A hydraulic test stand for demonstrating the operation of Eaton's energy recovery system (ERS)

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Abstract

Fuel cost represents a significant operating expense for owners and fleet managers of hydraulic off-highway vehicles. Further, the upcoming Tier IV compliance for off-highway applications will create further expense for after-treatment and cooling. Solutions that help address these factors motivate fleet operators to consider and pursue more fuel-efficient hydraulic energy recovery systems. Electrical hybridization schemes are typically complex, expensive, and often do not satisfy customer payback expectations. This paper presents a hydraulic energy recovery architecture to realize energy recovery and utilization through a hydraulic hydro-mechanical transformer. The proposed system can significantly reduce hydraulic metering losses and recover energy from multiple services. The transformer enables recovered energy to be stored in a high-pressure accumulator, maximizing energy density. It can also provide system power management, potentially allowing for engine downsizing. A hydraulic test stand is used in the development of the transformer system. The test stand is easily adaptable to simulate transformer operations on an excavator by enabling selected mode valves. The transformer's basic operations include shaft speed control, pressure transformation control, and output flow control. This paper presents the test results of the transformer's basic operations on the test stand, which will enable a transformer's full function on an excavator.

KEYWORDS: hydraulic transformer, fluid power control, off-highway vehicle

1. Introduction

Fuel costs have become a major issue in today's economy, and fuel efficiency improvements for off-highway vehicles have become a top priority for equipment manufacturers and end users alike. A hydraulic excavator for example, consumes a substantial amount of fuel during operation. However. less than 10% of the fuel energy actually is utilized for conducting productive work. A significant portion of an excavator's operational losses occur in the directional control valve with throttling/control losses across the proportional valves for each service. To improve the excavator's fuel economy a hydraulic energy recovery system is proposed, which is capable of achieving the baseline productivity without compromising the functionality and performance of the baseline machine. The energy is typically recovered into three formats. Hydraulic energy stored into an accumulator [1-5], electrical energy stored in a battery [6], and mechanical energy stored in a fly-wheel [7]. Depending on the energy storage forms, a key component to transform and deliver energy between the storage device and the baseline system should be developed, such as a motor generator set, a continuous variable transmission, etc. The key enabling technology for the hydraulic energy recover system is a hydraulic transformer. Innas has developed an Innas Hydraulic Transformer (IHT) [8]. The IHT is a three-port transformer based on a novel floating cup technology. Besides IHT, traditional hydraulic transformers are created with over center pump/motors. Eaton proposed a novel transformer architecture, which comprises a tandem over center pump/motors with the mechanical connection extended to the final drive.
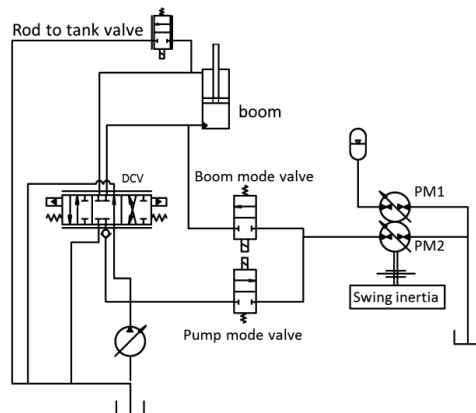
Implementing the transformer system directly into the excavator while developing the system control algorithm is deemed too challenging. In order to reduce this risk, the transformer's control development was conducted on a custom hydraulic test bench. The bench was designed to replicate all of the major operations of the transformer on the excavator while in a controlled environment. For a traditional hydraulic transformer composed of over center pump/motors, various system modeling, state estimator, control, and optimization approaches have been exploited, with solid simulation verifications[9-11]. One contribution of our work is to provide the experimental validation of the operation of a hydraulic transformer. Different hydraulic configurations on the test bench can be achieved by enabling selected flow paths via on/off mode valves. For each configuration, the control strategies of the transformer is specified. The common operations for the transformer across various hydraulic configurations are summarized as: transformer shaft speed control, pressure transformation control, and transformer

output flow control. The experimental demonstration of the basic operational modules is investigated.

The outline of the paper is as follows. In section 2, the transformer system and its operation will be introduced. In section 3, the machine functionality diagram and the corresponding test bench configurations will be presented. The control logic for each hydraulic configuration will be explained. In section 4, we will present the experimental results collected from the test bench. Finally, a conclusion will be presented.
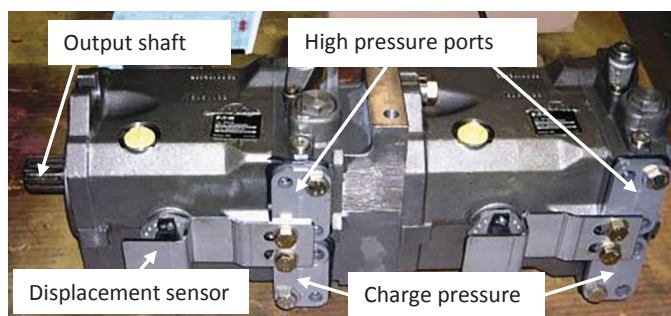
2. Transformer System

In this design, one tandem transformer is in communication with the main pump, the boom cylinders, and the swing function of the excavator. The transformer can achieve system power (energy) management by manipulate the energy among the main pump's output, the boom's overrunning kinematic energy, the swing's kinematic energy. This energy can be utilized instantaneously among those functions or the energy is stored in a hydraulic accumulator. In addition, the transformer, together with the service proportional valve, can control the boom motion and the swing motion.
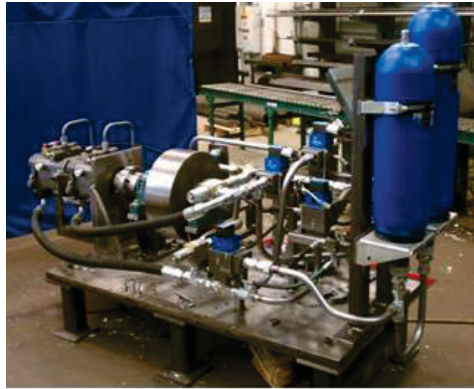

Figure 1: Transformer implemented on an excavator

Figure 1 shows the architecture of the transformer integrated into the excavator. For boom operation, the boom cylinder can be supplied from the main pump via the stock Directional Control Valves (DCV), or from the accumulator via the transformer, or a mixture of both. In the case of the stock DCV, flow can be directly supplied from the main pump's output via the DCV. In the second scenario, the boom can be supplied by the accumulator via the transformer alone, where the system controller determines the boom supply pressure from cylinder pressure sensors and flow based on a map of pressure,

flow, and sensed pilot pressure. The transformer is commanded to match the pressure and flow requirements and supplies the boom directly. The third scenario is a mixture of boom flow from the DCV and the transformer. The transformer supplies or sinks flow from the boom and the DCV provides the make-up flow depending on the energy status of the hydraulic hybrid work circuit HHWC system. When utilizing the transformer, the energy can be stored in the accumulator or used to provide torque to the swing. For the swing service, the inertia is driven directly from the hydraulic transformer with a clutch/brake connected between the motor and the inertia. During vehicle operation the clutch is active during swinging operations and the brake is active only when the upper structure is stationary. The swing circuit can be operated via the main pumps, overrunning boom flow, or stored energy in the accumulator. When the swing is operated in the first case, the main pumps are commanded from the system controller with a pilot control valve to supply the lower unit of the transformer. The lower unit operates as a motor and sends torque to the upper structure of the machine to swing. In this case torque can also be sent to the upper unit to store energy in the accumulator. In the second case, the boom is in an overrunning state, and the output flow from the boom can supply the lower transformer unit and supply torque to the swing or store energy as stated previously. In the last case, the accumulator has sufficient energy, and the upper unit of the transformer can act as a motor supplying torque through the lower unit to the upper structure. In this case, it is also feasible to supply the boom when swinging because the lower unit of the transformer can act as a pump. The transformer hardware consists of a tandem pump assembly modified to allow each unit to operate as a pump or as a motor independent of the other. The baseline assembly consists of two 135cc closed-loop pumps mounted in tandem. The transformer's arrangement and test bench are shown in **Figure 2** and **Figure 3**.
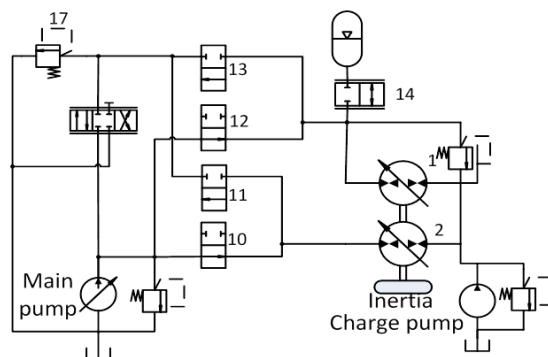

Figure 2: Transformer full view

Figure 3: Full test stand

3. Test stand configuration and transformer control strategy

A test stand was developed to test the full operation of the transformer before it is implemented on a real vehicle to reduce the development cycle time. The hydraulic circuit of the test stand is shown in Fig. 4. The test stand configurations are easily controlled by two-way, two-position mode valves 13 – 17. The flow path and the control strategy for each configuration will be described respectively. The test stand was initially implemented without an accumulator. The accumulator flow was simulated by a supply flow from the main test stand pump at a pressure determined by a main relief. In the next phase, the accumulator was installed, and the flow routing path varies from the previous case in the same testing scenario. The inertia connected to the output shaft of the transformer can be switched between low and high. The low inertia tests simulate the scenarios where the swing inertia is disconnected from the transformer, and the high inertia tests simulate the inertia of the upper structure during swing operation.
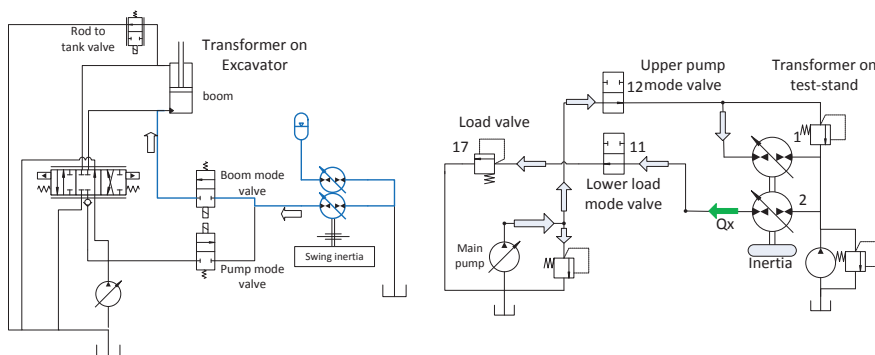

Figure 4: Hydraulic schematic of the test bench
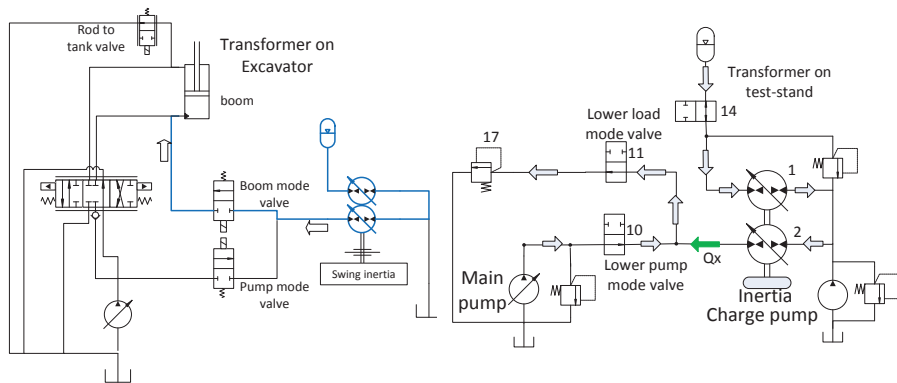
3.1. Case 1

For this trail, the transformer pressure/flow transformation capability will be determined. In this test, one pump/motor unit operates as a hydraulic motor, while the other one operates as a pump. Different configurations were selected with or without the accumulator installed on the test bench. Enabling different pair of mode valves (valve 10 – 13) simulates the scenarios which reflect the transformer as implemented on an excavator.

To imitate the scenario of boom up assist with the energy from the accumulator on an excavator, the configuration on the test is shown on **Figure 5**. Without the accumulator installed on the test stand, the bench pump is regulated at a constant pressure to resemble the accumulator, and the load valve imitates the resistance from the boom-head side. Valve 11 and valve 13 are open when the lower pump/motor is operated as the hydraulic pump, and the upper pump/motor as the motor. In comparison, by opening valve 12 and valve 10, we can replicate the same scenario with the upper pump/motor served as a hydraulic pump, and the lower unit as the motor. The control goal is to achieve speed tracking on the transformer shaft while tracking the flow demand to assist a load pressure.

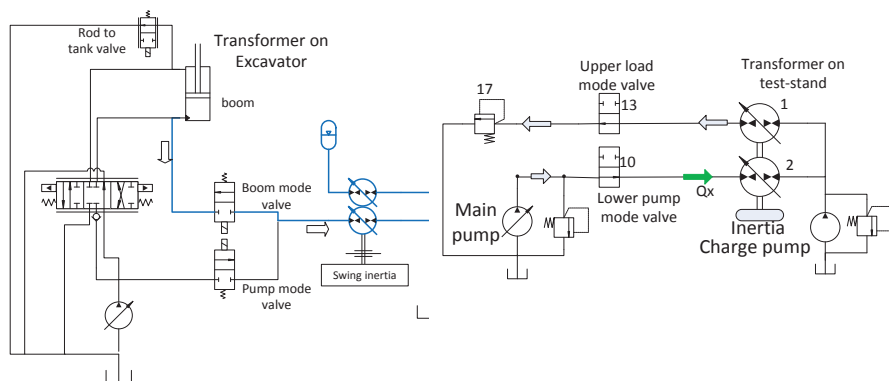**Figure 5:** Emulate boom assist without the accumulator

The hydraulic configuration with an accumulator installed on the test bench is shown in **Figure 6**. The boom assist energy is directly channeled from the accumulator through the transformer. Valve 11 is open to drive the load valve. Valve 13 can be open or close depending on whether the boom raising flow is provided purely by the accumulator, or it is a flow combination of both the main pump and the accumulator. The control goal is to achieve transformer shaft speed tracking while tracking the boom assist flow Q_x provided by the accumulator.

Figure 6 : Imitating boom assist with an accumulator

The third scenario is to recover the boom overrunning down kinetic energy into the accumulator. In this scenario, the hydraulic configuration without an accumulator installed on the test bench is shown in **Figure 7**. The bench pump emulates the flow coming out of the boom head side when it travels over-running down, and the load valve emulates the accumulator by providing some load resistance. The control goal is to achieve speed tracking on the transformer shaft while tracking the flow sink demand Q_x to dissipate energy over the load valve.

With the accumulator installed back onto the test bench, the "boom" over-running energy (provided from the bench pump) can directly charge the accumulator through the transformer. The hydraulic configuration of this scenario is shown in **Figure 8**. The control goal is to achieve transformer shaft speed tracking while tracking the boom recovery flow Q_x provided to the accumulator.

Figure 7: Imitating boom overrunning down energy recovery without an accumulator
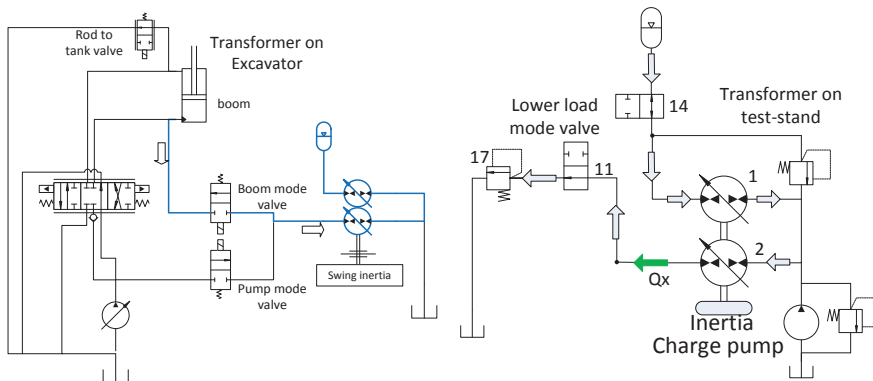
3.2. Case 2

This case explores directly charging the accumulator via the transformer to realize engine power management. Fluid from the main pump is supplied to the lower unit through valve 10, which acts as a hydraulic motor and the upper unit acts as a pump. The fluid charges an accumulator when valves 11, 12 and 13 are closed and valve 14 is open.

3.3. Case 3

This case studies an operation where two power sources (main pump and the accumulator) supply a single load simultaneously. The baseline operation of the excavator is done via a directional control valve. On the test bench, a sectional valve was incorporated to supplement the flow coming from the transformer when it is operated by the accumulator. Flow from the transformer via valve 11 is combined with the flow from the main pump through valve 16 before it goes to the load valve 17.

3.4. Case 4

In this case, the high inertia is installed onto the transformer, which imitates the swing-only operation. The swing acceleration can be driven by the accumulator via the upper pump/motor with all the mode valves closed, or by the main bench pump via the lower pump/motor with mode valve 10 open. To decelerate the swing, all the mode valves (10 – 13) are closed, and the resisting torque is provided by regulating the displacement of the upper pump/motor as it charges the accumulator.
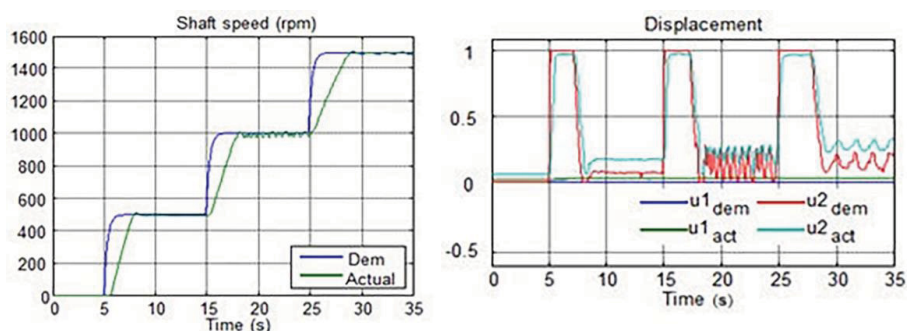

Figure 8: Boom over-running down, recovering energy with an accumulator

4. Test stand experimental results

The fundamental operation of the transformer includes the shaft speed control, the pressure transformation control, and the output flow control.

The transformer shaft speed control test was implemented first. The swing inertia was connected to the output shaft of the transformer and the output pressure of the main pump was regulated at 100 bar. **Figure 9**, shows the transformer speed response to a step command is 1.9 seconds. The response time can be tuned to be faster or slower via the controller gains. For the same controller parameters, the response is faster by increasing the circuit's supply pressure.
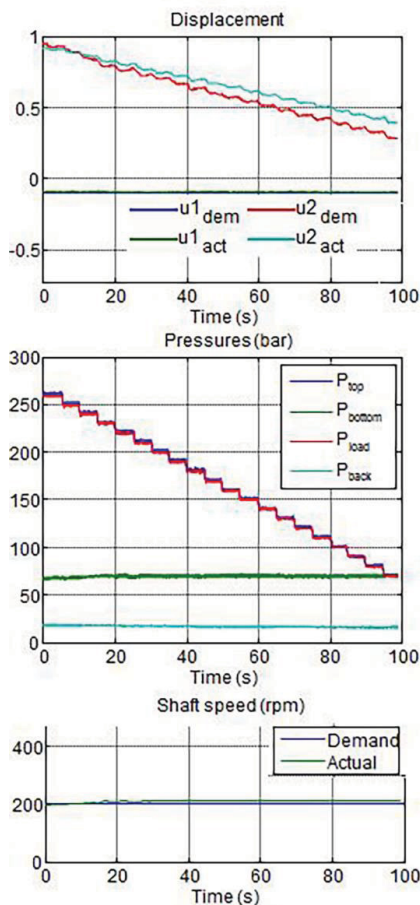

Figure 9: Transformer speed step response

In the next case the pressure transformation control was examined. The test stand main pump was used to supply flow to the transformer through mode valve 10 (in Fig 4). The transformer's shaft was controlled to track a constant speed using displacement control of the lower pump/motor. The upper pump/motor was set at a fixed displacement and supplied flow through mode valve 13 to the load 17. Load valve 17 was in pressure control mode to emulate the load pressure. The load pressure was controlled starting from 260 bar down to 10 bar in 10 bar decrements as shown in **Figure 10**. The transformer can perform pressure transformation ratios ranging from 1/7 to 4. Lower transformation ratios are limited by the ability to precisely control the swash plate at very low displacements. Higher transformation ratios are limited by the maximum torque provided by the driving system (pump or accumulator). At a given pressure, the torque is limited by the saturation of the swash plate displacement.
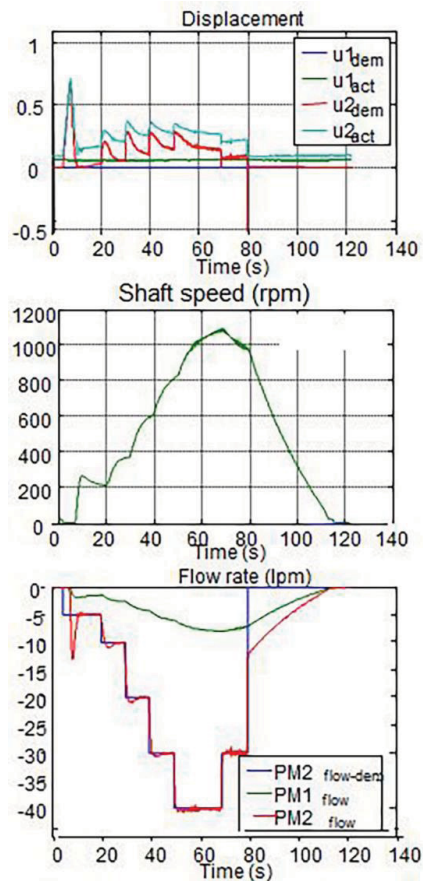
The third test focused on the flow control operation of the transformer. This test emulated the pure boom down motion with flow is channeled through the transformer. The swing was connected, but the speed was not constrained by the swing. A stepped desired flow profile with 10 seconds at each step is specified. The result is shown in **Figure 11**. It can

be clearly observed that the calculated flow tracks the demanded flow very well. Since the transformer's shaft speed is not controlled, the speed reaches over 1000rpm for only 40 lpm. Therefore, speed regulation should be incorporated with the flow control.

Finally, the transformer flow control with the shaft speed regulated was completed. The test results in **Figure 12** show the transformer can accurately track the speed command while the flow passes through the upper pump motor and the pump motor shaft speed can be stabilized at 50 lpm. The flow tracking is off after 55sec, which is caused by the saturation of the pump/motor's displacement.
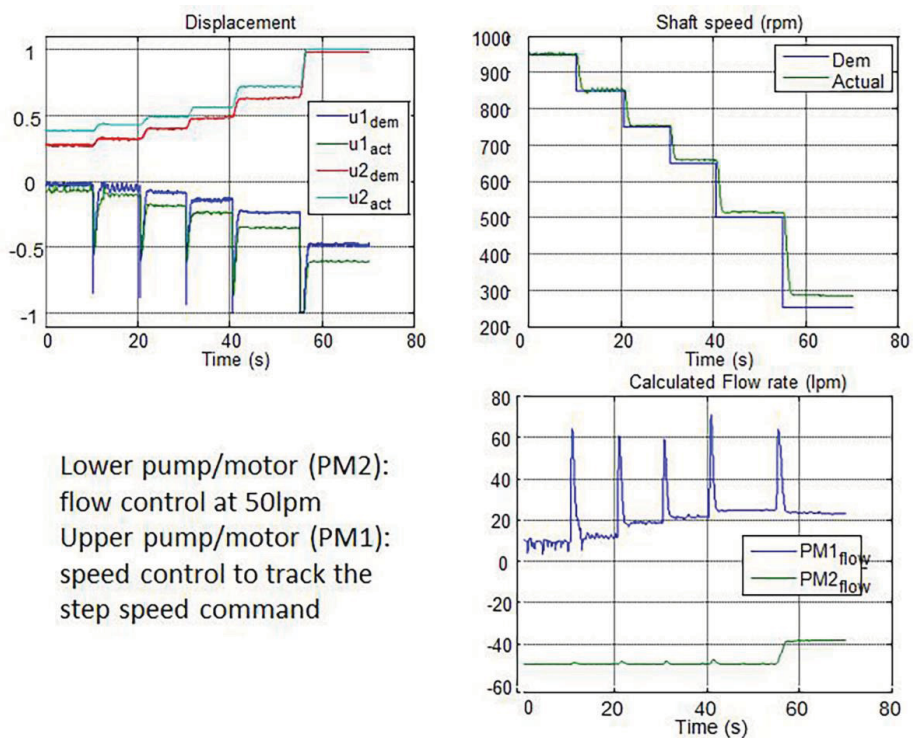

Figure 10: Transformation 260-70 bar load pressure in steps of 10 bars

Figure 11: Flow demand tracking for bottom pump motor

5. Conclusion

This paper describes a hydraulic transformer unit test stand, which is designed to be easily configured so that it can model different operation modes as if it were installed on an excavator. Various hydraulic configurations are achieved via enabling on/off mode valves. The test stand can significantly shorten the development cycle and mitigated many risks during development   of the transformer. The test stand also provides experimental data of the transformer's basic operations, including transformer shaft speed regulation, pressure transformation, and output flow control. These basic operations can further be manipulated with a supervisory controller to provide the full control spectrum for the excavator's operation.

Lower pump/motor (PM2): flow control at 50lpm
Upper pump/motor (PM1): speed control to track the step speed command

Figure 12: Transformer flow control with speed regulate

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