Design, Simulation and Control of Hydraulic System Topographies with Integrated Energy Recovery

Final Report 10/2011

KEYWORDS: fluid power, efficiency, redundancy, excavator, energy recovery

This project began in January, 2009 and concluded December, 2010. Purdue graduate student, John Andruch, advised by John Lumkes, developed, simulated, and tested the concept of a *Topography with Integrated Energy Recovery* (TIER). Milestones achieved during the project:

1. A full literature review was completed.
2. A dynamic model of the system was completed and simulation results were used to design and construct the test rig.
3. A fully operational test rig (mini backhoe arm) has been installed and instrumented in the ABE Fluid Power laboratory at Purdue University.
4. Data has been collected on the test rig while operating the system in various modes.
5. Results have been published at various conferences (see references section).

Executive Summary:

This project designed, modeled, simulated and tested a hydraulic system topography utilizing an intermediate pressure rail and a network of 2/2 proportional valves. The system is configurable via software to operate in multiple modes to maximize system efficiency and improve reliability. The valve network enables the system to operate with characteristics of multi-level load-sensing, displacement control, independent metering, energy recovery, and energy storage (with an optional accumulator). The modes can often co-exist and several new hybrid modes are possible. The TIER system (Topography with Integrated Energy Recovery) can re-route power in the event of component failure, allowing for future development of diagnostic and prognostic algorithms.

The system described here was built and tested at Purdue University using twenty-six proportional 2/2 valves to operate a small backhoe arm (four actuators: swing, boom, stick, bucket). Two variable displacement swash-plate units, driven by an electric motor, were used to power the valve block and backhoe arm. The pump/motors can be operated as two pumps, two motors, or split as a pump and motor depending on the load requirements on the system. Experimental results demonstrate the feasibility of multiple operating modes and reduced energy consumption.

(abridged from Lumkes and Andruch, 2011)

Introduction:

Energy costs continue to rise while many fluid power systems still control power through metering valves. This results in low system efficiency. More manufacturers, especially in mobile hydraulics, rely on pressure compensated load-sensing (PCLS) to reduce the metering losses. This works very well when all actuators need approximately equal pressures but when this is not the case, significant metering losses can still occur. Beyond PCLS, researchers have been working on decoupled metering valve (Jansson and Palmberg, 1999; Liu and Yao, 2002; Hu and Zhang, 2002; Shenouda, 2006), split level PCLS (Finzel et al., 2010), and displacement control systems. Several manufacturers have commercialized the decoupled metering valve systems (Andersson and Martin, 1996; Kolbe, 2004).

Displacement control systems remove all primary metering valves from the system but generally require a dedicated pump/motor for each actuator. The actuator speed and direction is controlled by varying the displacement of the pump/motor connected to the actuator. Extra valves are required for asymmetrical actuators, and several sizing constraints (retraction speeds under assistive loads) can lead to suboptimal pump/motor displacement sizing, but overall system efficiency can be greatly improved (Rahmfeld and Ivantysynova, 1998; Rahmfeld, 2000; Wendel, 2002; Rahmfeld and Ivantysynova, 2001).

Pressure-compensated load sensing, decoupled metering, and displacement control systems all experience design tradeoffs (performance, efficiency, cost, and complexity). This has led to additional solutions including additional valves and more efficient pump/motors (Heybroek et al., 2006 & 2007; Merrill and Lumkes, 2010). A similar solution to the research summarized here was presented in 2009 where the authors present a 6-way valve and third pressure rail that is always connected to an accumulator (Erkkil et al., 2009).

System Characteristics of TIER

An example four-actuator, two pump/motor TIER system is shown in Figure 1. Typical of many excavators and backhoes, the four actuators in figure 1 are used to control the swing, boom, stick, and bucket motions. During normal operation these types of machines also experience simultaneous actuator movements, a mixture of assistive and resistive actuator motions, and a wide range of loads. The TIER system in Figure 1 incorporates twenty-six 2/2 proportional valves and two variable displacement pump/motors. It is possible to use pump/motors of different sizes (Andruch and Lumkes, 2009) to keep each unit operating near maximum displacement over a wider range of load cycles, and since the flow from each unit can be summed or regenerated additional flexibility is achieved.

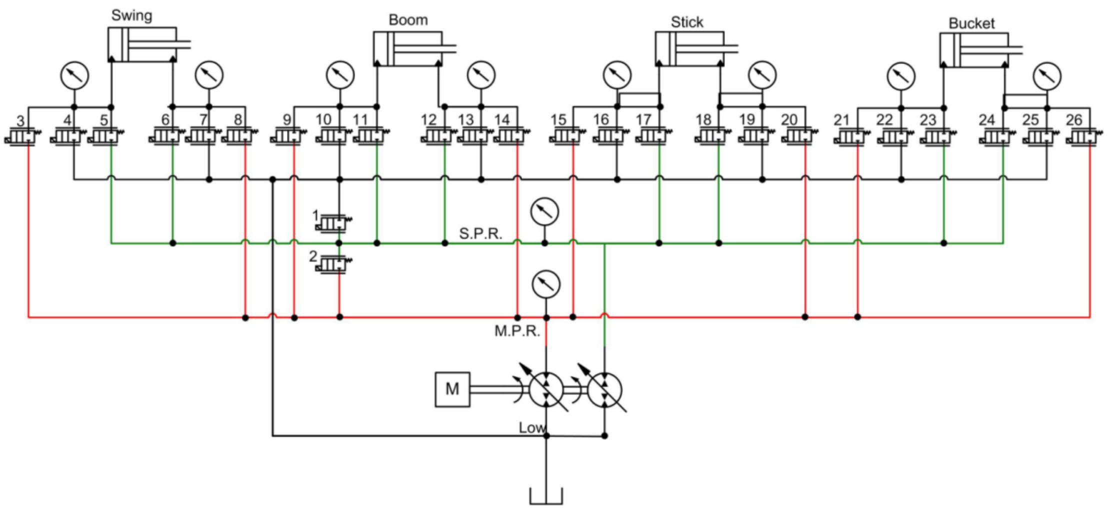


Figure 1. Example TIER System with 4 Actuators and 2 Pump/Motors

There are two pressure rails in the TIER system, the Main Pressure Rail (MPR) and Secondary Pressure Rail (SPR). There is also a third rail that is always connected to the reservoir. The MPR and SPR can be connected to either pump/motor or to each other. This system requires more valves than decoupled metering valve system and fewer pump/motors than a displacement control system. Table 1 compares some of the advantages and disadvantages of the TIER system relative to multi-level load sensing, decoupled metering, and displacement control systems.

Table 1. Advantages and Disadvantages of TIER relative to LS, DCM, and DC

	Advantages of TIER	**Disadvantages of TIER**
Load Sensing	Less valve metering losses Energy recovery Redundancy	Additional pump/motor(s) Additional valves Additional sensors/controls
Multi-Level Load Sensing	Less valve metering losses P/M flows can be combined Energy recovery Redundancy	Additional valves
Decoupled Metering Valves	Energy recovery Additional modes Redundancy	Additional pump/motor(s) More complex control
Displacement Control	Fewer pump/motors More optimal p/m sizing P/M flows can be combined Open loop system possible	Additional valves Valve metering losses More complex control

Load Sensing and Dual Level Load Sensing Systems

A single load sensing system is achieved by leaving valves 1 and 2 (Figure 1) closed to isolate the three pressure rails (MPR, SPR, and tank) and using only the MPR and tank lines. The MPR is pressure controlled using the displacement on one pump/motor to be a small differential above the largest required load pressure. Pairs of valves on each active actuator (for example, valves 3 and 7 or 4 and 8 on the swing actuator) are actively controlled to simulate a load sensing system. Operation of the dual-level load sensing mode is similar except that some of the actuators are assigned to the only operate between the MPR and tank, and other actuators between the SPR and tank.

Decoupled Metering Valve System

Valves 1 and 2 are closed to isolate the three pressure rails (MPR, SPR, and tank) and only the MPR and tank lines are used. The MPR is pressure controlled using the displacement on one pump/motor to be a small differential above the largest required load pressure. Instead of controlling pairs of valves as with the load sensing systems, only one valve on each active actuator will be actively controlled. For example, with a resistive load on an extending swing cylinder, valve 3 would be actively controlled (assuming there are simultaneous actuator movements and the MPR pressure is not directly controlled as in displacement control) and valve 7 would be fully open. Valves 4, 5, 6, and 8 are closed.

Displacement Control Systems

If the number of active actuators is equal to or less than the number of pump/motors in the TIER system, an approximate form of conventional displacement control can be implemented. If the number of active actuators is greater than the number of pump/motors, it is still possible to implement displacement control with one actuator (or several, depending on the number of pump/motors) and utilize another combined mode with the remaining actuators and pump/motors. It is important to note that the flow in and out of each actuator must still pass through at least two valves and therefore the efficiency will likely not be as a good as displacement control without any metering valves in the circuit (this metering loss depends on the size of the valves). However, this does allow for open-circuit displacement control (Heybroek et al. 2007), and some of these additional metering losses are recouped since the pump/motors can be sized and operated more efficiently. To illustrate this mode using Figure 1 and assuming a resistive extending load on the swing actuator, valves 1 and 2 remain closed, valves 3 and 7 are fully open, valves 4, 5, 6, and 8 are closed, and the first pump/motor displacement is controlled to control the extension speed of the actuator. During assistive loads this mode will recover energy and return it to the pump/motor shaft where it can be used to overcome losses (friction, engine, etc.) or resistive loads.

Multi-Level Load Sensing with Decoupled Metering

This mode is a natural combination of the load sensing and decoupled metering modes, taking advantage of the SPR and multiple pump/motors to provide multiple load sensing pressures and dynamically reconfigure actuators (changing which actuators are connected to which pressure rail) with similar load requirements. For example, if the swing and boom actuators are both requiring high pressure and the stick and bucket relatively low pressure, then one pump/motor can be assigned to the swing and boom and the other pump/motor to the stick and bucket. Where the TIER system is different than a dual-level load sensing system is: 1) the actuators can be dynamically reassigned based on required load pressures, and 2) the back pressure can be minimized using techniques similar to decoupled metering systems. This combination provides the benefits of both multi-level load sensing and decoupled metering systems.

Flow Summing (and Regeneration)

The flow summing mode is unique to TIER and involves several efficiency and performance trade-offs. The primary advantage is the ability to move large actuators more quickly when other actuators are not moving (or moving slowly in the system). The ability to sum the flow of multiple pump/motors also allows the pump/motors to be sized appropriately for the typical work cycle, and not oversized for the maximum required performance. This results in higher overall efficiencies since the pump/motors are operating, on average, at higher average displacement settings. The disadvantages when using flow summing include losing the ability to operate at multiple pressure levels (the MPR and SPR are connected) and to recover energy from some assistive loads (when the pressure from the assistive load is less than the rail pressure). To accomplish flow summing valve 2 is open and valve 1 remains closed; the other valves are chosen depending on the number of actuators active.

A second method available to increase actuator speed, already utilized in conventional systems with appropriate valves, is flow regeneration. Considering the stick actuator for this example, in the TIER system this mode is enabled by closing all valves connected to the SPR except for valves 17 and 18. While this mode has the same trade-off of speed versus force found as in conventional flow regeneration systems, using this mode in the TIER system does still allow other actuators to connect to the SPR (or MPR) and operate as decoupled metering systems with resistive loads. An example of this mode with a single actuator is shown in Figure 2.

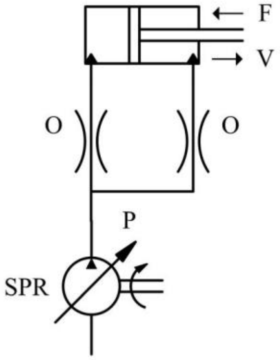


Figure 2. Example TIER System with Flow Regeneration on the SPR

Back Pressure Energy Recovery

Shown in Figure 3, in this example the pump/motor on the SPR is used to control the retraction of the cylinder by creating a back pressure on the bore end and using the pump/motor displacement controller to control the speed. To the right of the dashed line in Figure 3 the alternative is shown where larger metering losses are incurred on an equivalent actuator moving an identical load. It is possible to simply use the SPR on this actuator as a separate load sensing system with the trade-off being that the pump/motor would be operating at a relatively low displacement and possibly with lower efficiency. It is also be possible to use this mode for pressure intensification to recover energy to the rail with higher pressure. A recovery mode similar to this was proposed by Steinberg et. al. 2009, 2010.

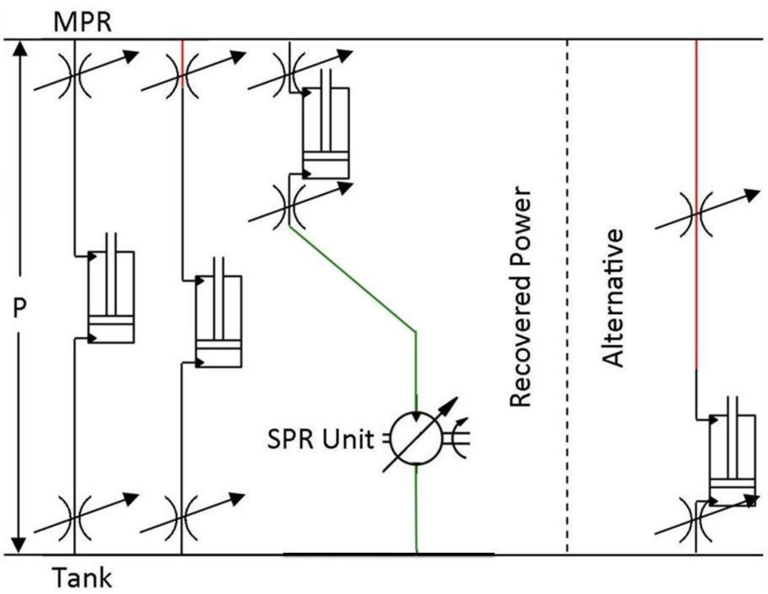


Figure 3. Example TIER System with Back Pressure Energy Recovery

Tier Implementation on A Small Backhoe Arm

To validate the concept of TIER a prototype system has been designed, installed, and tested using a four actuator small backhoe with power supplied by two variable displacement axial piston swash plate units capable of over-center operation. This system is briefly described here and is covered in more detail in Andruch, 2010. The backhoe arm as installed in the lab and the possible motions are shown in Figures 4 and 5, respectively.

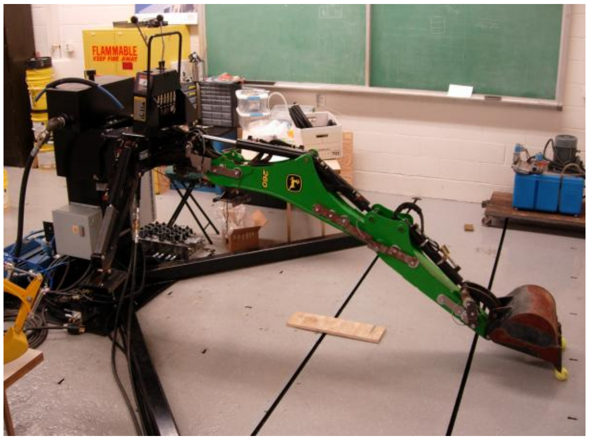


Figure 4. Four Actuator Prototype of TIER System (backhoe/excavator)

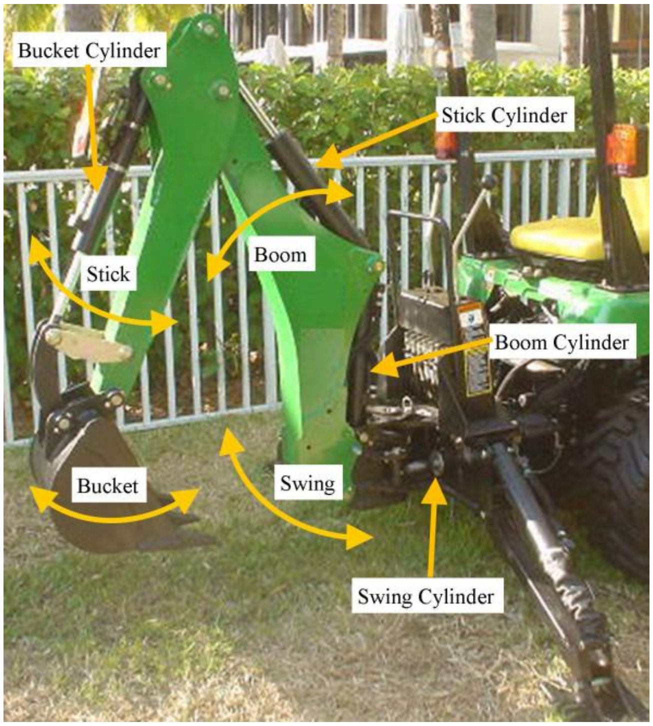


Figure 5. Definition of Four Actuators and Associated Motions

The 7 cc/rev pump/motors chosen were initially designed for use in a hydrostatic transmission for a zero-turn lawnmower (Figure 6). Two small cylinders and 4-way directional control valves were used to control the swashplate angles; each angle was measured using a hall-effect rotary angle sensor. A custom valve block was designed to accommodate the twenty-six 2/2 proportional valves (Figure 7).

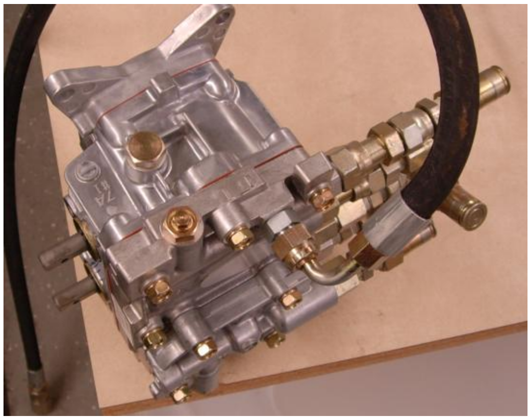


Figure 6. Two Pump/Motors in Housing

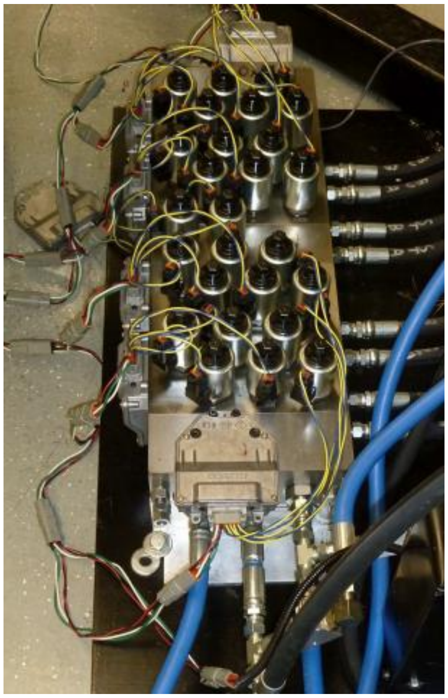


Figure 7. Twenty-six valves and sensors in Valve Block

Twenty-six INCOVA electro hydraulic poppet valves (EHPV) were used along with the available integrated pressure sensors and CAN bus controllers. The valves are characterized and discussed in more detail in Shenouda, 2006.

Rotary angle sensors were mounted to each backhoe joint to measure the motions of the swing, boom, stick, and bucket actuators. The CAN, swashplate and arm angles, and pressures at each actuator were connected to a dSpace DS-1103 hardware-in-the-loop control system for control and data acquisition.

Experimental Results

Initial experimental work has validated the general system operating concepts. The TIER system described here has been operated in load sensing, decoupled metering, and TIER specific modes. Efficiency calculations have not been completed until loads can be applied to the system to simulate the various dig cycles experienced in the field.

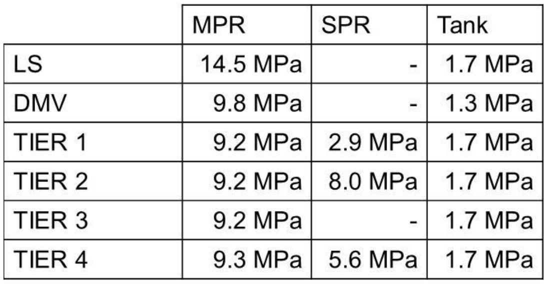
Four different motions, or stages, were used to validate the TIER concept.

1. Lifting the bucket out of the hole while swinging the boom over to a truck or pile: *both swing and boom cylinders simultaneously retract under resistive loads*.
2. Emptying the bucket: *the boom, stick, and bucket all move simultaneously to spread the load; the boom cylinder is extended with an assistive load and the stick and bucket cylinders are retracted with resistive loads*.

3. Moving the excavator arm back to the hole: *the swing cylinder extends under a small resistive load, becoming assistive as it decelerates*.
4. Lowering the boom into the hole: *boom cylinder is extended with an assistive load*.

To demonstrate possible energy savings the MPR, SPR, and Tank pressures were recorded for stage 2 and are given in Table 2. This stage was chosen since there are three simultaneous movements with one assistive load and two resistive loads. The LS was a traditional load sensing system with a single pump and the DMV was a traditional single pump decoupled metering valve system. In all cases the TIER configurations tested had equivalent or lower pressures and in certain modes were able to recover energy from the assistive load.

Table 2. Experimental MPR, SPR, and Tank Pressures during Boom, Stick, and Bucket Movements



	MPR	SPR	Tank
LS	14.5 MPa	-	1.7 MPa
DMV	9.8 MPa	-	1.3 MPa
TIER 1	9.2 MPa	2.9 MPa	1.7 MPa
TIER 2	9.2 MPa	8.0 MPa	1.7 MPa
TIER 3	9.2 MPa	-	1.7 MPa
TIER 4	9.3 MPa	5.6 MPa	1.7 MPa

The descriptions of the four TIER configurations shown in Table 2 and tested during stage two are:

- TIER 1 (Figure 8): Back pressure recovery mode used on the stick, displacement control on the bucket, and the assistive load on the boom is throttled to tank.
- TIER 2 (Figure 9): Equivalent of displacement control on the bucket using the MPR and load sensing decoupled metering on the stick using the SPR, with the assistive load on the boom being recovered (with throttling) on the SPR.
- TIER 3 (Figure 10): The assistive load on the boom is throttled to the tank and load sensing decoupled metering on the stick and bucket.
- TIER 4 (Figure 11): The boom assistive load is recovered on the SPR using the second pump/motor and load sensing decoupled metering on the stick and bucket.

While it is obvious that some modes are more efficient than others, this example does illustrate the many degrees of freedom with this type of system. Other researchers have noted this same efficiency and flexibility potential accompanied by difficult control challenges (Erkkil, 2009).

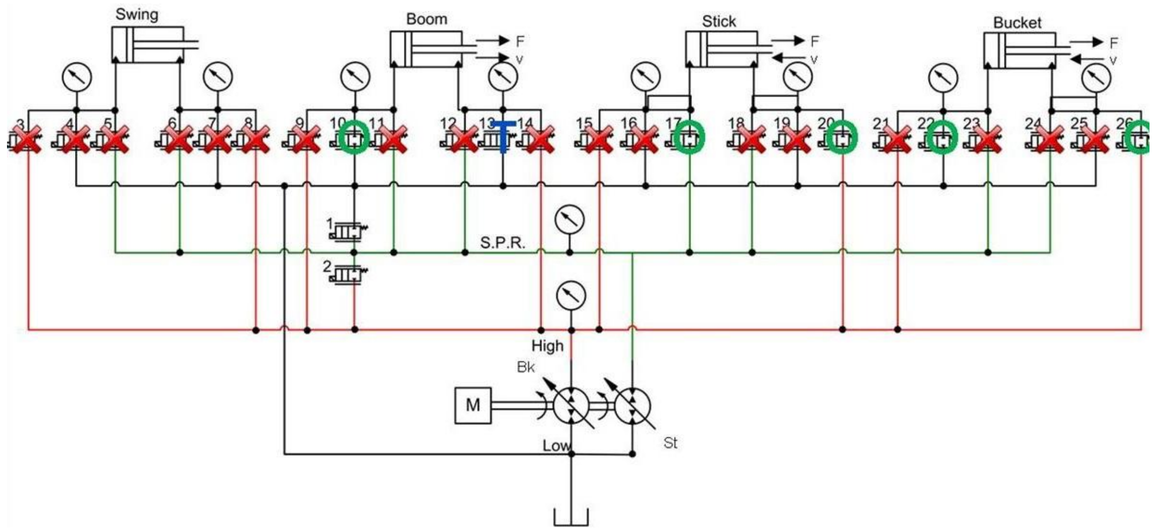


Figure 8. TIER 1 Configuration

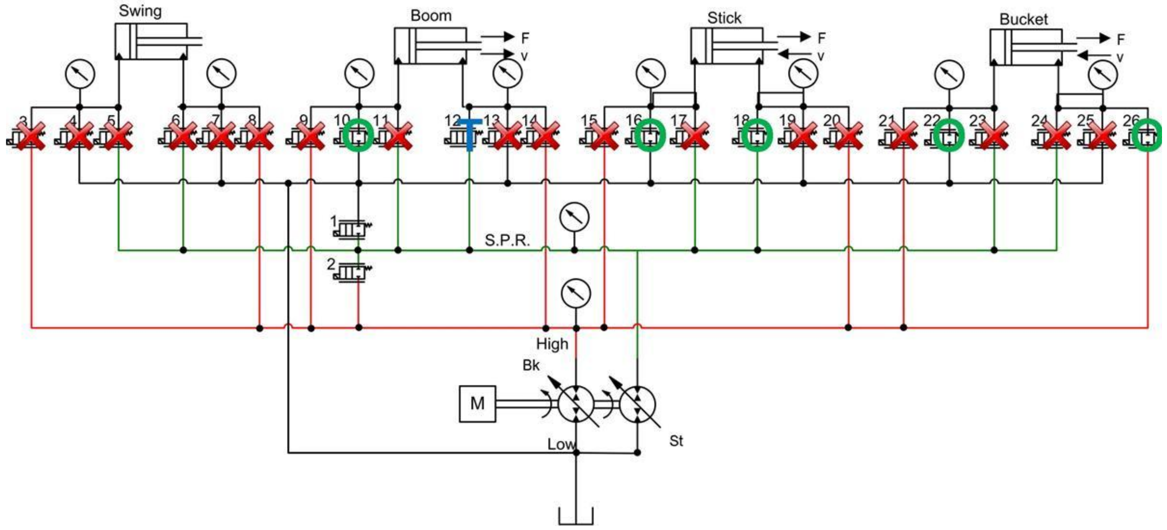


Figure 9. TIER 2 Configuration

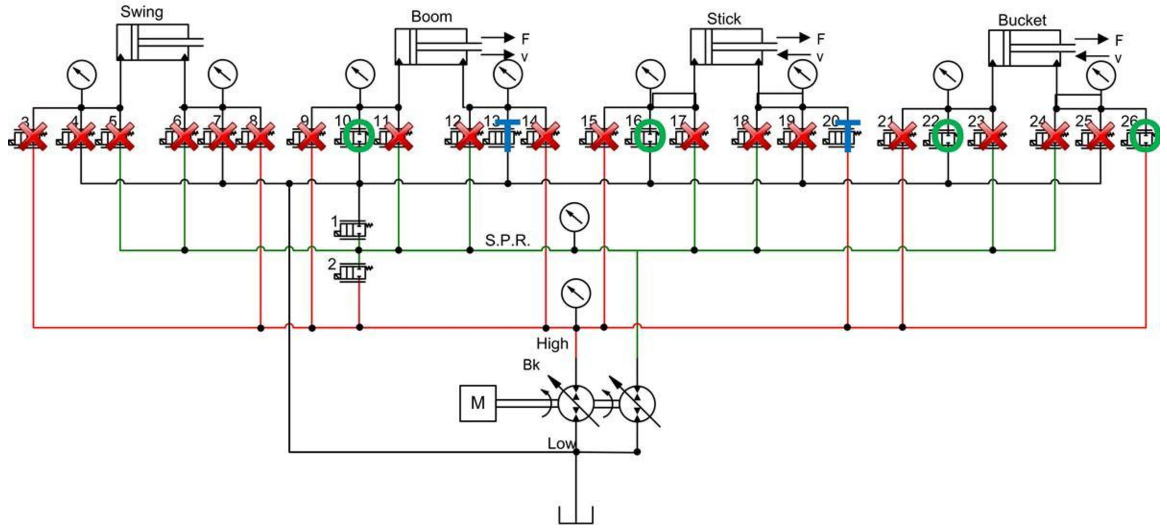


Figure 10. TIER 3 Configuration

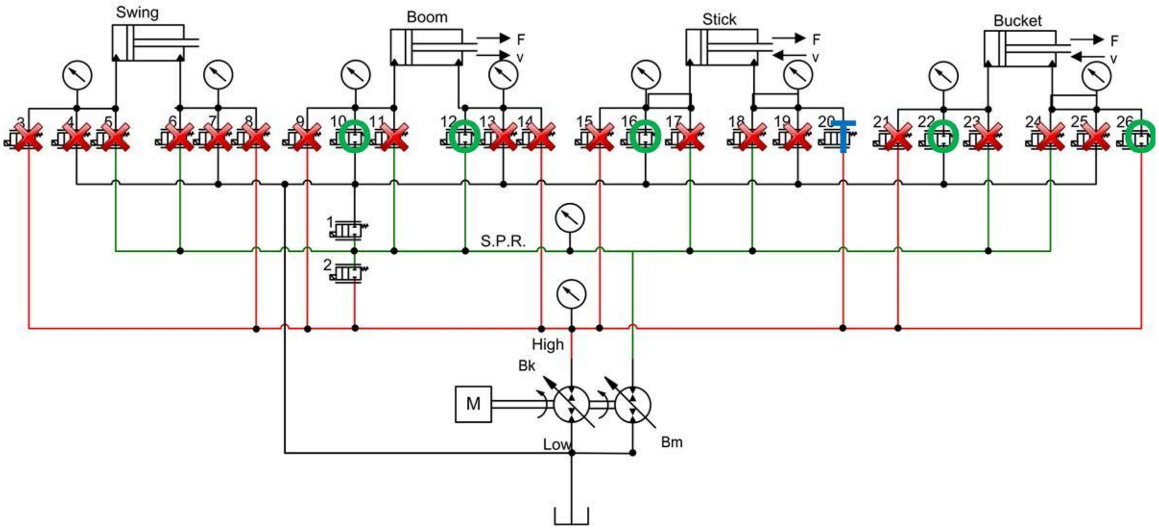


Figure 11. TIER 4 Configuration

As an example of the pressure traces on the MPR, SPR, and tank rails, Figure 12 is provided for the first TIER configuration (TIER 1). The pressure traces for TIER configurations 2-4 are similar (with the different values listed in Table 2) and not repeated here.

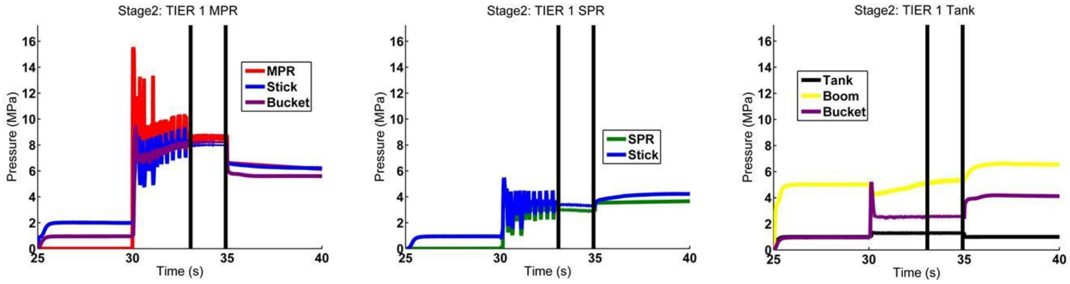


Figure 12. MPR, SPR, and Tank pressures recorded for the TIER 1 Configuration

Conclusion

This research project developed the TIER distributed valve system and demonstrated several of operating modes using a laboratory test excavator equipped with two pump/motors and twenty-six 2/2 proportional valves. There are many degrees of freedom leading to multiple operating mode choices for virtually all feasible actuator motions. Since there are redundant flow paths for every actuator and redundant control valves, there are possibilities for an electronic control system to automatically detect and "repair" certain faults until the machine can be repaired. Operating in this "limp home" mode will limit the number modes and likely the machine efficiency as well, but could allow the operator to finish the task before repairs are made.

Nomenclature

DMV	Decoupled metering valves (sometimes called independent metering valves)
EFRC	Energy Recovery Flow Control
MPR	Main pressure rail
PCLS	Pressure compensated load sensing (generally called load sensing)
SPR	Secondary pressure rail
TIER	Topography with Integrated Energy Recovery

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