Performance and Efficiency Aspects for Hydraulic System with LS Valve

PhD. Eng. **Fănel ȘCHEAUA**[1,*]

[1] "Dunarea de Jos" University of Galati, MECMET Research Center

* fanel.scheaua@ugal.ro

Abstract: *Hydraulic volumetric units are critical hydro-dynamical components in fluid transport systems across various industries and advancements in their performance and efficiency have become a key focus for energy conservation and operational optimization. Recent trends emphasize variable speed control, allowing pumps to adjust their speed dynamically through variable frequency drives (VFD) to match system demands, thereby reducing energy waste. Additionally, the integration of LS valve within the system, smart monitoring and predictive maintenance is enhancing real-time operation efficiency and failure prevention.*

Numerical simulations and experimental research are playing a pivotal role in optimizing hydraulic efficiency, leading to lower frictional losses and improved performance across diverse operating conditions. Furthermore, energy recovery systems, such as regenerative pumps and pressure exchanger technology, are being increasingly implemented to minimize energy consumption in industrial and water distribution applications.

Material innovations, including advanced coatings and wear-resistant materials, are also reducing cavitation and extending pump lifespan. The push towards sustainable pumping solutions, such as solar-powered and hybrid energy-driven pumps, is gaining momentum in response to environmental concerns. As industries shift towards AI-driven system optimization, real-time adaptive control mechanisms are expected to further enhance units efficiency, reduce downtime and lower costs. These trends indicate a future where hydraulic systems are more intelligent, adaptive energy-efficient, aligning with global efforts for sustainable industrial operations.

Keywords: *Hydraulic actuation, volumetric unit, LS valve, efficiency, numerical analysis*

1. Introduction

Pump performance and efficiency represents crucial aspects in hydraulic machines, as optimizing pump performance can lead to significant energy savings, improved reliability and longer equipment life.

Traditional pump units operation is achieved at constant velocity, even when the system doesn't require full capacity. This situation can be resolved using variable frequency drives (VFD) in order to control pump momentum velocity based on system demands, while this option is drastically improving efficiency values in operation.

The use of VFD combined with real-time monitoring and predictive algorithms to adjust pump velocity, pressure and flow rate values to the specific needs of the system represents a recent trend solution in the field.

Energy efficiency trends in pumping systems are directed toward to improvements in pumps efficiency by designing systems able to minimize energy losses, while this includes using more efficient pump impeller designs, improving motor efficiency and reducing friction losses in pipes.

The recent research activities and studies are showing the raising use of more aerodynamic impellers, optimized geometries and materials that can improve energy consumption, while additionally integrating energy recovery systems can help to reduce the need for external power.

Pump efficiency curves are used to identify the performance of pumps under various operating conditions. Knowing how to read and interpret these maps allows operators to select the most efficient pumps for their system.

New algorithms and software for dynamic pump performance mapping are allowing for real-time analysis and adjustments based on live data from sensors. Some systems now even use AI-based predictions to adjust pump operation for maximum efficiency.

Hydraulic losses (due to friction, turbulence, etc.) and mechanical losses (bearing friction and seal drag) can significantly reduce efficiency, while understanding and mitigating methods for these losses through improved designs and materials is a growing focus.

The use of advanced coatings, low-friction materials and design optimization (such as better shaft designs) is improving mechanical efficiency and further, based on advancements in CFD (computational fluid dynamics), better understanding and reduction of hydraulic losses are allowed.
Pump systems often consist of multiple pumps working together in a larger circuit network and the overall system efficiency depends not just on the pumps themselves but also on how they interact with each other and the surrounding infrastructure.
The Load Sensing valve brings significant advantages in hydraulic systems, particularly in terms of efficiency, cost savings, and system longevity. By dynamically adjusting the system's pressure and flow rate values in order to match the load demand, the LS valve reduces energy consumption, improves fuel efficiency, minimizes heat generation and wears on components, provides precise load control and enhances system performance and responsiveness.
These benefits make the LS valve a crucial component in modern hydraulic systems, particularly in mobile equipment, manufacturing, and industrial machinery, while it optimizes system performance at the same time as reducing operational costs and environmental impact.

2. Parametric models for volumetric unit’s performance and efficiency

Volumetric units, such as positive displacement pumps, compressors or hydraulic actuators, play a critical role in fluid power and energy conversion systems. Unlike dynamic pumps, volumetric machines operate by displacing a fixed amount of fluid per cycle, making their performance highly dependent on parameters such as displacement volume, rotational velocity, leakage losses and mechanical friction. Parametric modeling provides a systematic approach to analyze and optimize the efficiency and performance of these machines by correlating key design and operational variables.
The parametric model defines the relationship between input variables such as pressure, flow rate, rotational speed and temperature) and output performance metrics related to efficiency, power consumption and volumetric losses [1-3].
For hydraulic pumps, the flow rate and pressure are the composing parameters of the dynamic model and the approach is based on a model that accounts for the system's response to changing input conditions [1-7]:

$$\frac{dp(t)}{dt}=\frac{Q(t)\cdot R}{V_f} \tag{1}$$

where:
$\frac{dp(t)}{dt}$ - the pressure rate of change in the pump chamber;
Q(t) - the flow rate into the pump;
R - the system resistance (dependent on factors like pipe size, friction and valve settings);
V_f - the fluid volume inside the pump.
For hydraulic rotary motors, the output torque and rotational velocity are influenced by the pressure applied to the motor and the flow rate:

$$T(t)=k\cdot p(t)\cdot V_d \tag{2}$$

where:
k - a constant that accounts for motor efficiency and other losses;
p(t) - the pressure applied to the engine;
V_d - the motor displacement (fluid volume displaced per revolution).

$$N(t)=\frac{Q(t)}{V_d} \tag{3}$$

$$\frac{dN(t)}{dt}=\frac{T(t)-T_l}{J} \tag{4}$$

$$\frac{dN(t)}{dt}=\frac{k\cdot p(t)\cdot V_d-T_l}{J} \tag{5}$$

$\frac{dN(t)}{dt}$ - the angular acceleration of the motor;
T(t) - is the torque applied by the fluid pressure;
T_l - the external load torque;
J - the moment of inertia of the motor (a constant depending on the motor's design).

The efficiency model reflects how well the motor converts hydraulic power (input power) into mechanical power (output power), being defined as [5-9]:

$$\eta(t)=\frac{P_o(t)}{P_i(t)}=\frac{T(t)\cdot N(t)}{P(t)\cdot Q(t)} \tag{6}$$

The fluid flow rate *Q(t)* is related to the motor velocity *N(t)* by:

$$Q(t)=V_d\cdot N(t) \tag{7}$$

The energy model is the integral of power over time. The total energy supplied or consumed by the motor can be calculated as:

$$E=\int_{t_1}^{t_2}P_m(t)dt \tag{8}$$

where:

E - total energy;
P_m - instantaneous power supplied or consumed by the motor.

A LS valve mounted at the working circuit adjusts the system pressure based on the load. The pressure setting for the LS valve is typically a function of the load demand and is calculated as [10-13]:

$$p_{LS}=p+\Delta p \tag{9}$$

where:

p_{LS} - pressure set by the LS valve;
p - current load pressure demand;
Δp - low differential pressure to account for system losses and ensure operation at the optimal pressure.

The LS valve ensures the pump's output correlation with the load's pressure demand without producing excessive pressure, which would waste energy.

The LS valve also helps regulate the flow rate to match the load, often through proportional control or using a flow divider. The flow adjustment equation can be represented as [10-13]:

$$Q_{LS}=Q_d \tag{10}$$

where:

Q_{LS} - flow rate adjusted by the LS valve;
Q_d - flow rate required by the load.

In this way, the LS valve modulates the flow rate based on the load's requirements, ensuring the pump does not produce more flow than needed, which would otherwise lead to energy wastage.

The equation for instantaneous power is derived from the relationship between pressure, flow rate, and motor efficiency. The LS valve helps adjust these parameters to ensure that the system operates more efficiently minimizing wasted energy and reducing the power requirements during periods of low load [7-14].

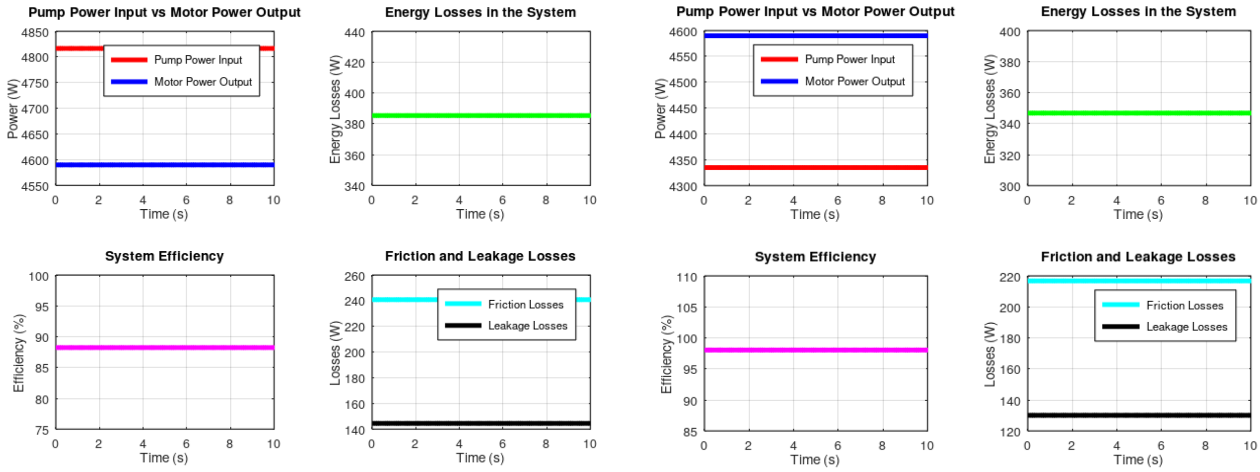
3. Efficiency system results with parameter modification depending on the output requirements

Considering the basic parameters for a hydraulic system model, the operating situation in the configuration with and without the LS system is analyzed in order to highlight the performance results achieved and to be able to describe the efficiency of the system.
The parameters of the initial and final states that are taken into account are presented in table 1.

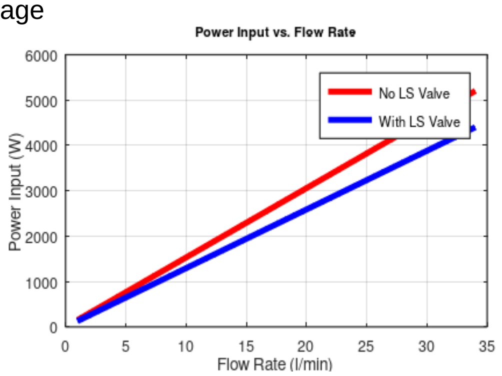
Table 1: Parameters for hydraulic volumetric units components

Parameter	Initial Stage (No LS Valve)	Final Stage (With LS Valve)	Unit	Description
Pump pressure (P_max)	130 Constant value	90-130 Variable, adjusted based on load	bar	Pressure provided by the pump
Pump Pressure (P_min)	50 Constant, fixed at minimum	50-90 Variable, adjusted based on load	bar	Minimum pump pressure
Pump Flow Rate (Q_max)	34 Constant, fixed flow	Variable, adjusts to match motor demand	l/min	Flow rate provided by the pump
Motor Pressure	90 Constant, set pressure	Matches pump output as controlled by LS valve	bar	Pressure required by the motor; varies with LS valve operation
Motor Flow Rate	34 Constant, set flow	Matches pump output as controlled by LS valve	l/min	Flow rate required by the motor; varies with LS valve operation
Pump Efficiency (η_pump)	85	85	%	Pump efficiency
Motor Efficiency (η_motor)	90	90	%	Motor efficiency
Friction Losses	5% of pump input Fixed, based on constant high pressure	Reduced due to lower pressures and variable flow rates	W	Friction losses reduced with LS valve optimization
Leakage Losses	3% of pump input Fixed, based on constant high pressure	Reduced due to lower pressures and variable flow rates	W	Leakage losses; reduced with LS valve optimization
Energy Losses	Higher, due to constant high pressure and fixed flow rate	Reduced, thanks to dynamic pressure and flow optimization	W	Total energy losses decreased with LS valve optimization
System Efficiency	Lower, 40-50% inefficient operation due to fixed high pressure	Higher, 70-80% optimized operation with LS valve	%	System efficiency significantly improved with LS valve
Motor Power Output	Dependent on the fixed pressure and flow	Optimized to match pump output based on load demand	W	Power delivered to the motor optimized with LS valve
Pump Power Input	Constant, fixed power consumption based on max pressure	Reduced power consumption, adjusted by LS valve based on load	W	Power input to the pump reduced with LS valve optimization

The characteristics between the working operation conditions are presented, while the advantages of introducing the LS solution are evident as highlighted in the numerical results in Figure 1. The defining advantages are related to losses reduction, counted with less friction and leakage values due to dynamic pressure regulation, higher system efficiency that is improved up to 80 % and improved motor operation control through lower pressure values dynamically adjusted according to real demands.



a) Initial stage b) Final stage



c) Power input function of flow rate values

Fig. 1. Analysis efficiency results

The results are presented in comparative terms of input and output power, efficiency over time and losses over time of the system for the two cases considered, as well as power as a function of the working fluid flow rate. The advantages of using the LS system for operation are visible because optimizations of the values of the parameters involved are obtained.

4. Conclusions

Based on the numerical analysis results, it is obvious the high impact of the Load Sensing (LS) operation valve on a hydraulic system. Without the LS, the system operates with a constant high pressure and fixed flow rate values, which results in low system efficiency. This inefficiency stems from excessive power consumption that does not align with real conditions load demands.
With the LS valve, the system dynamically adjusts the pressure and flow rate values based on the load, which results in significantly higher system efficiency. This dynamic operation helps avoid unnecessary power use and optimizes the system to match the exact load requirements, improving overall performance.
While the LS valve allows the system to adjust its power input based on the real load is leading to energy consumption reduction and is evident on the result plots, where the system with the LS valve consumes less power for the same flow rate and further the power input decreases as the flow rate decreases.
Without the LS valve, the pump operates at maximum power even when it's not required, leading to higher energy consumption and wasted energy. Energy losses from friction and leakage are significantly reduced with the LS valve as seen on obtained numerical results. The system with the LS valve operates at lower pressures and adjusts flow rate dynamically, resulting in lower friction and leakage losses compared to the constant high pressure system without the LS valve.
These reduced losses directly contribute to the higher system efficiency in the final state (with LS valve).

The LS valve optimizes both flow rate and pressure, ensuring that the system operates only at the levels needed for the current load. This avoids over-pressurizing the system and provides a much more efficient operation.

Without the LS valve, the system runs at fixed parameters that often exceed the needs of the load, resulting in wasted resources and inefficiencies.

The dynamic adjustments enabled by the LS valve allow the system to maintain optimized performance across a range of load conditions. In contrast, the system without the LS valve struggles with less flexibility and efficiency under variable loads.

The addition of a Load Sensing (LS) valve significantly enhances the hydraulic system's efficiency and performance, by dynamically adjusting the system's pressure and flow rate based on the load requirements, leading to lower energy consumption, maximize energy efficiency, reduce operational costs and extend the lifespan of system components.

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