ISSN 1454 - 8003
Proceedings of 2024 International Conference on Hydraulics and Pneumatics - HERVEX
November 13-15, Băile Govora, Romania

SYSTEM FOR RECOVERING AND CONVERTING POTENTIAL ENERGY INTO ELECTRICAL ENERGY FROM A DIGITAL HYDRAULIC CYLINDER

Ioan PAVEL[1], Radu- Iulian RĂDOI[1], Gabriela MATACHE[1], Ștefan-Mihai ȘEFU[1]

[1] National Institute of Research & Development for Optoelectronics/INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute/IHP, Romania

Abstract: *Energy recovery in hydraulic systems is becoming increasingly important for reducing energy consumption and carbon emissions. This article presents a solution for recovering and converting potential energy into electrical energy from a digital hydraulic cylinder. The solution was studied on a test stand for digital hydraulic cylinders. During the retraction of the cylinder rod under simulated potential energy load, the flow discharged from the three chambers of the digital cylinder is used to rotate a hydraulic motor/electric generator unit. The generated electrical energy was measured and stored in a battery. The results are promising, especially for mobile machinery that can store the recovered energy directly in a battery.*

Keywords: *Potential energy recovery, Digital hydraulic cylinders*

1. Introduction

The concept of digital hydraulics for hydraulic cylinders is based on discretizing the working surface, with each discretized size having two on/off states. By combining sections and states, active control of speed or force can be achieved at the actuator.
The studied solution for the digital cylinder involves discretizing the active surface into three concentric sections for extension and one for retraction. The result is a digital servocylinder, which operates with constant flow and pressure while providing seven selectable levels of force or speed.
The digital hydraulic cylinder can be used as an actuator in any hydraulic system that requires force and speed adjustments. For example, it can be applied to stamping presses that need high speed for idle strokes and high force for pressing. Traditional solutions use variable flow pumps and sophisticated multi-stage pressure valves, resulting in high initial costs and low energy efficiency.
Despite the good efficiency of hydraulic components, the overall efficiency of hydraulic systems is generally low. Hydraulic load-sensing systems with potential energy recovery, widely used in mobile applications, can offer an efficiency improvement of up to 4% [1].
The potential to reduce losses by over 33% in multi-actuator systems has been studied through simulations on a loader, replacing the traditional LS system with a digital hydraulic valve system (DVS) [2].
Another solution to minimize or eliminate the need for proportional valves involves the use of hydraulic transformers. These are powered by a pressure line that drives both the working mechanisms and the rotary drive system of a front loader [3,4].
A simulation was also conducted to obtain multiple speed levels at the rod of the digital hydraulic cylinder by using a signal source configured with five steps [5].
Energy recovery in hydraulic systems is becoming increasingly important for reducing energy consumption and carbon emissions. Recent studies focus on recovering potential energy in lifting-lowering equipment equipped with hydraulic cylinders, using hydraulic accumulators to offset consumption peaks.
An extremely efficient hybrid hydraulic system was also developed for an excavator, utilizing a multi-chamber cylinder and secondary control. A detailed energy analysis was performed, explaining energy flow in the hybrid system [6].
A solution for converting potential energy into electrical energy was evaluated through simulations on a digital hydraulic cylinder test bench [7].
In conclusion, the trend in modern hydraulic research is to minimize losses by investigating energy recovery methods [8,9,10,11].

ISSN 1454 - 8003
Proceedings of 2024 International Conference on Hydraulics and Pneumatics - HERVEX
November 13-15, Băile Govora, Romania

2. Test results on an experimental model of a digital cylinder

The test results were obtained using an experimental model of a digital cylinder with three extension chambers, mounted on a specialized test stand developed by the authors at INOE 2000 IHP.
The test stand (Figure 1) comprises: two electro-pumps, SP1 and SP2, a distribution block (BD) with four distributors, a motor-generator (MG) unit, a data acquisition board and virtual instrument software programmed in LabVIEW with embedded control logic for supplying the chambers of the digital hydraulic cylinder (CD) and the data acquisition system for the measured signals (force, displacement, pressure, flow rate).

Fig. 1. Test stand

The digital hydraulic cylinder (CD) tested in the laboratory (Figure 2) features a piston surface divided into three functionally independent annular zones. The cylinder was supplied with constant pressure, and by selecting combinations of active zones, seven force levels were achieved. These force levels can be controlled by commanding the distribution block via dedicated software.

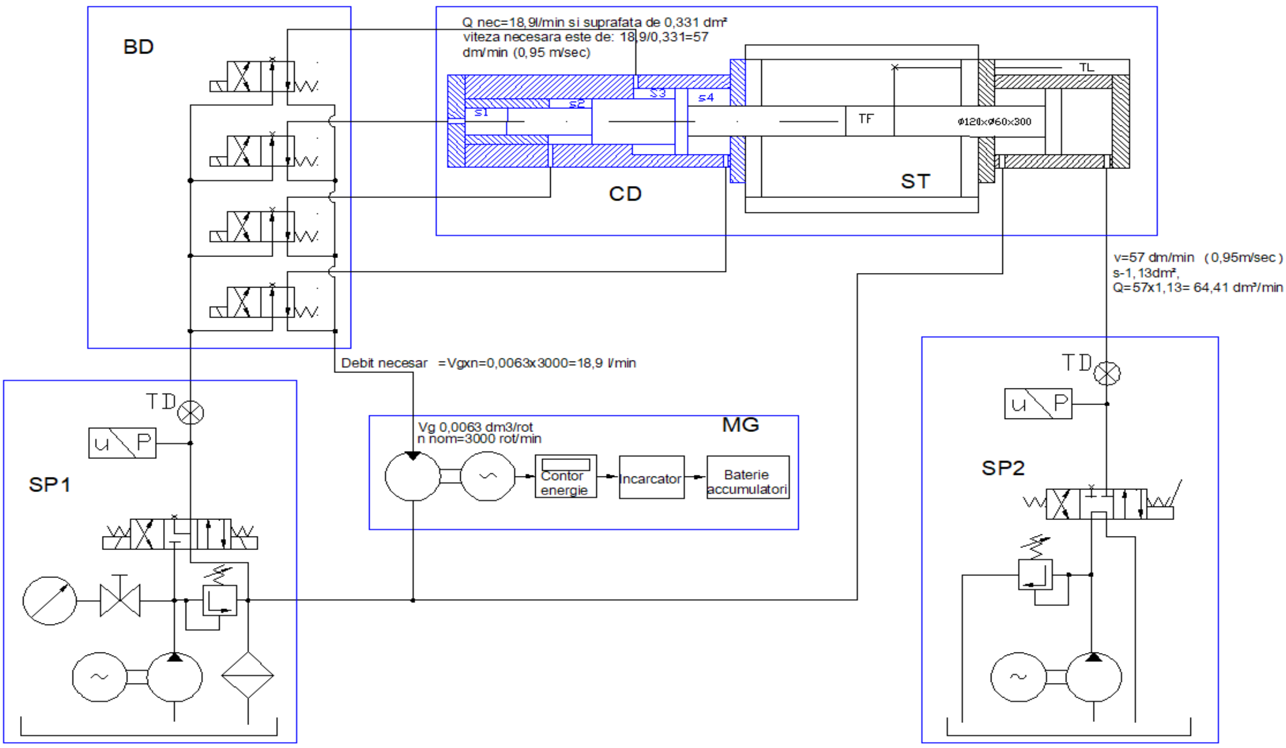

Fig. 2. Hydraulic diagram of the stand for converting potential energy into electrical energy

For energy recovery, a return of the digital cylinder under a load representing the potential energy targeted for recovery and transformation into electrical energy was simulated.

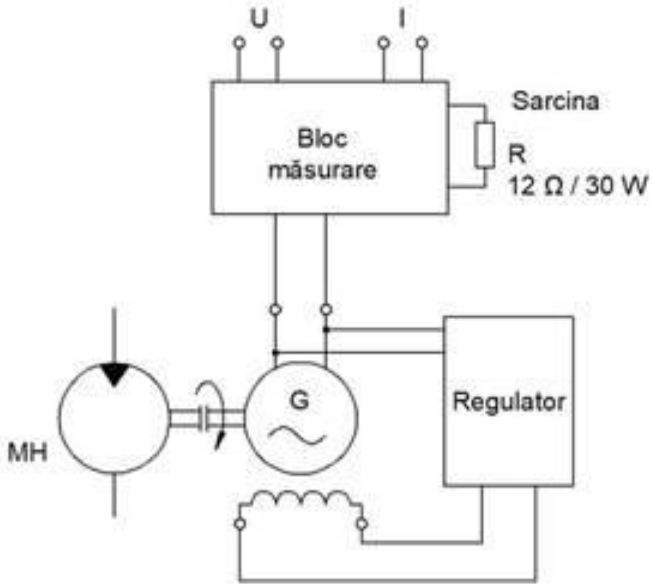

Fig. 3. Electrical diagram of the block measuring the recovered energy

The energy of the pressurized hydraulic fluid expelled from the hydraulic cylinder at retraction is recovered by driving a rotary hydraulic motor coupled with a synchronous electric generator (Figure 3). The generator contains an internal regulator that adjusts the excitation coil to provide a constant voltage. To measure the voltage and current delivered by the generator, a measuring block and a load resistor are used. The measuring block contains a bridge rectifier and a 0.3 ohm shunt for measuring the current, and a resistive divider is used for the voltage at the load resistor terminals, so that the measured voltage does not exceed the input level in the data acquisition board.
The tests were carried out in two stages:
1. In the first stage, the data acquisition was carried out for the advance of the digital cylinder in which the seven combinations of aligned chambers are ordered and the seven force stages are obtained (Figure 4).

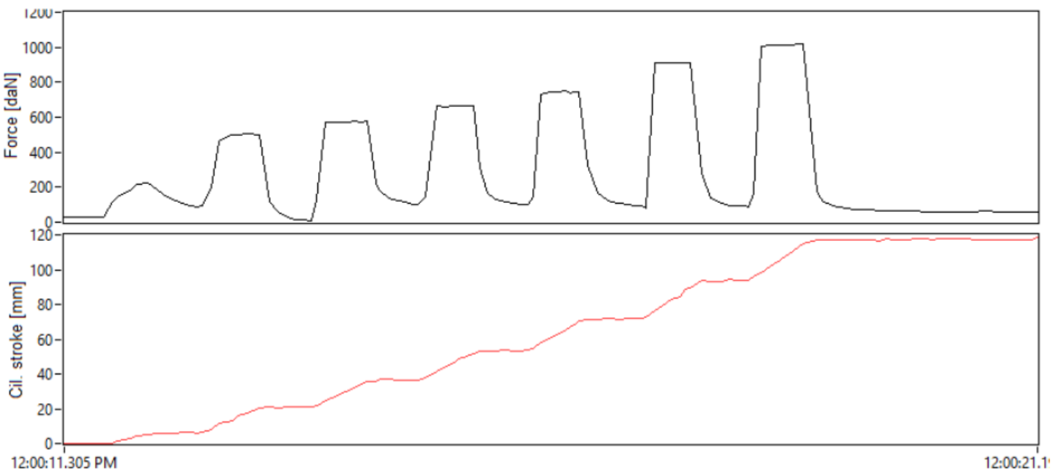

Fig. 4. Power steps obtained from powered chamber combinations

2. In the second stage, data acquisition was performed for the withdrawal of the digital cylinder (Figure 5) and the recovery of the simulated potential energy by using the flow discharged by the three chambers of the digital cylinder when rotating a hydraulic motor-electric generator unit. The

electricity obtained was measured (Figure 6) and stored in a battery. The sudden acceleration of the simulated load to approximately 2000 daN develops an initial measured force of almost 5000 daN after which it stabilizes at the set value throughout the rest of the stroke.

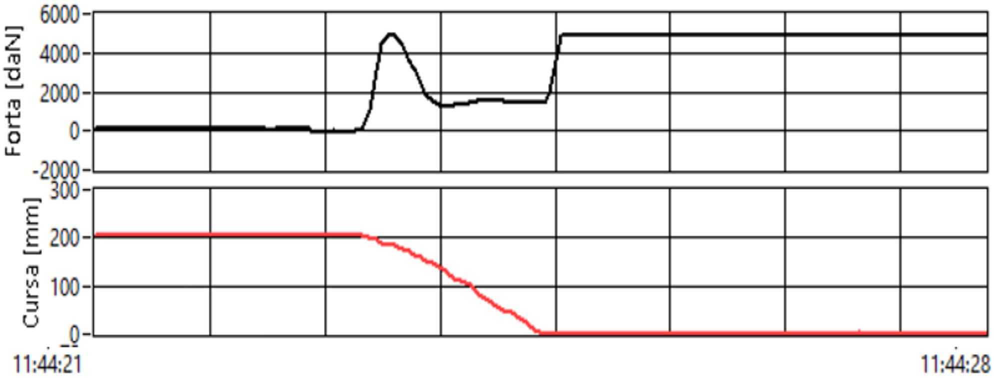

Fig. 5. Evolution of the force along the entire stroke of the digital cylinder at the rebound stroke with energy recovery

In order to measure the recovered energy, the values of current, voltage and power were acquired (Figure 6).

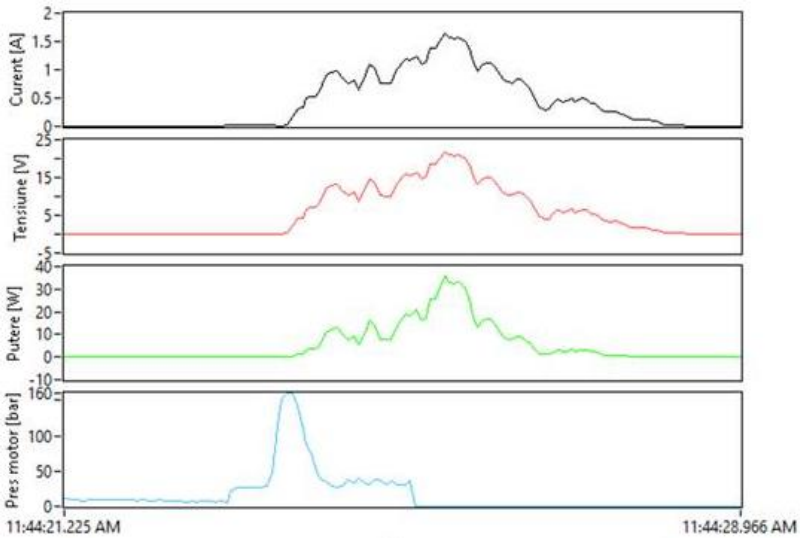

Fig. 6. Evolution of current, voltage, power and pressure at the hydraulic-electric generator motor unit during a rod retraction stroke

The current obtained from the recovery of the simulated potential energy was 1.5 A and the voltage was 15 V. The resulting power was approx. 20 W. The overload created at the initial acceleration of the simulated load created a pressure peak at the initial rotation of the hydraulic motor-electric generator set of 160 bar after which it decreased and stabilized at 40 bar.

4. Conclusions

The hydraulic cylinder is the most widely used piece of equipment in hydraulic drives and is an essential starting point in plant design. Digital cylinders allow the variation of the working area, and implicitly of the operating force and speed, offering innovative solutions for hydraulically driven equipment. The introduction of digital technologies in this field can pave the way for new, more efficient applications in modernized or newly designed facilities. It was found on this stand configuration (Figure 2), that in order to reach the nominal speed of the electric generator of 3000

rpm, a cylinder rod retraction speed of 57 dm/min (approx. 1m/sec) is required, thus ensuring a flow rate discharged from chambers C1, C2 and C3 of 18.9 l/min. To achieve this withdrawal speed, the SP2 pumping station must deliver a flow rate of 64.4 l/min. Even in these conditions, due to the short time in which the stroke is carried out and the pressure drops on the routes of the connecting pipes, although the hydraulic engine is accelerated, it does not reach the nominal speed. The voltage obtained under normal test conditions was 15 v and the current was 1.5 A, which means that the application is very well suited to mobile machines for recharging the battery. Even if at first glance the values of the recovered energy are small, if a lifting/lowering machine works continuously then the idea of recovery becomes interesting.
The energy savings resulting from the application of the right energy recovery solutions with digital cylinders can improve the technical-economic performance of production lines, mobile machinery, thus contributing to cost reduction and support for sustainable development.

Acknowledgments

This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of the Romanian Ministry of Research, Innovation and Digitalization (MCID), project no. PN 23 05.

References

[1] Garbacik, A., and J. Stecki (eds.). *Developments in Fluid Power Control of Machinery and Manipulators*. Virvalo, T., and M. Vilenius. “The Influence of Pumps and Valves on the Efficiency of a Hydraulic Boom.” Cracow, Fluid Power Net Publication, 2000.
[2] Huova, M., M. Karvonen, V. Ahola, M. Linjama, and M. Vilenius. “Energy Efficient Control of Multiactuator Digital Hydraulic Mobile Machine.” Paper presented at the 7th International Fluid Power Conference (7th IFK), Aachen, Germany, March 22-24, 2010.
[3] Heybroek, K., G.E.M. Vael, and J.-O. Palmberg. (2012). “Towards resistance-free hydraulics in construction machinery.” Paper presented at the 8th International Fluid Power Conference (8th IFK), Dresden, Germany, March 26-28, 2012.
[4] Mäkelä, J. (2020). *Energy efficiency of a digital hydraulic multi-pressure actuator for use in load-lifting applications*. Master Thesis. Aalto University School of Engineering, 2020.
[5] Rădoi, Radu, Ionel Pavel, Polifron Chiriță, Bogdan Tudor, and Vasilica Ștefan. “Energy efficient drive system with digital hydraulic cylinder for construction and agricultural machinery.” *INMATEH - Agricultural Engineering* 68, no. 3 (2022): 13-20.
[6] Heybroek, K., and M. Sahlman. (2018). “A hydraulic hybrid excavator based on multi-chamber cylinders and secondary control – design and experimental validation.” *International Journal of Fluid Power* 19, no. 2 (March 2018): 91-105.
[7] Pavel, Ioan, Gabriela Matache, and Ștefan-Mihai Șefu. “Recovery of potential energy by using a digital hydraulic cylinder.” *Hidraulica Magazine*, no. 3 (September 2024): 74-79.
[8] Bishop, E. “Digital Hydraulic Transformer - Approaching Theoretical Perfection in Hydraulic Drive Efficiency.” Paper presented at the 11th Scandinavian International Conference on Fluid Power, SICFP’09, Linköping, Sweden, June 2-4, 2009.
[9 Kogler, H., R. Scheidl, M. Ehrentraut, E. Guglielmino, C. Semini, and D. A. Caldwell. “Compact Hydraulic Switching Converter for Robotic Applications.” Paper presented at the Bath/ASME Symposium on Fluid Power and Motion Control (FPMC 2010), Bath, UK, September 15-17, 2010.
[10] Juhala, J., J. Kajaste, and M. Pietola. “Improving Energy Efficiency of Hydraulic Accumulator.” Paper presented at the Twelfth Scandinavian International Conference on Fluid Power, SICFP’11, Tampere, Finland, May 18-20, 2011.
[11] Linjama, M., H-P. Vihtanen, A. Sipola, and M. Vilenius. “Secondary Controlled Multi-Chamber Cylinder.” Paper presented at the 11th Scandinavian International Conference on Fluid Power, SICFP’09, Linköping, Sweden, June 2-4, 2009.