Research Paper Engineering

Maximum Efficiency Control – A New Strategy To Control Electrohydraulic Systems

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ABSTRACT

One of the most wanted goals on all fields of research is improvement of machines' energy efficiency and electrohydraulic systems are no exception. Improvements of the control concepts can result in quite substantial energy savings. Equipping an electrohydraulic machine with a variable frequency drive controller and a variable displacement pumpgives an additional degree of freedom, whichenables maximum efficiency tracking for all operating points. Controlling such combination with a new control strategy called maximum efficiency control ensures that the pump always operates optimally. The presented maximum efficiency controller calculates the optimal pump setting (displacement, rotational speed) for each operating point (pressure, flow). Therefore, the electrohydraulic system is able to convert electrical energy to hydraulic energy with minimum losses. The following article presents the basic concept of the maximum efficiency controller. Furthermore it uses experiment to compare the maximum efficiency controller with other existing electrohydraulic drive concepts, such as a variable pump coupled with motor running at constant rotational speed and a fixed displacement pump driven by a speed controlled electromotor.

KEYWORDS efficiency, maximum efficiency control, simulation, measurement, variable frequency drive, variable displacement pump, fixed displacement pump

INTRODUCTION

The modern development tendencies in the direction of environmentally user-friendly drives and directives on the reduction of the noise are leading to more complex control concepts and solution in electrohydraulic drive technology. This is especially important in areas where higher energy density is required as well as in the segment of machinery and equipment that operates continuously, autonomously, at remote sites and without the presence or supervision of the maintenance staff.

Machines that require big forces for their operation are mainly powered by electrohydraulic drives. Big forces especially when combined with high speeds result in high power requirements that reflect in high-energy consumption. Even the slightest (at the percentage level) optimizations regarding the energy efficiency of such machines results in significant savings over long operating periods. Therefore, improved efficiency and reduced energy consumption are two of the main goals during the design period of modern electrohydraulic systems.

This paper will present state of the art in the field of electrohydraulic drives, which will be followed by a detailed explanation of the newmaximum efficiency controller. All the existing electrohydraulic drive concepts will be presented and experimentally compared in terms of efficiency and dynamic responses.

STATE OF THE ART

Most of the energy in electrohydraulic drives is wasted in the electrical to hydraulic energy conversion stage. In general there are two main ways of controlling hydraulic energy:

- the throttling principle (by throttling on a directional valve)
- the volumetric principle (by adjusting the displacement volume of the pump)

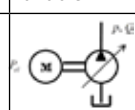
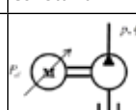
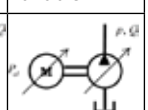
The throttling principle displays good dynamic behaviour, but its energy losses are substantial, because all the excess energy not consumed by the hydraulic part of the system is wasted on the valve [1]. The volumetric principle is more energy-friendlier but has slower dynamic response[2]. Due to its better energy efficiency, the volumetric principle is mostly used nowadays.

The pumps displacement can be adjusted with two different approaches:

- the direct approach (by changing pump's displacement physically)
- the indirect approach (by changing pump's rotational speed)

Because there are three different drive concepts available all of them should be considered when designing an electrohydraulic system. Table 1 shows a comparison between all of the known drive concepts: variable pump and constant motor (C1), constant pump and variable speed drive (C2) as well as variable pump and variable speed drive (C3).[3]

TABLE – 1 COMPARISON OF DIFFERENT ELECTROHYDRAULIC DRIVE CONCEPTS[3]

	Concept 1 (C1): Asynchronous Motor Variable Axial Piston Pump	Concept 2 (C2): Variable Frequency Drive Controller Asynchronous Motor Constant Gear Pump	Concept 3 (C3): Variable Frequency Drive Controller Asynchronous Motor Variable Axial Piston Pump
pump'srotational speed	constant	variable	variable
pump's displacement	variable	constant	variable
scheme			
efficiency	lower	higher	highest
reliability	high	high	high
operating costs	highest	higher	lower

system dynamics	highest 4.4	low 1	control principle dependant (approx. 4)
purchase price	higher	lower	highest

C2 has asserted itself mainly due to good efficiency and a wide operating range [4]. It also excels at lower operating costs and consecutively smaller effects on the environment. Lower operating costs and higher efficiency have come mainly from a more efficient connection of the motor to the electrical grid – via a variable-frequency drive controller [5]. However, C2 also has one major drawback – a slow system response that occurs due to rotating parts' moment of inertia (motor rotor and rotary parts of the pump). The response of C1 is up to 5 times faster than the response of C2 [6], but both responses are good enough for the most hydraulic applications [7,1]. The response of C3 highly depends on the control type and amplitude of the pressure error [8]. If higher efficiency is pursued the dynamic response of C3 is generally lower than C1, but still about 4 times higher than C2 [9]. The biggest drawback of C3 is the highest purchase price among the all concepts, because a variable frequency drive controller and a variable displacement pump are needed, where the variable displacement pump is the most expensive piece of the required components [10].

Because C3 has an additional degree of freedom, it requires a robust SIMO (single input multiple output) controller. This is one of the main reasons why C3 is not used in electrohydraulic systems yet. There are not many control strategies for such a control problem.For repeatable machine cycles a model predictive controller can be effectively used[11], but because many machines do not have defined cycles (excavators, cranes,…)such controller is useless. Therefore a new control strategy has been developed, which can utilize the additional degree of freedom of C3 to track maximum efficiency – the maximum efficiency controller.

THE MAXIMUM EFFICIENCY CONTROLLER

The maximum efficiency controller which is based on a combination of a look-up table and a classic PID controller can be used to effectively control C3. A scheme of the maximum efficiency controller is shown in Figure 1, and will be described in detail in the next subsections.

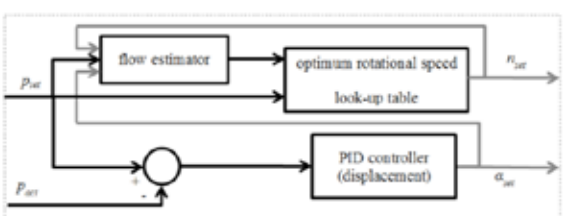


Figure 1: Block diagram of the maximum efficiency controller

The PID Controller

The PID controller is used to control the displacement of the axial piston pump. The advantages of using a PID controller for displacement control are elimination of steady state error, fast response to rapid pressure changes and ability to track pressure when rotational speed of the motor is changing to the optimum.

The Look-up Table

The »intelligent« part of the maximum efficiency controller is hidden in a three-dimensional look-up table. The first two dimensions represent the operating point of the machine (pressure, flow) and the third – resulting dimension is the optimal rotational speed for the chosen operating point. As most of the hydraulic machinery is not equipped with a flow sensor the flow is estimated from the pump setting and its rotational speed.

The look-up table is created during the final testing stage of the electrohydraulic drive production (variable frequency drive controller, motor and variable displacement pump). An electrical power meter is connected between the machine and electrical power grid to measure electrical input power. To measure hydraulic output power a flow and a pressure sensor are installed after the pump. Moreover a proportional valve is added to the hydraulic circuit to simulate different loads. Input and output power is then measured for all the operating points – pressure and flow combinations, where flow is created by different rotational speed and pump settings. In this case we obtain a five dimensional mesh (1) of efficiency versus pressure (p), flow (Q), rotational speed (n) and pump setting (α). If pump's volumetric losses are neglected, a further simplification of the mesh can be made. Because flow is proportional to product of pump's rotational speed, pump setting (2) and pumps maximum displacement, the pump setting can be eliminated from the mesh due to one dimension redundancy. This yields the final measurement result of a four dimensional mesh (Figure 2).

$$\eta(p,Q,n)=\frac{P_{hydr}(p,Q,n)}{P_{el}(p,Q,n)} \quad \textbf{(1)}$$

$$Q=n\cdot\alpha\cdot V_g \quad \textbf{(2)}$$

The resulting mesh must be inverted and redimensioned in order to become useful for a look-up table. For each pressure and flow combination the optimal rotational speed (rotational speed that results in maximum efficiency) (n_{best}) is chosen. This process eliminates another dimension and makes the look-up table useful for control (3). Such look-up table may be presented using a three dimensional mesh as shown in Figure 3.

$$n_{best} \quad n(p,Q) \quad \textbf{(3)}$$

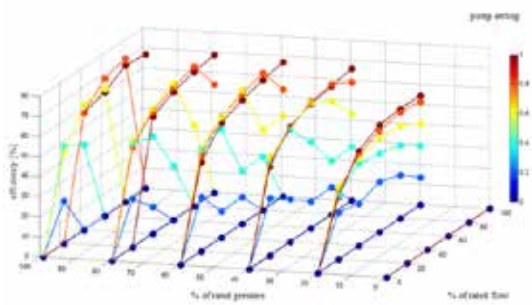


Figure 2: Efficiency of the electrohydraulic drive with a variable piston pump vs. pressure, flow and pump setting

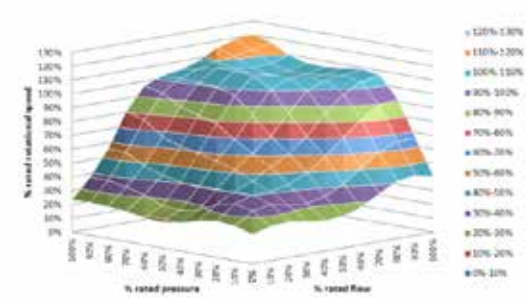


Figure 3: Rotational speed that results in maximum efficiency of the drive vs. the operating point (pressure and flow) – used as a look-up table for the maximum efficiency controller

EXPERIMENTAL SETUP

A test-stand was built to test efficiencies of all of the drive concepts. Block diagrams are shown in Figure 4. The block diagram of the experimental setup of C1 consists of an asynchronous motor (ASM) directly connected to grid, a variable displacement axial piston pump, and ideal variable hydraulic load; C2 consists of a variable-frequency drive controller with

an ASM connected to it, a fixed displacement internal gear pump, and hydraulic load; C3 consists of a variable-frequency drive controller with an ASM connected to it, a variable displacement axial piston pump, and hydraulic load. C3 can be controlled straight-forward by using two PID controllers or using maximum efficiency controller (C3-ME).

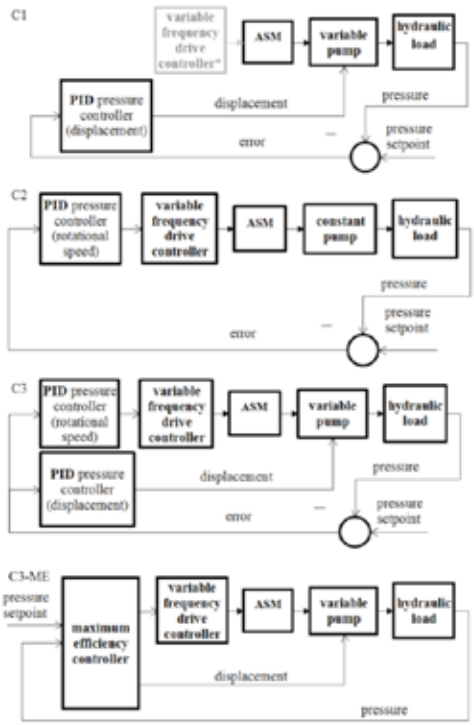


Figure 4: Block diagrams of all three concepts

The variable frequency drive controller used is a Siemens MIDIMASTER Vector 6SE32. Its main features are SVC (Sensorless Vector Control) and analogue input for rotational speed set point. It is used to power Siemens 1LA7 166-4AA60 15kW asynchronous motor. The motor is coupled to either Bosch-Rexroth PGF3-31/032RE07VE4 fixed displacement internal gear pump or Mannesmann-Rexroth A10VSO-28 variable displacement axial piston pump. Proportional directional valve DBEM10-51/200YG24K4M by Bosch-Rexroth is used as a variable hydraulic load.

EXPERIMENTAL RESULTS

All the concepts were tested using a combined pressure cycle which consists of a step, ramp and a sine. Pressure, flow and energy consumption was measured during the test. The concepts performed similarly at following the combined pressure cycle as shown in figure 5, where pressure set point is shown in blue, response of C1 in red, C2 in green and violet, C3 in light blue and C3-ME in orange.

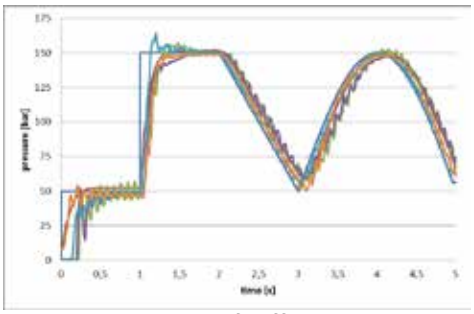


Figure 5: Responses of different concepts to combined cycle

In order to make the concepts more comparable a weighted average of average efficiency, used electrical energy, produced hydraulic energy, root mean square error, settling time and overshoot were calculated. The weights are shown in table 2.

TABLE – 2 WEIGHTS USED FOR AVERAGE RESULT CALCULATION

category	energy			dynamics			
weight	60%			40%			
criterion	average efficiency	used electrical energy	produced hydraulic energy	RMSE	RMSE sine	settling time	overshoot
weights by category	50%	30%	20%	60%	20%	10%	10%
final weights	30%	18%	12%	24%	8%	4%	4%

All the experimental results are collected in table 3, where best performer in each category is marked with bold. It can be seen, that the maximum efficiency controlled concept performs better in terms of energy efficiency than all the other concepts which use the variable frequency drive controller (C2 and C3). Because C1 does not use the variable frequency drive controller its efficiency is better than efficiency of all the other drive concepts.

TABLE – 3 EXPERIMENTAL RESULTS

concept	average efficiency	used electrical energy [kJ]	produced hydraulic energy [kJ]	RMSE [bar]	RMSE sine [bar]	settling time [s]	overshoot [bar]	average result
C1	57,7 %	46,2	26,7	12,55	8,10	0,22	1,63	94,0 %
C2	56,9 %	45,4	25,8	21,22	14,42	0,28	7,07	79,7 %
C3	53,6 %	47,5	25,5	14,49	4,45	0,13	14,00	89,3 %
C3-ME	57,4 %	45,4	26,0	16,68	8,28	0,28	0	87,8 %

CONCLUSION

The presented maximum efficiency controller is suitable for electrohydraulic systems. Its energy efficiency is somewhat similar to C1, but its dynamics are a bit slower. The presented maximum efficiency controller should be further optimized for better operation on machines that require highly dynamic pressure cycles. Moreover it could be used in different control applications that have one extra degree of freedom to track maximum efficiency.

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