is typical with conventional swash-plate piston pumps in the HPU.

1.3. Project Goals

With the goal of gaining substantial efficiency improvements, and to differentiate themselves in the market, MTS began investigating the use of Danfoss DDP technology for their newest models of HPU. The industry-leading efficiency and control was a key driver for MTS in pursuing the technology. An MTS HPU utilizing DDP technology could reasonably expect a 3 to 5 year payback time based on lower operating cost but would vary depending on the cost of energy and other factors.

The system must be able to deliver the peak flow, but, from an economic point of view, it is also important to know at what flow rates the system is going to operate most of the time. To find the total cost of operating the HPU, the running cost at each operating condition must be calculated and summated. A duration diagram helps estimate HPU energy costs via a histogram distribution of how many hours during an annual period required a given flow rate.

As the project developed, significant challenges became apparent. Because of its digital flow control principle, DDP produces larger flow and pressure ripple output than conventional piston pumps. Flow pulsations can cause control instability and undesirable noise and vibration. A system architecture combining up to 6 DDP modules in parallel, each operating separately in pressure control mode, amplified the pressure oscillations. Quiet, smooth operation was a major goal of the project and a requirement for bringing DDP to production in MTS HPU.

The present paper describes two sets of experiments with the same DDP HPU. The pressure ripple test (see section 4.1) compares the first prototype control system with distributed pressure control to a more sophisticated, centralized pressure control system. The energy test (see section 4.2) compares the energy efficiency of the DDP HPU with centralized pressure control to a traditional HPU with swash-plate type pumps.

2. System Control Description

As previously mentioned, the hydraulic power units built by MTS presented a unique challenge in combining outlet flow in parallel while coordinating the pressure control of up to 6 DDP units in a single HPU. Initially, a distributed pressure control was attempted by relying on an embedded pressure transducer at each pump’s outlet in conjunction with its DPC12 pump microcontroller. However, there were difficulties in matching pressure setpoint levels between pumps due to variations in transducer tolerances. DDP pressure ripple and interactions between pumps produced substantial noise and hose vibration.

Through testing and analysis, an alternative solution was established through incorporating a stand-alone Danfoss Plus+1 system controller. A unique software architecture was successfully developed around the system controller and implemented in coordination with the DPC12 (pump controllers). The system controller received user setpoint information from the HPU user interface display (pressure setpoint, and maximum flowrate) along with a pressure transducer measurement taken at a single location at the HPU’s outlet. The software in the system controller then calculated appropriate displacement values for each DDP in the system and sent the necessary commands to the pump controllers, thus “centralizing” the control. Figure 4 shows the control system architecture; note that HPU outlet pressure is measured by two sensors for redundancy.

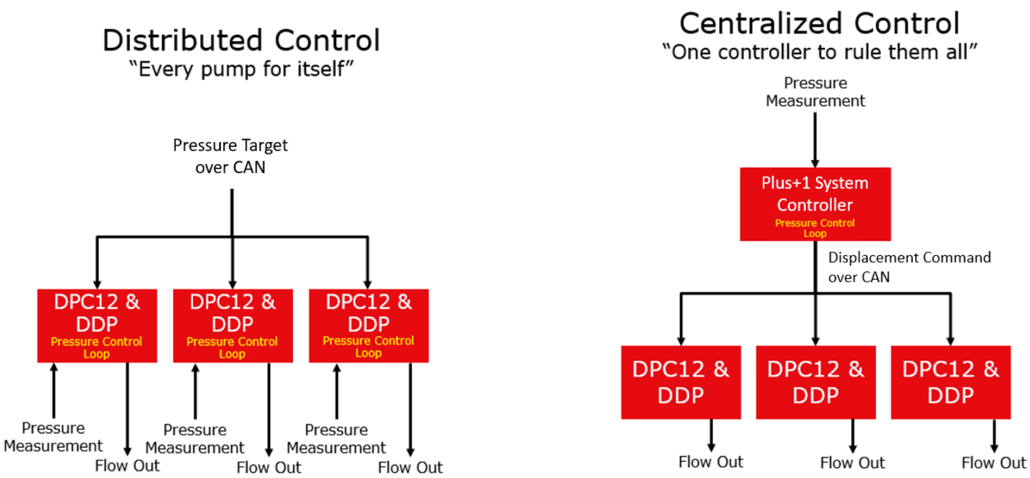


Figure 2: Distributed Pressure Control vs Centralized Pressure Control

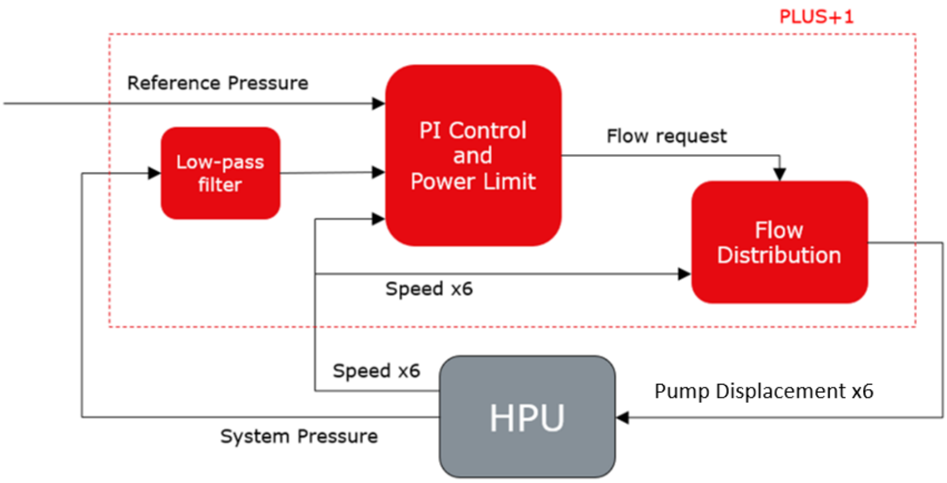


Figure 3: Centralized Control Software Flowchart

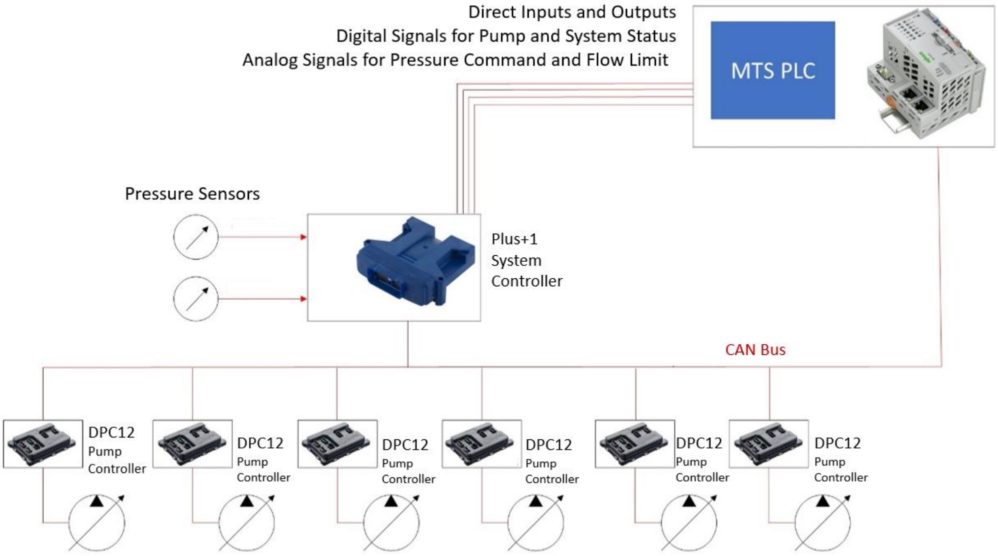
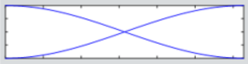
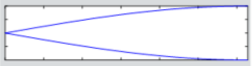


Figure 4: HPU Physical Control System Network Diagram with Centralized Control

DDP's flow output inherently produces low-frequency pressure ripple [10]. The pressure ripple frequency spectrum depends on operating condition, specifically the shaft speed and fractional displacement. Pump pressure ripple caused several problems in the distributed multi-pump system. Pump pressure ripple output due to the digital flow algorithm was amplified by the pressure control loop, so-called "self-excitation". There were undesirable interactions between the pressure control loops with each DPC12 controller responding to pressure changes from other pumps in the circuit. Furthermore, pressure pulsation at certain resonant frequencies caused standing waves in the hydraulic hoses, particularly for the longest hoses in the circuit. Altogether, the distributed control system suffered from significant noise and vibration.

Based on line resonance theory, Danfoss was able to understand and calculate the fundamental theoretical frequency at each module based on an "open on one end" boundary condition. From test results, the quarter wave, "one end open" boundary condition was selected as the ideal case approximation for the pump outlet hoses on the HPU. The hydraulic circuit downstream of the HPU junction manifold has very low hydraulic stiffness; it includes high-pressure filters, accumulators, and long 2-inch diameter distribution pipes. Pressure waves generated at the pumps reflect back from the junction manifold, almost like a pipe with one end open. The 4x factor in the fundamental frequency equation below gives insight as to why the HPU is so sensitive to line length.

Table 1: Line resonance with ideal boundary conditions. The "open on one end" case is a good approximation of the DDP outlet hoses on the HPU.

Boundary Conditions	Wavelength	Fundamental Frequency	Graph (wave displacement)
Open on both ends	$\lambda = 2L$	$f = \frac{c}{2L}$	
Closed on both ends	$\lambda = 2L$	$f = \frac{c}{2L}$	
Open on one end	$\lambda = 4L$	$f = \frac{c}{4L}$	

$c = speed\ of\ sound\ (m/s)$
$L = Hose\ Length\ (m)$

Table 2: Calculated fundamental frequency of pump modules based on line resonance theory.

	Module 1	Module 3	Module 4	Module 6
Fundamental frequency from theory (Hz)	54	69	79	112

assume c = 1000 m/s

Table 3: Summary of improvements with centralized pressure control.

Problem	Solution
Extensive tuning due to part-to-part variation between pressure transducers	Centralized control measures pressure at a single point in the circuit
Interaction between pumps increases pressure oscillation	Centralized control has one pressure feedback loop with the measurement point at the junction manifold rather than at a pump outlet port
"Self-excitation": pressure feedback loop amplifies pressure ripple	Low-pass signal filter on measured pressure
Pump pressure ripple excites line resonance	Quantization scheme: pumps with longer lines run at constant displacement levels to avoid resonant frequencies.

With the knowledge of each line's calculated fundamental frequency, a displacement quantization algorithm was developed and applied to the Centralized Pressure Control that avoids exciting resonant frequencies [11]. Operating pumps at any displacement fraction between 0 and 100% results in a range of fundamental frequencies between 0 and 12 times speed (360 Hz at 1800 rpm). These include enabling frequencies (1) which are pulsations generated by cylinders as they are activated and used. Also present, are disabling frequencies (2) which are generated by the pump as cylinders are deactivated and unused.

The quantization scheme allows one pump to continuously vary its displacement while all other pumps operate in quantized displacement steps (in this case, 0%, 25%, 75%, and 100%). The quantization scheme also considers the relative proximity of each pump to the junction manifold; the pump closest to the junction is continuously variable. Quantizing displacement commands at selected fractions produced smooth flow and low pressure ripple compared to less favorable displacement fractions. The pressure and flow requirements of the hydraulic system are still maintained by activating and phasing in pump modules as they are needed.

$$f_{enable} = \frac{n}{60} N_p F_d \quad (1)$$

$$f_{disable} = \frac{n}{60} N_p (1 - F_d) \quad (2)$$

$$n = shaft\ speed\ (rev/min)$$

$$N_p = number\ of\ pump\ pistons$$

$$F_d = fraction\ of\ total\ pump\ displacemet\ (0\ to\ 1)$$

Below, Figure 5 shows the enabling and disabling frequency outputs while operating in quantized steps. As can be seen, the quantized steps avoided outputting low frequency content below 90Hz which is in the resonant frequency range of the hoses.

Table 4: Enabling and disabling frequencies based on pump quantization value.

Displacement (%)	F_d	n (rev/min)	N_p	f_{enable} (Hz)	$f_{disable}$ (Hz)
0	0	1800	12	0	360
25	0.25	1800	12	90	270
50	0.5	1800	12	180	180
75	0.75	1800	12	270	90
100	1	1800	12	360	0

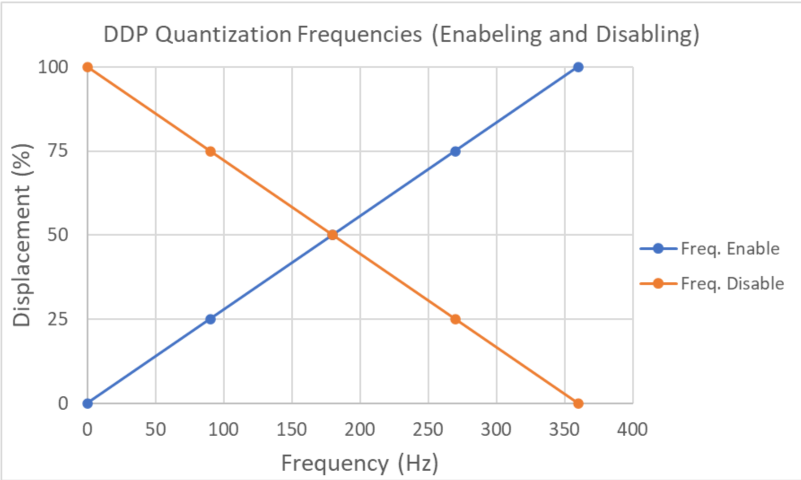


Figure 5: Quantized DDP Enabling and Disabling Frequency Outputs

3. Pressure Ripple Test

3.1. Setup

In addition to the Ames HPU, Danfoss had periodic access to a 6-bay HPU at MTS' facility in Eden Prairie, Minnesota. This HPU dubbed "HPU62" was used for development purposes as well as to provide downstream hydraulic flow for internal test stands at MTS. As this was the only accessible 6-bay, all DDP HPU, it was essential in tuning and validating the production intent version of the centralized pressure control software architecture.

A series of controlled displacement sweep tests at 3,000 psi (207 bar) were performed utilizing a servo-controlled load valve downstream of the HPU (not pictured in Figure 7). The following pressure ripple results are an analysis of these tests.

Figure 6: MTS HPU62 (6 bay DDP)

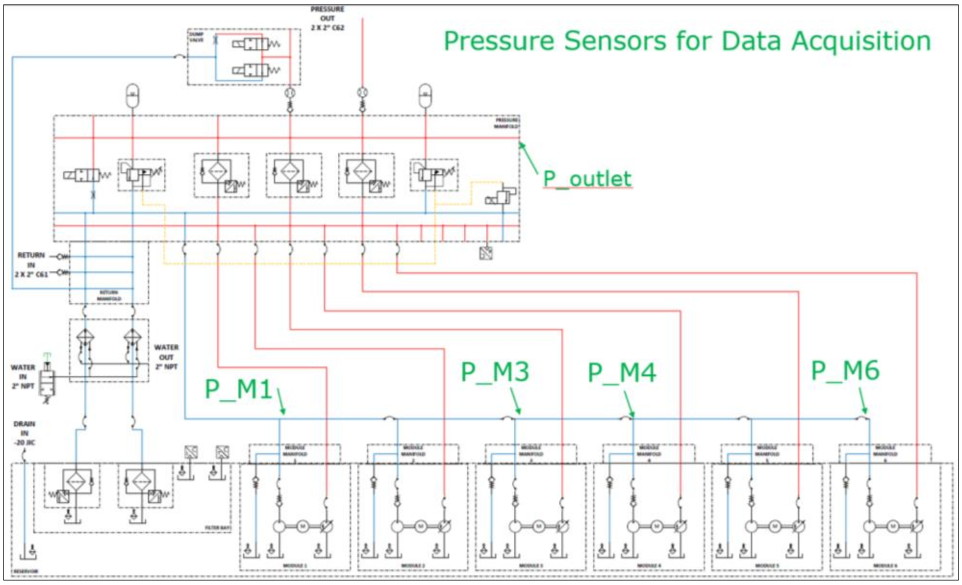


Figure 7: Hydraulic Schematic, MTS HPU62

3.2. Results

Frequency spectrum results are shown to relay the effectiveness of the centralized pressure control and how quantization changes the frequency profile of the pressure pulsations. The results presented represent data collected on MTS' HPU62. As previously show in Figure 6, module 1 is the furthest from the control cabinet and consequently has the longest hose length. Due to its length, resonance frequencies generated in this hose were the greatest source of noise and vibration when using the distributed pressure control. Much of the focus and marks of success in applying the Centralized Pressure Control revolved around improving or eliminating resonant frequencies in this module.

Power spectral density of the pressure signals is presented to show the power of the periodic signals in the frequency domain. Also shown are the post-processed average power and average band power of module pressures in the 0 to 100 Hz domain. Using this method allows for a visual and quantifiable representation of the improvements made by the Centralized Pressure Control.

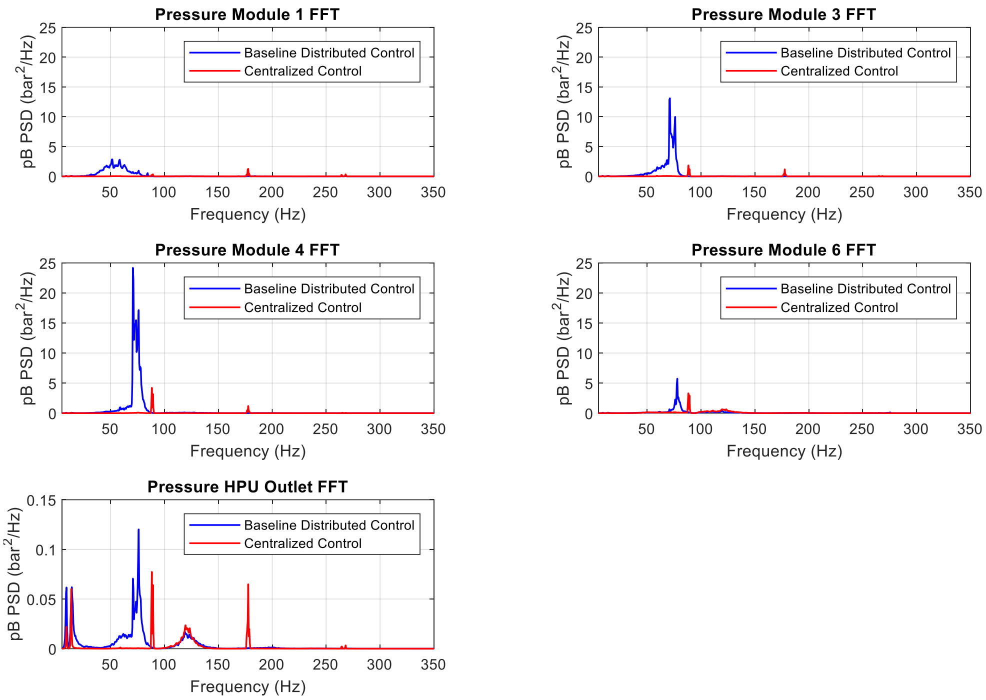


Figure 8: Pressure Spectral Density FFT Results, MTS HPU62

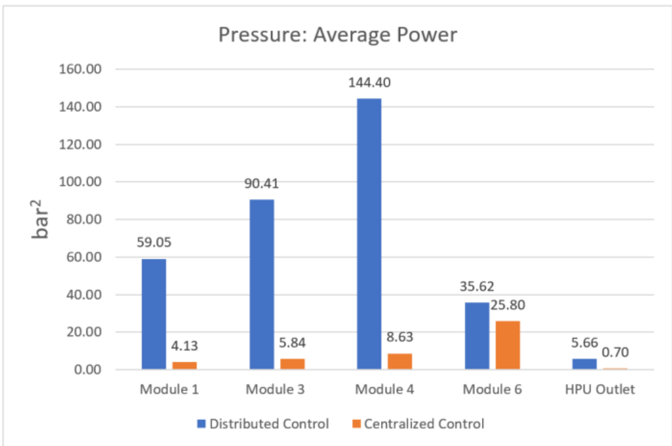


Figure 9: Average signal power (pressure ripple) per module

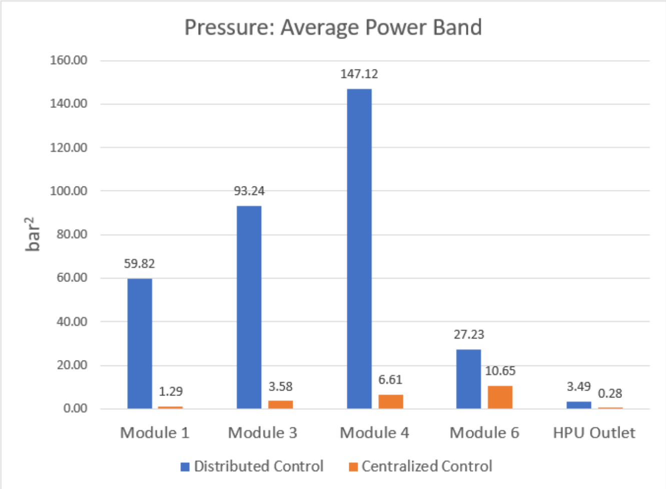


Figure 10: Average band power <100 Hz (pressure ripple) per module

Table 5: Resulting Percent Improvement by Centralized Control

Percent Improvement

Location	Pressure: Average Power (bar^2)	Pressure: Average Band Power (bar^2)
Module 1	**93%**	**98%**
Module 3	**94%**	**96%**
Module 4	**94%**	**96%**
Module 6	**28%**	**61%**
HPU Outlet	**88%**	**92%**

Figures 11 and 12 below show comparative displacement sweep tests from HPU 62. With the distributed control, the peak to peak displacement of the pumps was large as each pump controller (DPC12) tried to maintain a pressure setpoint of the DDP it controlled. The result was a high level of pressure ripple. With the centralized control utilizing quantization, a much smoother displacement characteristic could be achieved in addition to decreasing pressure ripple.

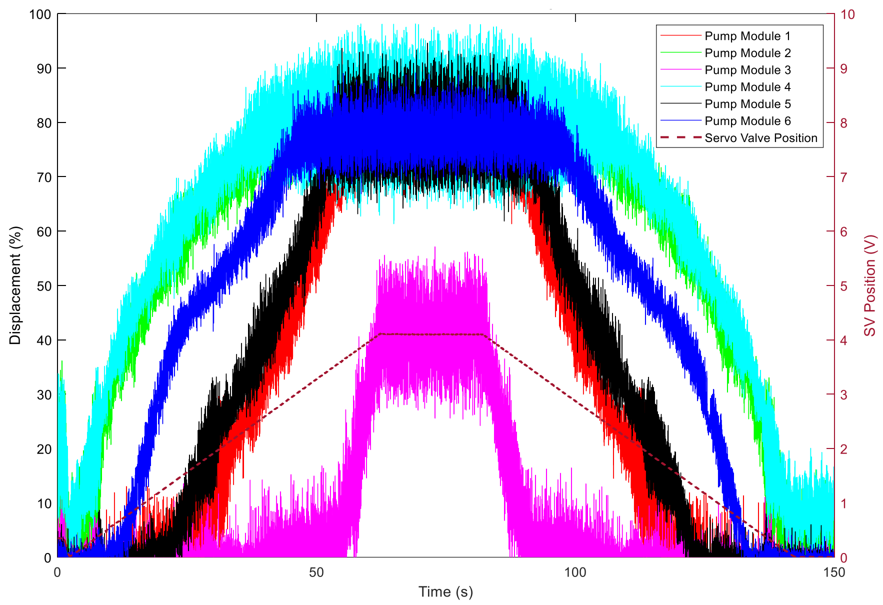


Figure 11: MTS HPU62 (6 DDP) Displacement Sweep with Distributed Control (All modules operate in continuously variable mode)

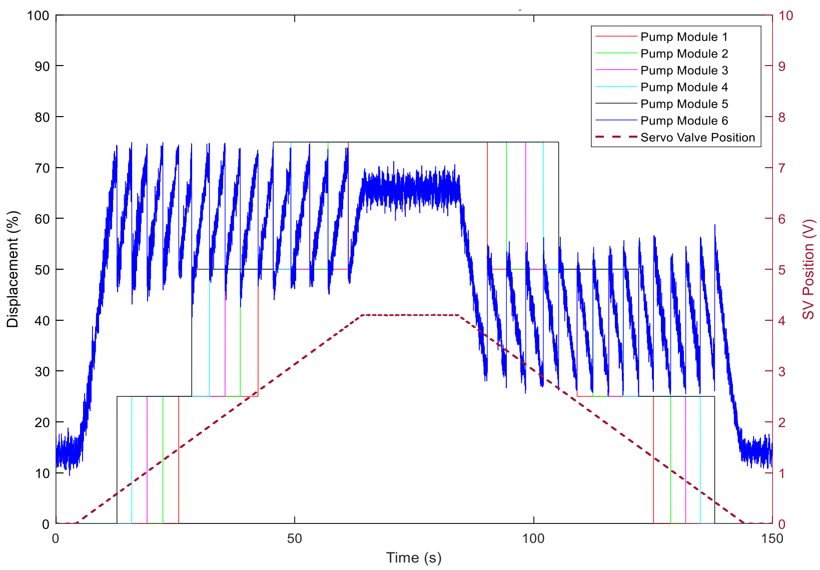


Figure 12: MTS HPU62 (6 DDP) Displacement Sweep with Centralized Pressure Control (module 6 operates in continuously variable mode while all other modules are quantized)

4. Energy Efficiency Tests

4.1. *Drive Profile Test Setup and Results*

An energy efficiency study was performed using MTS 329 Test Rig (Figure 13) running a specific repeating drive file. The rig was first powered by HPU61 which is a 6-bay HPU utilizing only swashplate pumps. The output flow, pressure, and total electrical power was recorded over the test duration (10 minutes) and then the test was repeated powered only by HPU62 which as mentioned previously, is a 6-bay HPU utilizing only DDP. HPU62 required **37.5%** less electrical energy to produce the same flow demand.

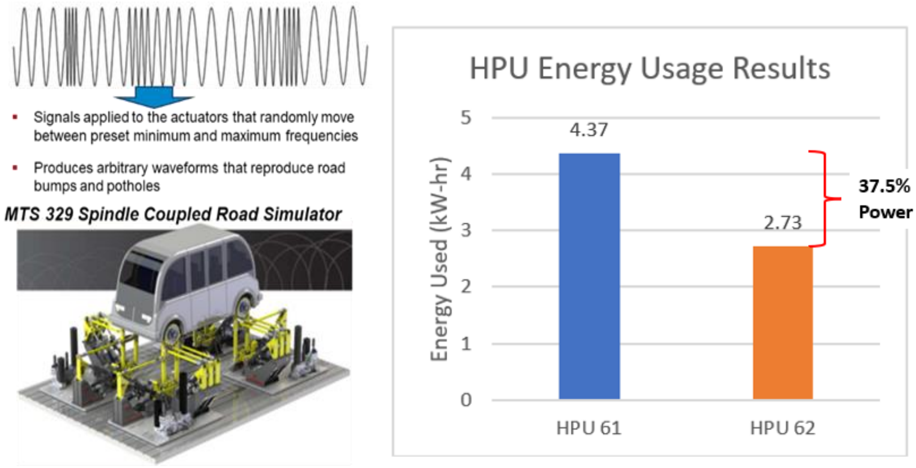


Figure 13: MTS Energy Audit Results

4.2. *Calander Year Comparison Test Setup and Results*

Over a calendar year of plant operations, HPU 61 and 62 were used to supply the fluid power to the MTS hydraulic distribution system (HDS). By capturing the total kW-hrs of electrical energy the HPUs consumed per day, the hours in operation per day, the total fluid output (in gallons) per day, and a consistent pressure setpoint of 3,000 psi (207 bar), the overall energy efficiency of each HPU could be calculated. Figure 14 shows the recorded fluid flow and the related HPU efficiency based on consumed electrical power analysed over the year.

HPU efficiency is the ratio of fluid energy output to electrical energy input. The observed data shows that HPU62 (All DDP) is increasingly more efficient than HPU61 (all swash) as the flow output increases.

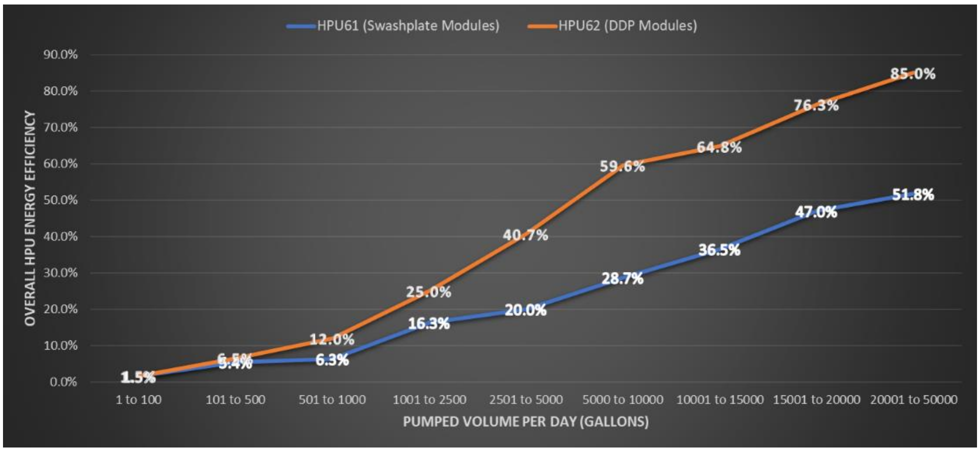


Figure 14: HPU Efficiency Based on Flow Output

5. DISCUSSION

As can be seen in the testing results, low frequency pressure pulsations in the 30 – 80 Hz range were noticeably reduced. As the primary resonance frequencies for the pump modules lie within this range, there was a significant improvement the stability of the HPU. Though it was not quantified in the report, audible noise levels seem to be lower as a result of reducing resonance frequencies, and it can be estimated that the life of mechanical components in the system (hoses, brackets, etc) will be improved. There is evidence that the magnitude of some higher frequencies were slightly increased by moving to the centralized pressure control with quantization, however, their influence on the noise and vibration of the HPU was not nearly as noticeable. With quantization, pressure wave energy still exists, but what is there shifts outside of the resonant frequency range of the hoses. This explains the reduction of lower frequency content in Figure 8, in exchange for some increases at higher frequencies.

Noticeable efficiency improvements of HPU 62 (DDP) over HPU 61 (Swashplate) were seen in both a controlled test scenario and in accumulated data over a calendar year. With a lower power consumption compared to swashplate pumps across the displacement range (0 to 100%), the HPUs equipped with DDP benefit from a compounding effect that increases with the number of DDP pumps used. This explains the larger difference between the two HPU's energy efficiencies as flow increases and the number of active DDP modules increases. As a result, HPUs with DDP can produce more fluid flow per kW-hr of energy consumed.

6. CONCLUSION

In conclusion, it has been shown through a multitude of tests, and analysis that the centralized pressure control with quantization was able to solve a large potential issue associated with pressure pulsations of DDP in the MTS HPU system. Analysis proves that the control strategy measurably reduced the magnitude of average pressure ripple power by 28% to 94% and the average pressure ripple band power by 61% to 98% depending on the analysed pump module. These pressure pulsations in the resonant frequency range of the hydraulic lines were reduced while still meeting the flow and pressure demands required of the system.

In application, the DDP equipped HPUs showed a 37.5% reduction in energy consumption when compared to a swashplate only HPU in a controlled test scenario. Based on output flow, pressure setpoint, and known energy usage captured over a calendar year of plant operations, efficiency improvements of up to 33% were observed on HPUs with DDP compared to those with swashplate only pumps.

7. ACKNOWLEDGMENTS

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