HEAVY MOVABLE STRUCTURES, INC.
SEVENTEENTH BIENNIAL SYMPOSIUM

October 22-25, 2018

Hydraulic Power Trends

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ORLANDO, FLORIDA

1. Introduction/Abstract

In the landscape of hydraulic power there are several concepts which, despite the technical and commercial merits, have yet to become common place in the world of movable bridges. Hydraulic power is a critical aspect of drive and control and its inherent benefits are leveraged by many applications. Each application has its challenges and as these challenges are overcome the solutions gradually develop into trends as part of the evolutionary nature of technological improvements. It is important to be mindful of these trends because other applications can benefit from the solutions. Some of the trends that are visible today are palletized solutions, speed control via variable frequency drives (VFDs), and connected hydraulics. This paper will explore the technical merit, commercial merit, and considerations for implementation in movable bridge applications.

In concept, the palletized solutions are intended to provide a fully tested piece of machinery which will incorporate as much of the movable bridge operating system as possible with the benefit of minimizing on-site installation, alignment, and testing during construction. An example of a palletized solution is a torque arm drive system (TADS) which incorporates the hydraulic power unit, controls, hydraulic motor, and torque arm within a self-contained unit. In a similar fashion, a hydraulic cylinder can also be converted into a self-contained hydraulic actuator (SHA). The technology which is utilized in these palletized solutions is not new, but what is new is how these palletized solutions are packaged together. Palletized solutions are also a natural fit for VFD technology.

At one point variable frequency drives (VFDs) were too expensive, but over the past (4) decades power electronics technology has reduced the cost and size and has increased performance. Although the most popular advantage of VFDs, is the potential to save energy costs, for hydraulic systems, an additional benefit is speed control. A fixed displacement pump connected to a VFD provides a good solution for speed control and simplifies the hydraulic system which reduces the mysticism of hydraulics for users not comfortable operating and maintaining hydraulic systems but are comfortable working with VFDs.

Connected hydraulics is part of the fourth industrial revolution, (industry 4.0, or i4.0) arguably the biggest technological leap in recent decades for hydraulic equipment. Connected hydraulics involves data gathering, remote operations, diagnostics, condition monitoring, and process monitoring. The implementation of this technology will have a significant impact on the way hydraulic equipment is maintained and operated.

Each of these concepts can help overcome existing challenges and merits implementation into the movable bridge industry or any application with heavy movable structures. Based on expressed priorities from end users and discussions within the movable bridge community, it would appear that these concepts are beginning to take hold and the inertia of using existing solutions is being overcome.

2. Speed Control via VFD

To determine the relevance of speed control via VFD in hydraulic power systems, it is important to review the different types of hydraulic systems. Traditionally a hydraulic power system would utilize what is referred to as driving technology or braking technology. See Figure 1 for a breakdown of hydraulic power systems.

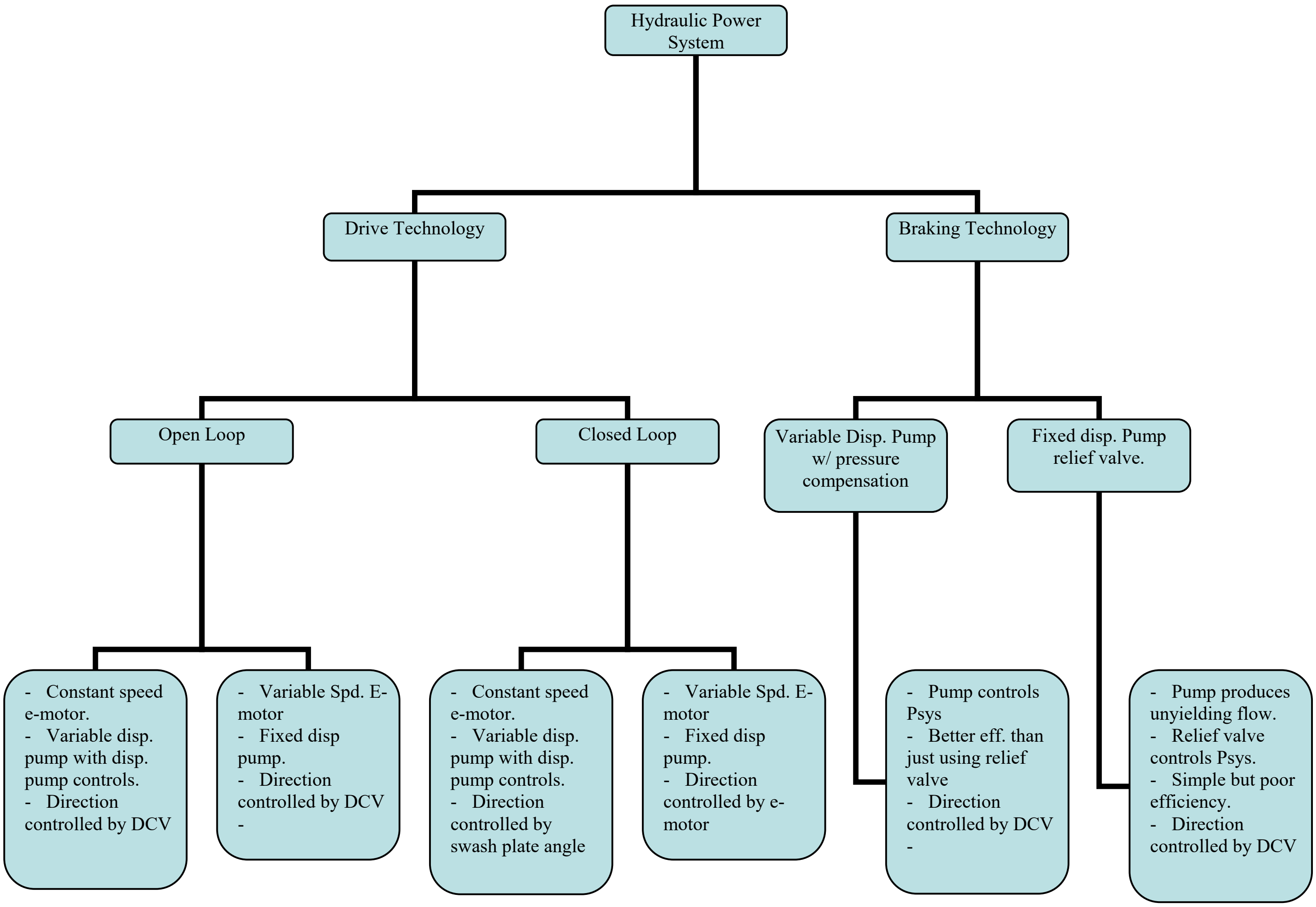


Figure 1: Hydraulic Power System Breakdown

A hydraulic system which utilizes braking technology supplies an unyielding flow and uses different components to control the direction of flow and to hold back that flow in response to a pressure being met as a means of controlling the hydraulic system. In the circuit shown below (Figure 2) the maximum pressure is limited by the unloading relief valve and the flow rate to the cylinder is controlled by the throttle valves. At one point the throttle valves will create enough resistance to flow to actuate the relief valve and direct more hydraulic fluid through the relief valve and less to the cylinder. As the throttle valves create more resistance less flow is going to the cylinder and more flow is going to the relief valve. This circuit is simple and in many cases works well but it is inefficient. The hydraulic fluid flowing through the relief valve performs zero work.

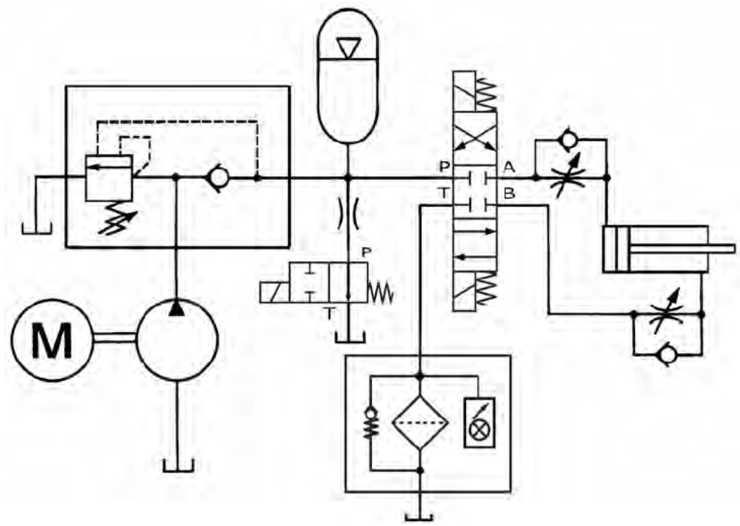
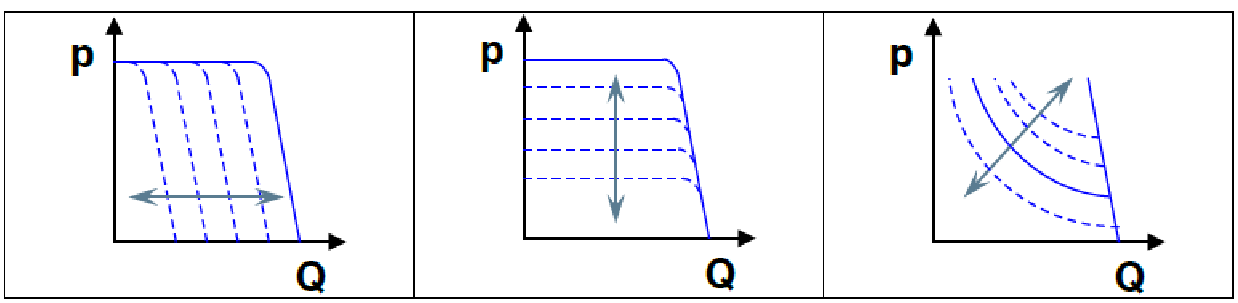


Figure 2: Fixed Disp. Pump Circuit

This same circuit can be made more efficient by replacing the fixed displacement pump with a variable displacement axial piston pump. A variable displacement axial piston pump has the benefit of having different types of pump controls. See Figure 3.

One of the pump controls is a pressure compensator, which means that the pump can be set to maintain a constant pressure in the system and the flow from the pump is determined by the resistance in the circuit. In that scenario, there is no flow going over a hydraulic relief valve, which makes the hydraulic system more efficient. All variable displacement axial piston pump controls come equipped with a pressure compensator and could be equipped with other types. For instance, there is a load sensing pump control which maintains a constant differential pressure across an orifice, which in turn maintains a constant flow to the load. Another type is a horse power limiter which maintains a constant horse power. It produces higher flows when pressure is low and lower flows when pressure is high. There are many other types of pump controls and different reasons for using each in a hydraulic system. However, it is important to note this is a subset of pump controls which respond to pressure in the system. If pressure gets too high the variable displacement pump reduces the swashplate angle and decreases the flow going to the system. There is essentially a "braking effect" when pressure reaches a certain point.



A B C

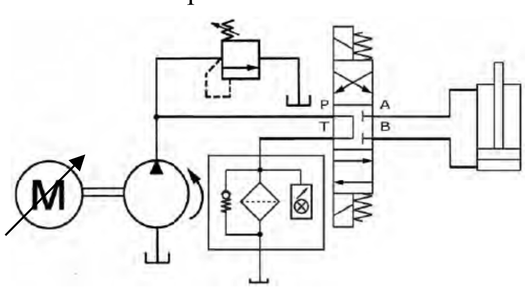
Figure 3: Effects of different types of pump Controls. A-Pressure Compensator, B-Load Sense, C-Horsepower Limiter

In contrast driving technology does not rely on a throttle valve to control the flow rate in the system. Instead it utilizes a subset of pump controls which directly controls the angle of the swashplate. As shown in Table 1 driving technology can consist of the following configurations.

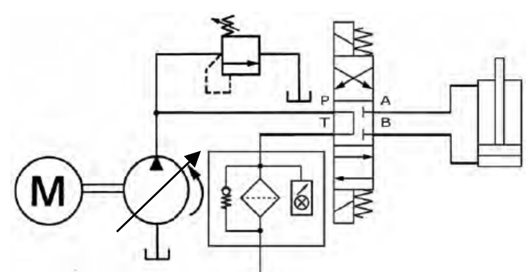
Table 1: Driving Technology Configurations.

Open Loop.		**Closed Loop**	
Constant speed e-motor	Variable speed e-motor	Constant speed e-motor	Variable speed e-motor
Variable disp. pump with disp. controls	Fixed disp. pump.	Variable disp. pump with disp. Controls	Fixed disp. pump.
Direction control via DCV	Direction control via DCV	Direction control via swashplate angle.	Direction control via e-motor
.			

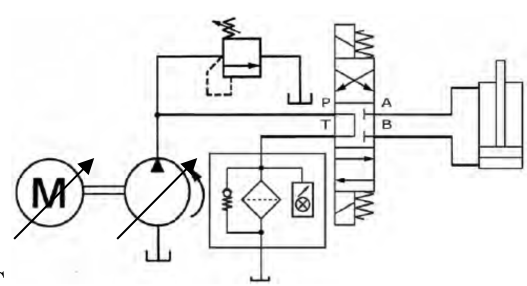
In open loop or closed loop systems, when the configuration uses a VFD to control the e-motor and a fixed displacement pump, flow rate is controlled by the speed of the e-motor (Figure 4A and 5A). In the configuration with a constant speed e-motor and a variable displacement pump, flow is controlled by the angle of the swashplate (Figure 4B and 5B). When the configuration utilizes a VFD to control the e-motor and a variable displacement axial piston pump the speed is a controlled by a combination of the two (Figure 4C and 5C). Although this configuration is more complex, the added benefit is that the system can operate at optimum efficiency by finding the right combination of e-motor speed and swashplate angle based on the performance curves of the e-motor and the pump. In many cases the benefit of a more efficient system pays dividends because the system operates for long periods, but in other applications the benefit is not fully realized because the system operates intermittently which is the case with many heavy movable structures such as movable bridges. Although open loop systems incorporate many components which fall under the category of driving technology, the open loop configuration limits the system's ability to fully leverage the benefits of driving technology. For instance, the direction of flow is still controlled by a directional control valve (DCV). In a closed loop configuration there would not be a need for this additional component.



A.

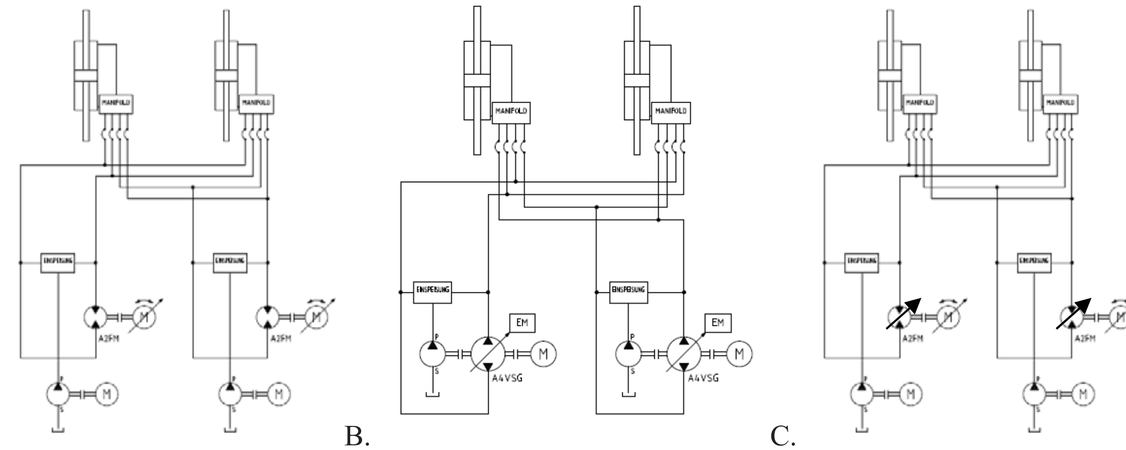


B .



C

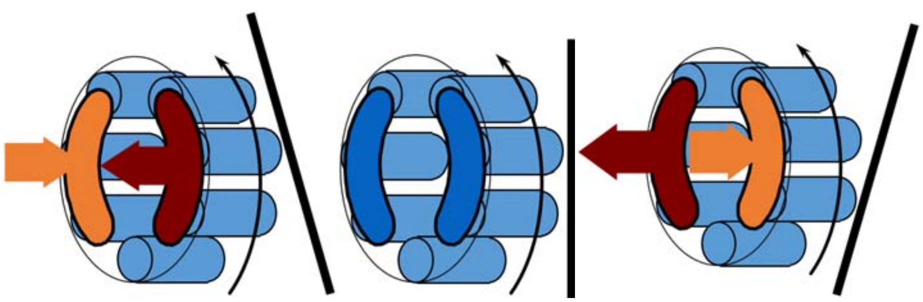
Figure 4; Open Loop Driving Technology Configurations



A. B. C.

Figure 5: Closed Loop Driving Technology Configurations

In a closed loop system the flow rate is controlled in a similar fashion as in the open loop systems, but the direction of flow is controlled either by the pump or by the e-motor. Intuitively, one can see flow reversing direction when the direction of the e-motor is reversed. In the configuration with a constant speed e-motor the swashplate angle controls the direction of flow. See Figure 6. With the swashplate in the neutral position (Figure 6 (B)), there is no flow and as you move to swashplate angle to one side you can see the pistons begin to take a suction from one port and supply flow out the other port (Figure 6 (A)). When the swashplate "goes over center" the flow reverses direction (Figure 6 (C)).



A **B** **C**

Figure 6: Over Center Capable Variable Displacement Axial Piston Pump

In the open loop configuration direction of flow is controlled via a DCV which is an additional component compared to the closed loop system and is some cases less components can be highly beneficial. For instance, compact palletized solutions are made possible by decreasing the number of components needed in a system. Palletized solutions will be discussed further in Section 3.

Closed loop systems have an inherent braking effect (See Figure 7) not present in the open loop systems. As a load transitions from being "resistive" to "running away" as shown by the tractor as it climbs up the hill and subsequently down the hill. The response of the driving system has to compensate to adequately control the load. In a closed loop system as the load transition to running away the hydraulic motor will turn into a pump which is driven by the weight of the tractor since it is directly coupled to the tires. The hydraulic motor is now supplying flow which has to flow through the pump in the system. As fluid flows through the pump the prime mover inherently resists the rotation.

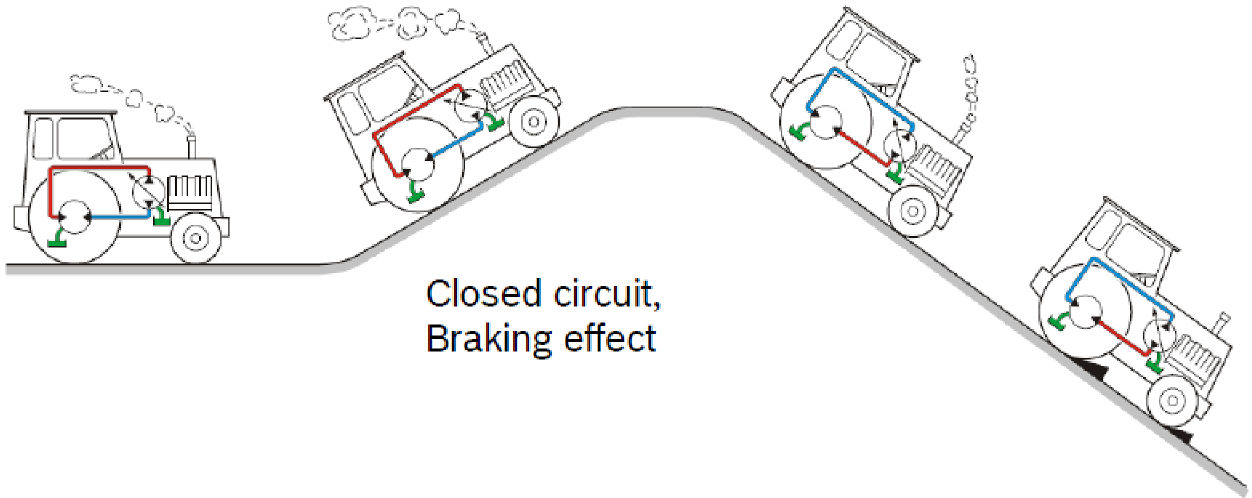


Figure 7: Closed Loop Breaking Effect

In the case of an open circuit the hydraulic motor turns into a pump driven by the weight of the tractor, but the fluid dumps directly into the reservoir which offers little resistance. Consequently, the load “runs away.” (See Figure 8).

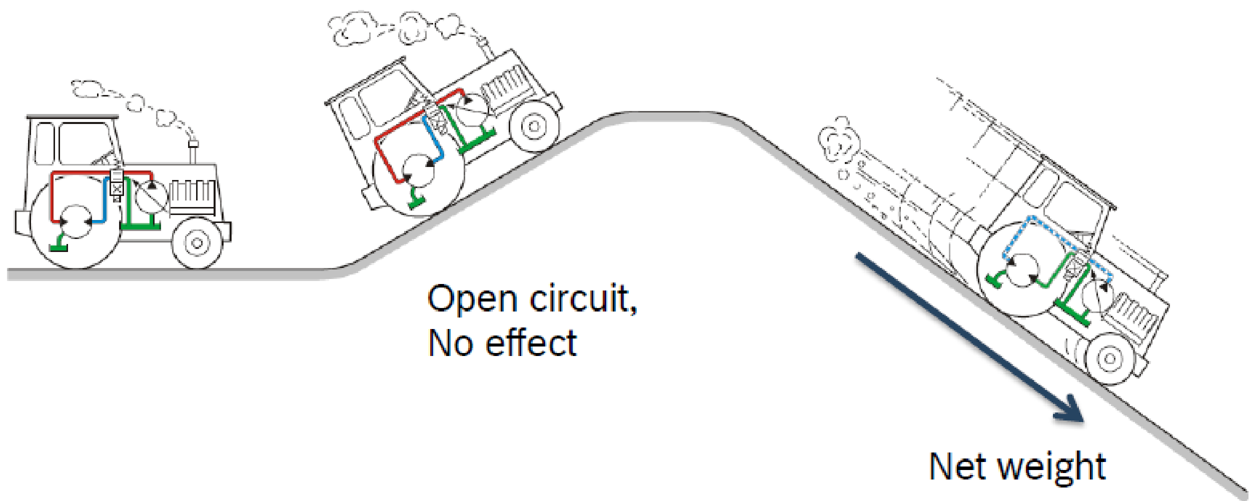


Figure 8: Open Circuit and Runaway Load

To compensate, open loop circuits incorporate braking valves which offer the resistance needed to control the load when the load is “running away.” (See Figure 9)

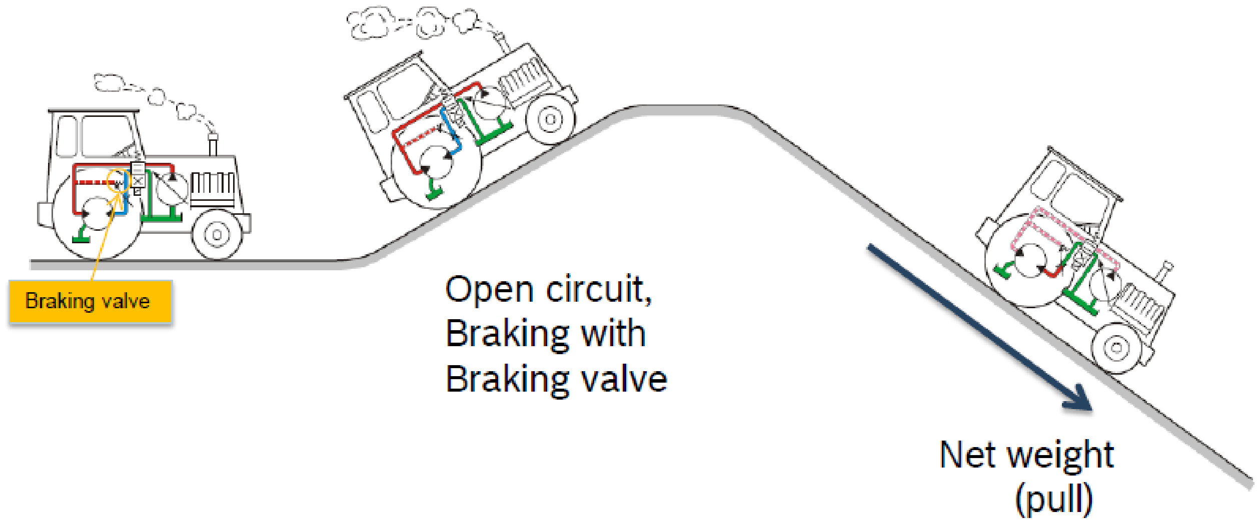


Figure 9: Open Circuit with Braking Valve

When the prime mover in a closed loop circuit is an e-motor, the VFD allows the braking effect to be controlled with digital precision. The same applies for when the load is resistive. Digital precision can be utilized to control the flow of hydraulic fluid which translates into speed control.
The rotor of an e-motor, which is coupled to a hydraulic pump, is driven by the rotating magnetic field in the stator created by the incoming power. See Figure 10. In a constant speed e-motor the speed of the rotating magnetic field is dependent of the number of poles in the e-motor and the frequency of the incoming power from the utility company (60 Hz in the US). See Equation 1.

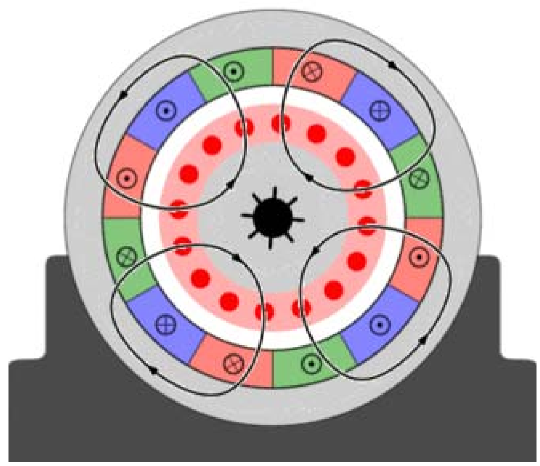


Figure 10: Induction Motor Cutaway

Equation 1

$$n=120f/P \quad \text{(Eqn 1)}$$

n= Speed of magnetic field (RPM)
P=Number of Poles
f=Frequency of power supply (Hz)

In the case of a (4) pole induction motor connected to the grid (frequency 60Hz), the resultant speed of the magnetic field is 1800 RPM. If the frequency of the incoming power could be controlled one could control the speed of the rotating magnetic field, which is precisely what a VFD can do. A VFD converts the incoming AC power to DC and the output to the induction motor is a step sinusoidal wave form with a desired frequency. See Figure 11.

The shaft RPM does not equal the speed of the magnetic field and that is due to ‘slip.” Due to the nature of induction motors there has to be a speed difference between the rotating magnetic field and the speed of the rotor to generate a torque. Depending on the torque on the motor (ie the flow and pressure being supplied to the hydraulic system) the speed of the rotor will be 0.5% to 5% less than the speed of the rotating magnetic field when supplying flow to a resistive load. In the case of a load which is running away the speed of the rotor will be 0.5% to 5% faster to supply a torque which is acting as a brake in the hydraulic system via the hydraulic pump. With the ability to supply a brake at the hydraulic pump it is conceivable to remove the brake valves from the hydraulic circuit.

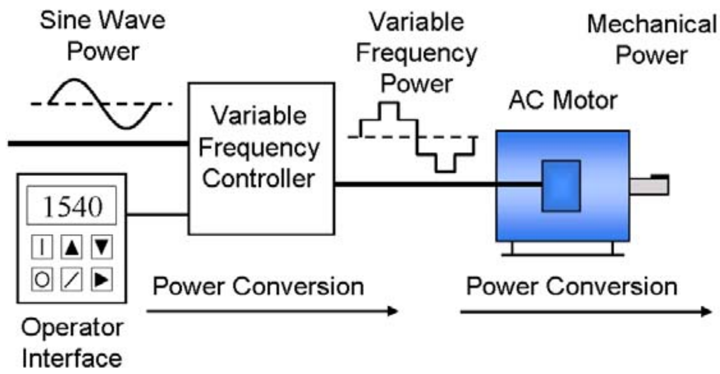


Figure 11: VFD Functional Description

The main feature of a VFD allows the user to set a desired shaft RPM and the power signal produced by the VFD will automatically adjust to achieve the desired shaft RPM. One application for this feature would be a movable bridge which is being moved on a windy day. The implication for the hydraulic system is that a varying load would result in a varying flow which results in varying speed. However, in the case of a hydraulic pump controlled with a VFD the response to the varying load is virtually instantaneous. The VFD will adjust the power signal to achieve the set shaft RPM which leads to consistent and repeatable speed control.

As hydraulic power systems transition from braking technology to driving technology the net effect is to eliminate components, increase efficiency, and increase repeatability. When flow rate and direction are no longer being controlled by valves, components are eliminated. When hydraulic fluid no longer has to be throttled through a valve efficiency is improved. When a hydraulic system goes from an open loop configuration to a closed loop configuration the reservoir gets smaller. Digital control of pump RPM and swashplate angle allows for repeatable and consistent flow which is closely tied to speed control. The trade-off is that hydraulic power systems which utilize driving technology are not dynamic, but in some applications such as heavy movable structures that is a good trade-off.

3. Palletized Solutions

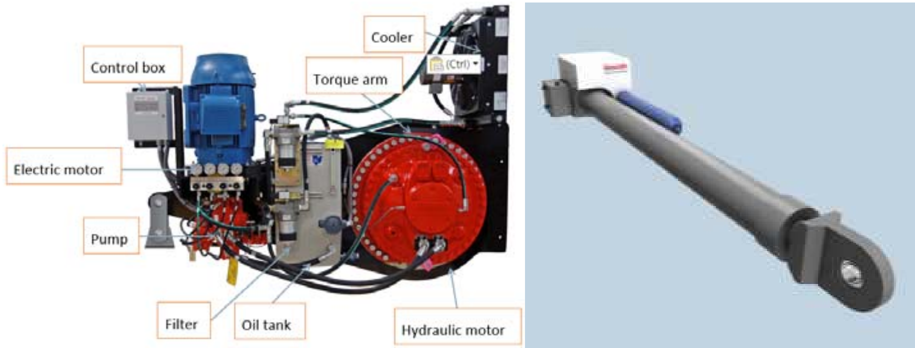
In the previous section the suggestion was made that transitioning from braking technology to driving technology will have the following net effects.

- Components eliminated
- Reservoir size decreased
- Speed controlled consistently

Those effects can be leveraged to create palletized solutions, and palletized solutions have the potential of delivering the following benefits.

- Expedited installations.
- Less crowded machinery rooms.
- Simplified maintenance plan.

Examples of palletized solutions are shown in Figure 12. Item A is referred to as a **T**orque **A**rm **D**rive **S**ystem (TADS) and Item B. is referred to as a **S**elf-Contained **H**ydraulic **A**ctuator (SHA).



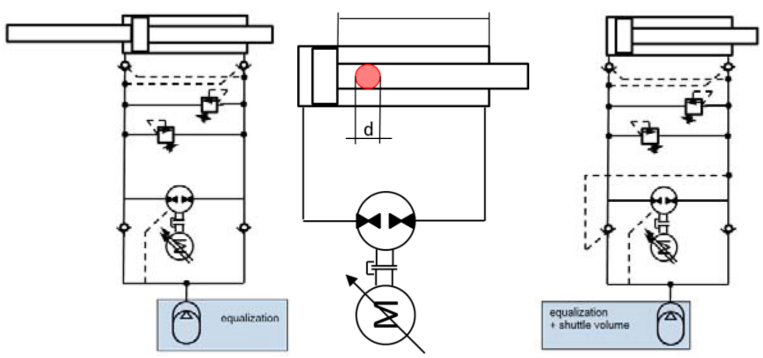
A B

Figure 12: Palletized Solutions

In addition to leveraging the benefits of transitioning from braking technology to driving technology, research and development led to significantly reducing the size of the radial piston hydraulic motor used in the TADS. In most cases the weight of the motor has been reduced by more than 50%. A smaller motor makes it easier to develop a palletized solution.

A TADS is intended to be a replacement for conventional electric mechanical systems. For a hydraulic motor the classic solution is to use a closed loop system; therefore, many of the benefits of driving technology are typically utilized in these types of systems. Because the hydraulic motor does utilize the closed loop configuration the reservoir is smaller when compared to the open loop configuration. This is the major factor which allows the solution to be palletized. The other components are then mounted on the torque arm. See Figure 12 (A).

An SHA in concept and benefits delivered is very similar to the TADS; however, the main difference is that the TADS is a hydraulic motor and the SHA is a hydraulic cylinder (see Figure 12 (B)). The biggest factor which has to be overcome for a cylinder to realize the self-contained concept is the shuttle volume.



A B C

Figure 13: Shuttle Volume Solutions for SHA

The shuttle volume is the volume of hydraulic fluid taken up by the cylinder rod within the hydraulic system (See Figure 13 (B)). When the cylinder is retracted there has to be a place to store that volume of fluid. One solutions would be to eliminate the shuttle volume by using a double acting cylinder (See Figure 13 (A)) which is not always possible.

There are also options for single acting equal area cylinders. See cylinder illustration in Figure 15. These cylinders would typically cost more and would be slightly larger than the equivalent standard cylinder with equal performance requirements (ie stroke, extending force, and retracting force). The other solution is to store the volume in a reservoir. See Figure 13 (C). Depending on the application the reservoir could be a standard accumulator (See Figure 13 ©). Standard accumulators are limited in size. As the cylinder increases in size, the shuttle volume will exceed the capacity of standard accumulators. Other reservoirs could be custom made and equipped with a bladder which would allow the shuttle volume to come in and out without interacting with the environment which would maximize the integrity of the hydraulic fluid. See Figure 14. Other solutions could include a custom axial piston accumulator which would serve the same purpose, but could compensate for larger shuttle volumes. In fact, axial piston accumulators would offer the largest capacity to compensate for the shuttle volume. Regardless of how the concept is achieved a self-contained unit, either SHA or TADS, would result in ease of installation, less crowded machinery rooms, and a simplified maintenance plans.

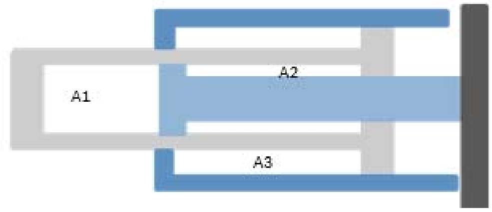


Figure 15: Equal Area Single Acting Cylinder

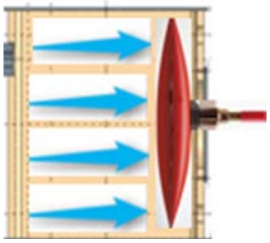
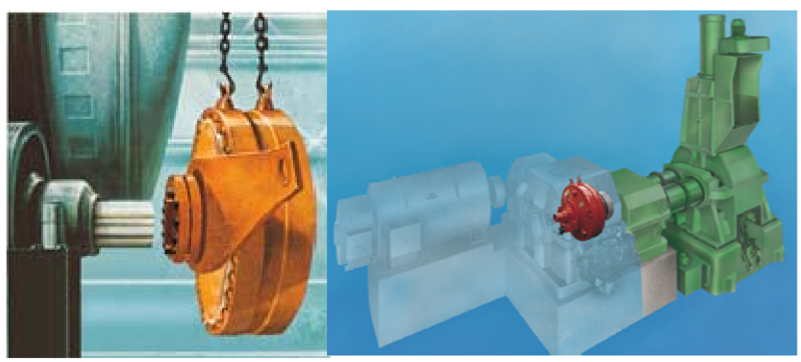


Figure 14: Reservoir equipped with bladder

Ease of Installation:

Figure 16: TADS Ease of Installation

A **B**



Typically a conventional electric mechanical solution will include an electric motor, primary reducers, shafts, and secondary gearboxes which all have to be aligned with great precision to avoid any issues during operations. See Figure 16 (B). In contrast the TADS is all self-contained and can be installed in the same fashion as shown in Figure 16 (A). Similarly, the SHA is as close as possible to a plug and play solution. Besides the pinned connections of the cylinder, the only other connection is the electrical connection for the electric motor.

Compared to a typical hydraulic system, for the TADS and SHA there is no piping to be installed which simplifies the installation. Because the TADS/SHA is self-contained it can be delivered to the site fully tested. Since it utilizes driving technology the speed control of the system is consistent and repeatable which minimizes the impact of site specific conditions. There is still site testing that has to be done, but it is greatly reduced. Just the fact that the systems does not have to be flushed and cleaned is a significant time saver.

Less Crowded Machinery Rooms:

Compared to electric mechanical solutions the TADS greatly reduces the crowding in the machinery room because it consists of one palletized solution as opposed to many components for the electric mechanical solution.

Machinery Rooms are also less crowded with self-contained solutions because they eliminate the piping that has to be installed and they eliminate the reservoir.

Simplified maintenance plan:

Since the TADS/SHA is a closed loop system the hydraulic fluid is less susceptible to degradation due to contact with the environment. This would allow the system to operate with the same hydraulic fluid for the life of the equipment. It is foreseeable for the system to operate with no issues until the point when it has to get refurbished from normal wear and tear. When the existing unit has to be refurbished it would be replaced with a spare unit which is relatively quick to remove and install. The existing system would then be refurbished and ready to replace the next unit.

Since the TADS is so flexible in its capabilities it is possible for different assets to utilize the same equipment which could reduce the required parts needed in stock to conduct repairs on the systems.

In terms of ease of installation, less crowded machinery rooms, and simplification of maintenance the self-contained solutions have significant benefits to offer. One of the trade-offs is that the self-contained solutions do not offer the level of redundancy to which heavy movable structures have been accustomed. However, with the advent of connected hydraulics the risk is mitigated because the health of the systems can be more closely monitored and it allows end users to be proactive and plan maintenance to avoid unplanned periods of inoperable equipment.

4. Connected Hydraulics

4.1. What is Connected Hydraulics:

Connected Hydraulics is the implementation of the fourth industrial revolution (Industry 4.0, or i4.0) to the field of hydraulics. Each of the first three industrial revolutions, mechanization, electrification, and automation, were caused by significant technology advances that brought about industrial process changes, increasing productivity and profitability. Industry 4.0 or “Connected Industry” utilizes information technology (IT) to bring about new process changes.

Similar to technology leaps in the previous industrial revolutions, Connected Industry strives to improve the bottom line for manufacturers; decrease unplanned downtime, increase operational efficiency, and help identify causes of process inefficiencies by increasing data transparency. In order to begin to identify these causes and take action against them, the first step must be to access machine and process data.

In the 3rd Industrial Revolution, Automation, access to data from the system became necessary in order to implement control and automation techniques. With Connected Industry this step is again necessary. In fact, the core foundation of Connected Industry truly is “data

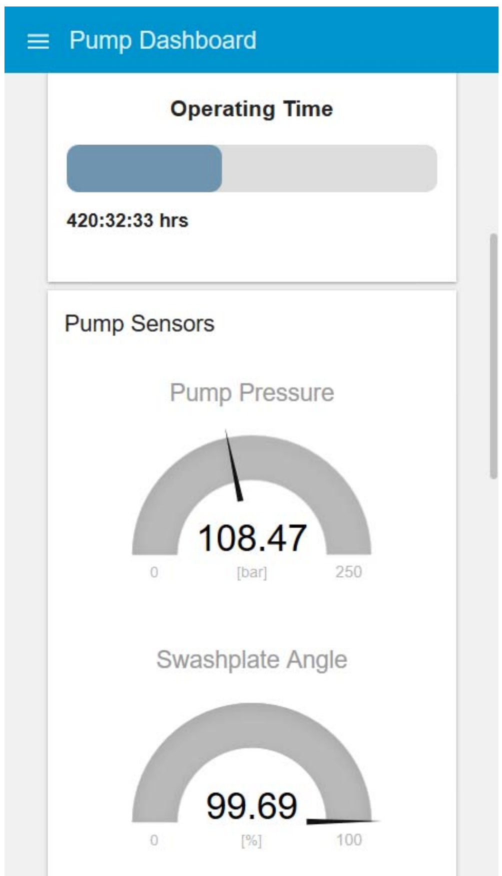


Figure 17: An Example Dashboard for Condition Monitoring

accessibility." Instead of using this data for control this information is utilized by various systems with intelligent algorithms to draw important, valuable conclusions.

4.2. Condition Monitoring:

With the implementation of automation into various industries, machines and systems needed to be able to measure information from specific processes. In this way, the control system was able to monitor the system. Similar to this topic, Condition Monitoring is the process which people are able to monitor the condition of a system, machine, or component based on measurements from sensors. With Condition Monitoring, it became possible to determine when filters were clogged, when oil needed to be changed, and when there were significant errors in a process.

The value from Condition Monitoring becomes clear when considering maintenance on a system, particularly during an unplanned downtime situation. Without any sensors providing the technician with information on the system, it would take significantly longer to troubleshoot and recover from a breakdown. A system with Condition Monitoring provides an informational overview, allowing maintenance to clearly understand the operational status of various components in the overall system. However, Condition Monitoring does little to identify the cause of failures, and it is incapable of predicting these on its own.

4.3. Predictive Maintenance:

Many industries are interested in learning about Connected Hydraulics with the goal of achieving longer machine lifetimes, less machine down time and maximum return on investment. In the movable bridge community as well as other industries, one significant topic that has become possible with Connected Industry technology is Predictive Maintenance.

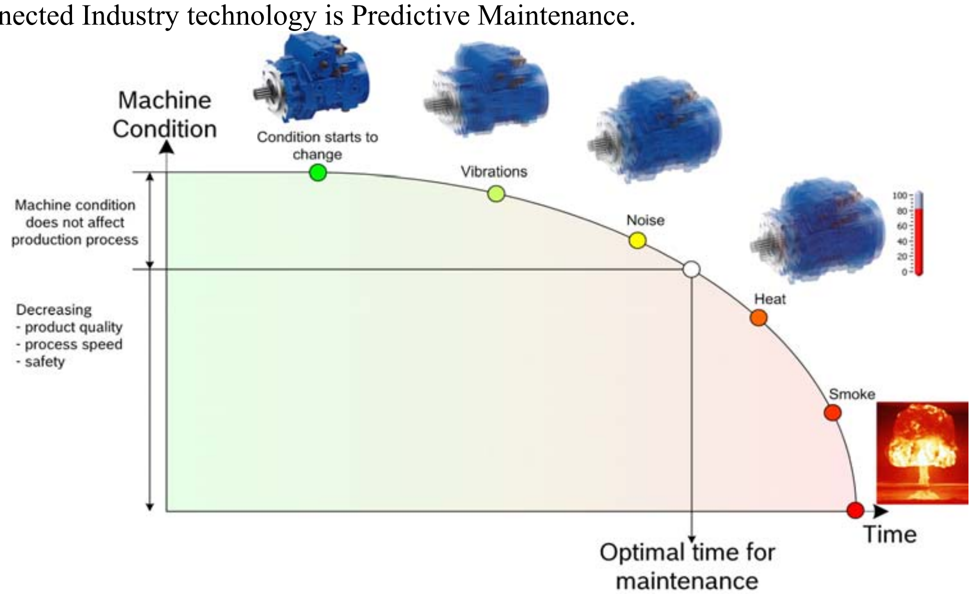


Figure 18: A Hydraulic Component on a Path to Failure

With Predictive Maintenance on a hydraulic system it is possible to predict a component failure prior to a resulting system breakdown. The same system data which allows a maintenance technician to understand the Condition of a system is used in Predictive Maintenance. However this data is then aggregated and analyzed in an algorithm. Using various types of algorithms (often based in Machine

Learning), Predictive Maintenance solutions are able to predict a component failure and identify the root cause. With this prediction, it is then possible to schedule maintenance and order replacement parts before the system becomes inoperable.

4.4. Implementing Connected Hydraulics:

By 2020, it is expected that there will be 50 times the amount of digital information compared to what exists today. Beyond the expected increase in sales from “smart” consumer technology like the virtual assistants Alexa and the Google Assistant, various industries are beginning to adapt and implement technology from Connected Industry. As a result, suppliers are creating new development roadmaps to create “connected” products. Companies, for example, have committed to transform their entire product line in such a manner over the next decade; creating integrated sensors, connected hydraulic actuators, and intelligent control systems.

However, it is already possible to begin to implement Connected Hydraulics. While this can seem a daunting task, especially for large systems, there are a few rules that can be followed to help with this:

1. **Target the Greatest Need:**
   Over engineering is easy to do. The most effective use of time and money is to exclusively target the area in which there is great potential for improvement. These are normally situations where there are significant downtime losses, difficulty accessing machinery, or other costly maintenance processes.

2. **Start Small:**
   Don’t try to install millions of dollars on a massive system. Start with an individual component or a specific process and build up from there. It will cost less to implement up front and in the long run once the mistakes are worked out the first time.

3. **Find the Right Partners:**
   Connected Industry is incredibly complex. It spans a multitude of different fields from manufacturing, electronics, control theory, dynamics of physical systems, IT networking, and data security. Most small and medium sized companies don’t have the expertise in house to face all of these challenges. No one does Connected Industry alone, so be sure to find the right partners to help.

Following these, it is then possible to determine where to start an implementation project. In some instances, it may make sense to retrofit an existing system with new sensors, electronics, and networking devices. In other cases, it may make more financial sense to purchase a new system with integrated Connected Industry technology; allowing for Condition Monitoring, Predictive Maintenance, or other solutions that are continually being developed within Connected Industry. Every system is different, and every process has different inefficiencies and sources of these problems. Again, the overall goal of Connected Industry is to increase transparency to increase productivity and reliability from the system. With these improvements, it is possible to increase the lifetime of the system and maximize the return on investment.

5. Conclusion

Speed control via VFD, palletized solutions, and Connected Hydraulics have technical and commercial merit for being implemented in drive systems for heavy movable structures, but it will take time to find the right application, validate the concept and ultimately prove to designers, end users, and suppliers the solutions are sound. The next step is to explore the possibilities for these concepts whenever possible; in the early stages of the design phase for a new construction project or in a refurbishment type project.