Drive & Control
profile

Technical Article

Speed-variable revolution in hydraulics

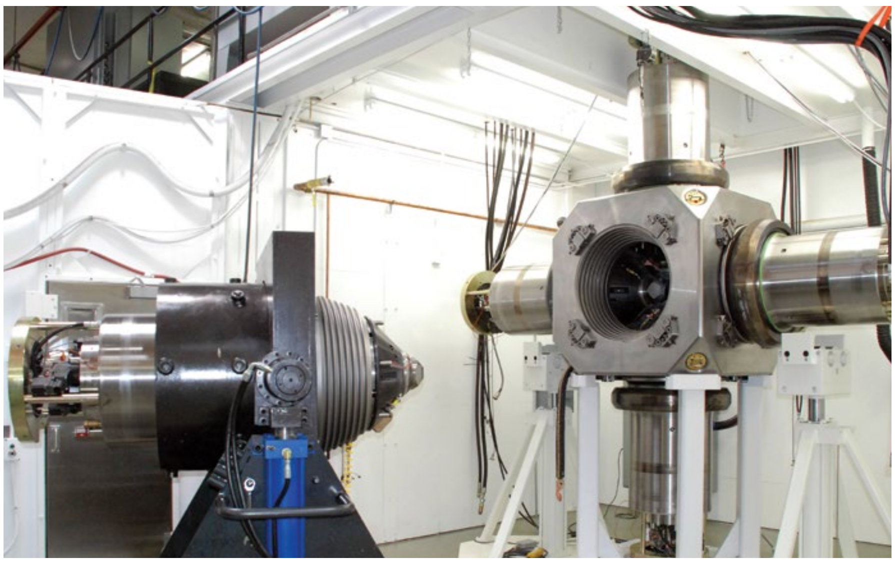

Photo credit: Sky Evans

Novatek's 4,000-ton super-material production Press is powered by a 125 cc Rexroth DFEn variable displacement pump, driven by a 100 HP VFD controlled AC motor.

Challenge:

Create hydraulic and electro-hydraulic machines that are energy efficient, quiet, inexpensive, fast and precise by using variable-speed hydraulic components

Rexroth Solution:

- Variable-speed pump drives
- Variable displacement pumps
- Combined electro-hydraulic systems

Key Insights & Considerations:

- Electro-hydraulic systems combine the advantages of both traditional hydraulics and electric drives, including robustness, power density, drive intelligence and ease of integration with factory automation systems
- Variable-speed pumps and drives reduce energy demand and improve efficiency
- Internal gear or piston pumps provide high efficiency, low flow ripple, low mechanical inertia and high pressure
- Axial piston pumps have high efficiency at low drive speeds

Faster, cheaper, quieter, more precise, more robust and, last but not least, more energy efficient—this is a typical wish list a machine builder gets from a customer. It is not hard to imagine that design engineers are often wracking their brains to fulfill all of these often contradictory requirements. In recent years, tremendous progress in the machine design and control methods has been observed. One of the main changes is the migration of drive technology from the fluid power to "full electric" solutions. As a result, electro-mechanical actuators, featuring high efficiency, ease of integration and high precision, are replacing traditional hydraulics. The absence of hydraulic fluid and the associated maintenance is an added feature. Nevertheless, electro-hydraulic drives are still indispensable when large forces and high torques are required. The well-known advantages of fluid power include high power density, robustness and simple realization of fast linear movements under load. These features help hydraulics win the battle against electro-mechanical servo drives. This is especially true in key market segments, i.e., plastic machinery, stamping and forming presses, metallurgy, testing machinery, and other “heavy duty applications.”

The current trend of “electrification” in industrial machinery has also influenced the landscape of fluid power with the introduction of variable frequency drives (VFDs) and servo drives to replace traditional fixed speed AC motors. The combination of advanced electric drive technology coupled with hydraulics opens a new chapter in electro-hydraulic drive systems. Machine builders can now maintain characteristics of “traditional hydraulics,” robustness and power density, while acquiring advantages of electric drives: drive “intelligence” and ease of integration with factory automation systems. Additionally, adjusting the pump speed to the demanded flow provides an increase in energy efficiency and dramatically reduces the audible noise and sound pressure level, especially during part-load operations when less than maximum pump flow is required.

Look for system inefficiencies

When analyzing the energy efficiency of the overall system, the machine’s duty cycle and its hydraulic and electric operating points need to be reviewed. The relationship between hydraulic and electric process variables should be carefully evaluated. Pump pressure and flow (motor speed) correlate to the drive’s motor torque (resulting from drive current) and should be examined. Electrical engineers typically understand machine load as the motor torque and the machine speed as drive speed, while fluid power engineers operate in pressure and flow units. The difference in how we define the machine motion using motor torque and speed as

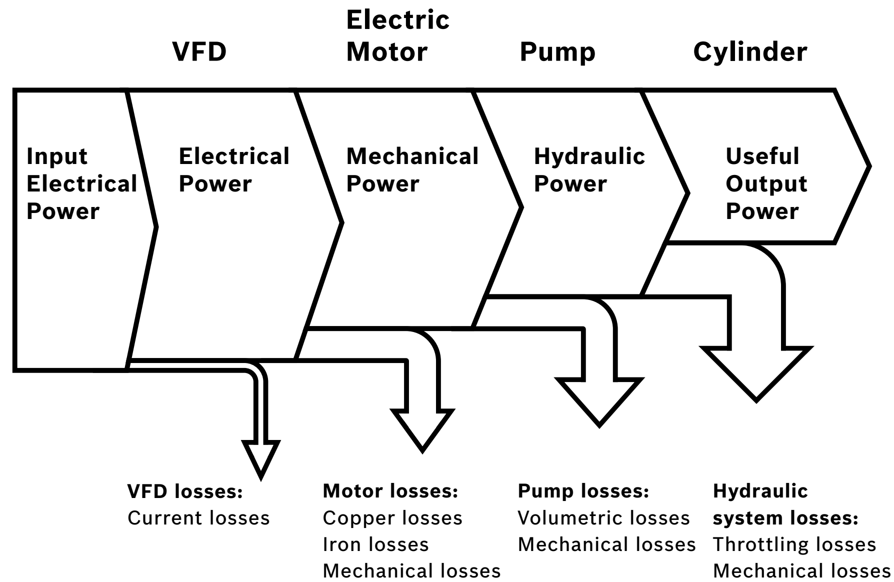

Figure 1: Energy losses in hydraulic systems.

compared to pump pressure and flow should be understood. Often these different terms lead to communication issues between electrical and fluid power specialists who are sizing the system and its components. Luckily, the hydraulic and electric values can be easily correlated using a few simple formulas.

The relationship between pump pressure and motor loading torque is expressed as:

$$M_L = \frac{V_P \cdot \Delta p}{24 \cdot \pi \cdot \eta_{mech}} \quad \text{(lb-ft)}$$

and the pump speed is defined as:

$$n = \frac{Q \cdot 231}{V_P \cdot \eta_{vol}} \quad \text{(rpm)}$$

where:

Δp=Pressure differential in psi,
V_P=pump displacement per revolution in in^3,
Q=pump flow in gpm and
η_{mech} and η_{vol}=pump mechanical and volumetric efficiency.

The resulting power that needs to be delivered to the pump is therefore calculated as:

$$P = \frac{n \cdot M_L}{5252 \cdot \eta_P} = \frac{\Delta p \cdot (V_P/231)}{1714 \cdot \eta_P} * RPM \text{ (HP)}$$

overall pump efficiency $\eta_P=\eta_{vol}\cdot\eta_{mech}$

When calculating the electrical input power for a motor-pump group, the efficiency of the motor, η_{mot} should be considered: $\eta_T=\eta_P\cdot\eta_{mot}$

While the calculations appear to be straightforward, in reality, calculating the overall efficiency of a motor-pump group can be a tedious task, because most power losses are the result of many variables.

Efficiency of a variable displacement pump is primarily a function of three variables: pump pressure, speed and displacement (pump stroke). Generally, the efficiency of the variable displacement pump is higher when the pump operates at a greater displacement. The losses in a

VFD + AC motor	Servo PM motor fixed pump	VFD + AC motor variable displacement pump
Basic dynamics	**High dynamics**	**High dynamics & high power**
		
• Pressure and flow control	• Pressure and flow control • Force and velocity control • Position control	• Pressure and flow control • Power control

Figure 2: Dynamic performance of a variable-speed system depends on the motor type, size and pump type. Pump and motor selection should be tailored to the application.

pump are divided into volumetric and mechanical losses. Volumetric losses are a function of the pump's internal leakage; the dissipated power is a product of leakage flow, Q_L and the pump's differential pressure, $P_L=\Delta p\cdot Q_L$. Pump mechanical losses are the product of frictional torque and drive speed: $P_{Fr}=n\cdot M_{Fr}$.

The electrical losses for the drive motor are divided between copper losses and iron losses. The iron losses are approximately proportional to the motor's drive frequency, and therefore its speed: $P_{Fe}\sim n$, which also correlates to pump flow. Copper losses in the drive motor result from resistance in the windings and are proportional to the square of the motor current: $P_{Cu}\sim I^2$; current is proportional to torque.

When a VFD is used to drive the motor, current losses in the VFD electronics are typically proportional to motor current: $P_I\sim I$.

Motor current is a function of motor torque, $I\sim M_L$, which is directly related to pump pressure and displacement, and thus the electric losses depend directly on the hydraulic operating point.

Analysis of the above relations between hydraulic flow and pressure, hydraulic output power, system power losses and the resulting input electric power shows that power consumption of a hydraulic power unit can be reduced by:

1. Using higher efficiency components, e.g., premium efficiency AC motors or permanent magnet servos rather than standard AC motors and pumps with higher volumetric efficiency, and keeping components well maintained.
2. Sizing and utilizing the system so that the working points for most of the operating cycle are at the highest efficiency point for the hydraulic pump and electric motor. This can be achieved by adjusting the pump's displacement and pump speed to match the flow requirements while keeping load on the drive at a "sweet spot of efficiency."
3. Reducing hydraulic throttling losses by operating the pump at lower pressure which can reduce the overall power requirement. This, however, may reduce controllability of the hydraulics in some systems. Eliminate the use of proportional valves and other traditional throttling control methods by using more efficient volumetric control, where flow is controlled by changing the pump drive speed and/or adjusting the displacement of the pump. All pressure reducing and flow throttling valves are resistive components which reduce

overall efficiency. By reducing throttling losses, the amount of heat transferred to the oil is reduced. Reduced heating allows for smaller cooling system capacity and lowers the parasitic power needed to maintain optimum oil temperature.

A properly designed variable-speed pump system can satisfy all of above points.

System considerations

For optimal utilization of variable-speed pump drives, design engineers need to understand the unique features of VFDs, hydraulic systems and the properties of the process being driven. In many cases, further elimination of throttling losses may require a review of the system design, and modifications to a hydraulic system design may be required.

The goal is to have a system that meets the dynamic requirements and accuracy, but that also focuses on overall energy efficiency. When applying a VFD/induction motor or a permanent magnet servo motor (PMM) as a pump drive, the dynamic behavior will differ from a traditional system using a constant-speed pump drive and throttling control valves.

A number of different design solutions can be applied to systems using variable-speed pump drives. Selection of the best (or correct) design depends on a number of factors. Dynamic performance and power requirements can determine the choice of the motor type. For applications requiring the fastest response times and high accuracies, a PMM is often the best solution. This technology is used extensively today in plastic injection molding machines. These drive systems offer extremely high performance and high productivity rates.

Due to their high power density and low mechanical inertia, PMMs have the highest acceleration capabilities. The high dynamics allow for complex machine control tasks, such as force, speed and cylinder position control, to be realized without using hydraulic proportional valves. The main limitation of PMM drives is the maximum continuous output power, typically less than 60kW. Power units requiring output power higher than 60kW may require multiple PMM pump units.

Standard asynchronous induction motors driven with VFDs can be used in higher power applications, where direct control of high dynamic axes is not required. Using standard motors with VFDs, operating in a sensorless vector control mode (no separate motor feedback device required), can offer a cost-effective solution. However, the system designer should be aware of the limitations when using these drives.

System response times are longer due to the high mechanical inertia of the induction motor. Variable-speed pump drives, using standard induction motors and VFDs, are widely used in woodworking; press forming; and stamping presses, plastics machinery, heavy industry and machine tool cutting applications where the control requirements are typically regulating system pressure or flow.

When selecting a pump for variable-speed operation, several additional factors beyond pressure and power must be considered. Unique requirements, not usually considered in conventional designs, such as drive speed and acceleration rates of the pump's rotating elements, must be reviewed. Internal gear or piston pumps are commonly used with variable-speed drives. Internal gear pumps are characterized by high efficiency, low flow ripple, low mechanical inertia and high pressure capability. As a result of these features, they are often the pump of choice when driven by PMMs on injection molding machines. Limitations of internal gear pumps

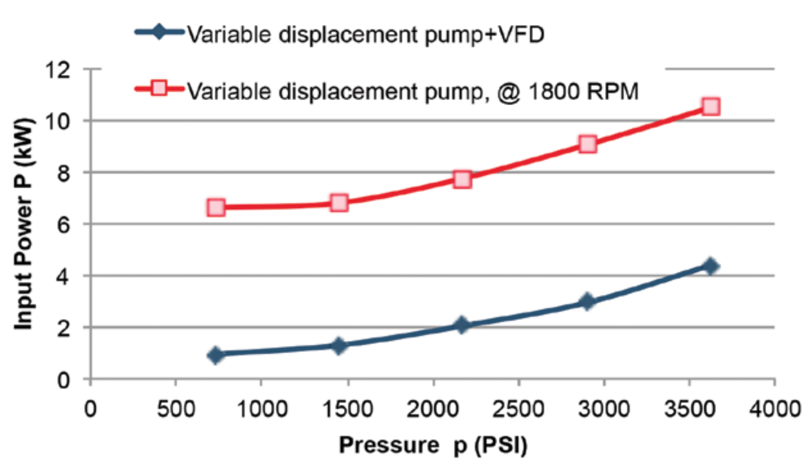

Figure 3: Measured HPU's energy consumption during pressure holding operation (Q=0 GPM). Measured for 125 cc Rexroth DFEn variable displacement pump, driven by a 100 HP NEMA premium, VFD controlled AC motor.

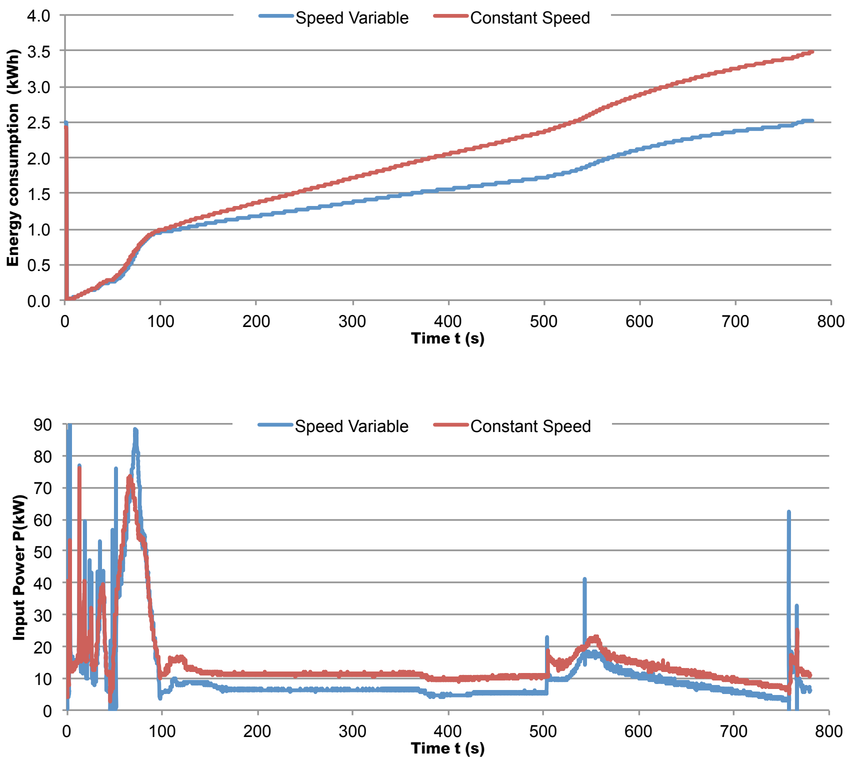

Figure 4: Measured, energy demand and power comparison of the hydraulic drive during an 800 second long press cycle, with the pump operating in both variable- and constant-speed modes.

include a fixed displacement and the requirement of a minimum drive speed when supplying low flow at high pressure.

Axial piston pumps, either fixed or variable displacement, have the advantage of high efficiency at low drive speeds, making them ideal for pressure holding over long operating cycles. Using a variable displacement piston pump allows for adjustment of pressure, the pump displacement and motor speed (torque and speed) to optimal working points, thereby minimizing electric, hydraulic and mechanical losses. Additionally, VFD current and motor copper loses can also be reduced by optimal drive speed and displacement adjustments. Figure 3 presents energy consumption of a variable displacement pump during pressure holding, when operating in both variable- and constant-speed modes. The measurement shows that the energy consumption during variable-speed operation is affected mainly by pressure dependent volumetric losses in the pump, while increasing the pressure had little effect on the current related losses in the VFD and motor.

A high-response variable displacement pump, utilizing closed loop displacement control such as Rexroth's DFEn, can compensate for the relatively low dynamics of a VFD/induction motor drive. Because the pump displacement control can respond a magnitude faster than the motor drive speed control, high control dynamics can be achieved. This is a significant advantage when used in high-horsepower hydraulic drives.

Variable-speed pump for 4,000-ton super-material production press

An application of a "Smart VFD controlled pump" is on a hydraulic power unit for a 4,000-ton solid frame super-material press, designed by Novatek Inc., of Provo, UT. Novatek plays a leading role in the field of high-pressure, high-temperature materials engineering. The press features a cubic base with six cylindrical cartridges, each tipped with tungsten carbide tooling. A work piece, which is a cell containing raw material, is placed in the center of the press. Inside the press, raw materials are subject to extreme pressure and temperature, similar to those found deep within the earth. Chemical and mechanical transformations of the raw material require a certain time until the process is completed. This production process can take several minutes or up to hours, depending on the materials to be processed and size of the work piece.

Hydraulic presses that have long cure or forming times can benefit by using variable-speed pump drives. This is especially true when high forces are required, but little movement (flow) is needed. During pressure holding, adjusting the pump's speed and displacement results in significant energy savings as well as greatly reduced system acoustic noise. Measured noise reductions between 10-15 dB(A) were realized as a result of variable-speed pump drives on this application.

Novatek's solid frame press is powered by a 125 cc Rexroth DFEn variable displacement pump, driven by a 100 HP VFD controlled AC motor.

Bosch Rexroth and Womack Machine Supply teamed together to specify the right components for the application. Womack's long-standing relationship with Novatek and working knowledge of the application was critical to implementing this technology.

Figure 4 shows the energy comparison of the hydraulic drive during an 800 second long press cycle, with the pump operating in both variable- and constant-speed modes. Lowering the speed during long pressure holding considerably lowers the energy demand.

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