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OPTIMIZING CONSUMPTION IN AGRICULTURAL MACHINES AND INSTALLATIONS BY USING DIGITAL HYDRAULICS

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Abstract: In this article, the authors propose two solutions of digital hydraulic equipment for their use in agricultural machines. The proposed pieces of equipment are: (1) a Digital Hydraulic Pumping System (DHPS) consisting of 4 fixed flow pumps driven by a biaxial motor, 4 3/2 on/off electrohydraulic directional valves connected on the pump outlets, a 4/2 control valve, 4 one-way valves and a rotary hydraulic motor and (2) a Digital Flow Control Unit (DFCU) consisting of 5 electrohydraulic directional valves type 2/2, of different flow rates, connected to a fixed flow pump, connected to a hydraulic motor. The two digital systems are simple, reliable and are serviced by electronic control modules (ECUs), which send signals to close or open the on/off type electrohydraulic directional valves depending on the operator's commands in the cab. Due to these characteristics, the systems can obtain a flow regulation with lower energy losses, compared to the classic hydraulic systems that use a resistive regulation (with high energy losses), so that the consumption of agricultural equipment is also reduced. Authors will present the achievements obtained after the simulation of the two digital hydraulic systems.
Keywords: digital hydraulic, efficiency, agricultural industries, numerical simulation, hydrostatic transmission

INTRODUCTION

In recent years, the big problem in hydraulics has been to reduce energy losses, thus reducing CO_2 emissions into the atmosphere. Numerous studies and articles have shown that hydraulic systems are high energy consumers and about 30% of the energy consumed is lost by transforming it into heat. In general, a large part of the hydraulic energy is dissipated on the internal energy losses and on the valves.

The current trends of the industry are the reduction of energy losses in hydraulic systems, but keeping the technical specifications at a high level *(Scheidl et al., 2012)*.

In the 21st century agriculture, agricultural machines and equipment are a vital component without which agri-food production could not meet current demand.

Most agricultural machines have one or more hydraulic systems. These become very complex from a constructive point of view.

Digital hydraulics is a relatively new concept, and it is developed by teams of researchers such as those led by Scheidl et al., (2012), or Linjama (2011), and companies *(Hyöty, 2012)* such as Artemis and Bosch-Rexroth. The possibility of developing digital hydraulics arose with the development of electronic systems, so that more reliable hydraulic equipment could be created.

According to Zang et al., (2020), the main features for digital systems are:

- Active control of outputs.
- Use of electrohydraulic directional valves on/off type.
- Intelligent system control (use of microprocessors or PLCs).

Digital hydraulic systems are divided into:

- Systems with several electrohydraulic directional valves connected in parallel coded using different series:
  - Encoding using binary series 2, 4, 8, 16… etc., or Fibonacci number is called Pulse Code Modulated (PCM).
  - Coding using series 1, 1, 1, etc. is called Pulse Number Modulated (PNM).
- Hydraulic systems that use a single PWM operated electrohydraulic directional valve where the flow variation results from the sum of the open or closed periods.

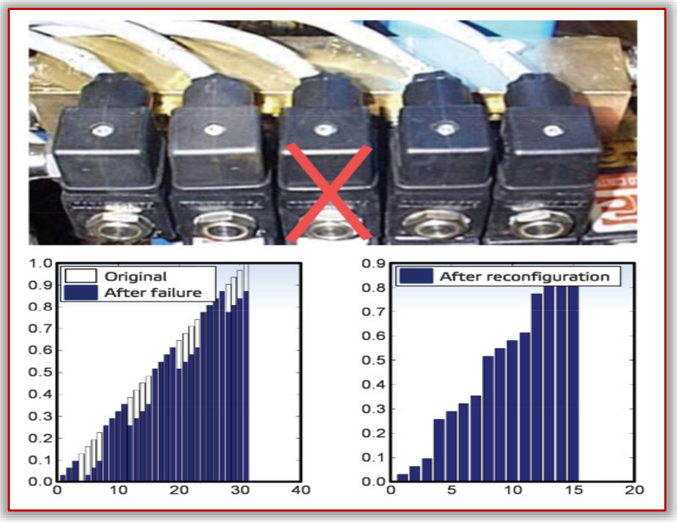

Figure 1 - If one electrohydraulic directional valve fails, the remaining valves are automatically reconfigured to produce a response curve that allows the machine to continue to run (***wpp_digihydraulics)

The advantages of digital hydraulic systems are:

- Due to the fact that digital systems use simple electrohydraulic directional valves that do not have high requirements on the working fluid, they increase the reliability of the system.
- Using a programmable logic controller (PLC) and the fact that several components are used to adjust it, if one of

them fails, the system will still be able to operate, even if not with the same high characteristics, as one can see in figure 1.

- The acquisition cost is lower than other servo or propo systems.

The disadvantages of digital hydraulic systems are:

- There are pressure shocks when switching the electrohydraulic directional valves, but this can be solved by using a hydro accumulator.
- The adjustment is made in discrete points, not continuously as the servo and propo equipment do.

A representation of a DFCU with n on/off electrohydraulic directional valves system can be seen in figure 2 *(Drumea et al., 2016)*.

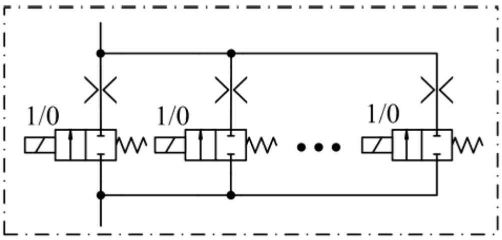

Figure 2 – Digital Flow Control Unit

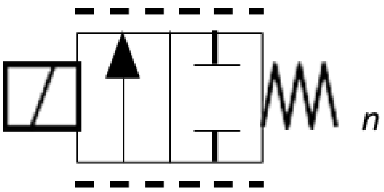

Figure 3 – Simplified symbol of DFCU

The simplified representation of the DFCU can be seen in figure 3, where „n" is the number of electrohydraulic directional valves that the system is composed of.

To implement a parallel connected DHPS, there are two independent ways, one of them is based on the direct control of the pump pistons (for the radial hydraulic pumps or motors *(Drumea et al., 2016)*), and the other is based on controlling the outputs of serval hydraulic pumps, which have a fixed geometric displacement (*Linjama, 2011; Locateli et al., 2014*).

For the implementation of the parallel connected DFCU, the authors have chosen the binary encoding method, of five electrohydraulic directional valves, with five different flows.

The simulation of the two digital systems was done with the help of the AMEsim software, and obtaining table for flows, showing in this way, that variable flow can be achieved with digital hydraulic systems, at low energy consumption.

MATERIALS AND METHODS

The digital systems proposed by the authors are equipment consisting of components of different capacities, which are in a binary progression of the form 2,4,8,16 ... etc., which can be practically called 2^n, where „n" is the number of electrohydraulic directional valves/pumps. Using the calculation formula 2^n-1, we can obtain the number of discrete points of flow variation for each system *(Mantovani et al., 2016)*.

Presentation of the systems sketches

Next, we will present two digital hydraulic systems:

- Digital Hydraulic Pumping System (DHPS) with four fixed capacity pumps with cylindrical capacity in binary progression. Using the formula 2^n-1, where n = 4, we obtain 16-1 = 15 discrete points of variation of the flow.
- Digital Flow Control Unit (DFCU) with five on/off electrohydraulic directional valves of different flow rates, also in binary progression, where a flow variation can be obtained in 31 discrete points. Using the formula 2^n-1, where n = 5, we obtain 32-1 = 31 discrete points of variation of the flow.

DHPS System

The DHPS system consists of four fixed flow pumps with coded capacities using the binary series P1-P4, an internal combustion engine marked M with a speed of 750 rpm, four on/off type electrohydraulic directional valves (DV1-DV4) with inactivated position that has the consumers connected to the tank to manage the energy losses when the equipment is in standby. Four CV1-CV4 direction valves, DV5 hydraulic motor direction selector valve HM, a flow transducer marked FM, a pressure transducer PT, Programmable Logic Controller (PLC) that drives the whole process. The system is also equipped with a filter F and a safety relief valve RV.

System operation:

The system is designed not to consume much energy when the equipment is in standby and is suitable for either applications with hydraulic cylinders or hydraulic motors.

When the operator wants to start the movement, he sends a command to the PLC, which in turn selects one or more DV1-DV4 electrohydraulic directional valves to achieve the desired flow by the operator.

When the equipment is not used, the four pumps send all the flow to the tank at low pressure, so that the pressure loss is minimal.

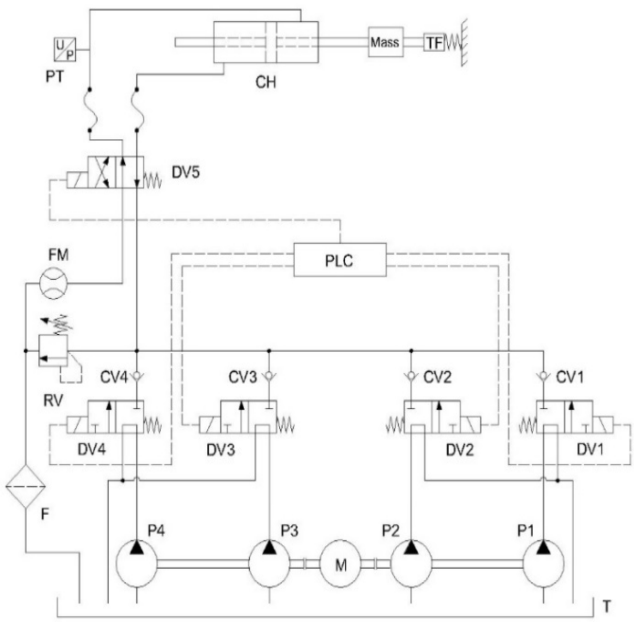

Figure 4 - Hydraulic diagram of the DHPS system with 4 binary coded pumps

Modeling the DHPS drive system

The hydraulic circuit was modeled in AMESim. The hydraulic components have the sub-models in table 1 and the parameters value are shown in table 2.

Table 1. Components of sub-models in the simulation

Component	Sub-model
Pump	PU001
Directional valve 3/2	HSV23_01
Directional valve 4/2	HSV24_01
Dynamic time table	SIGUDA01
Hydraulic cylinder	HJ021
Pressure control	RV010

Table 2. Parameters of the simulation

Parameters		
Hydraulic Hose	Directional valve (2/3)	Relief valve
Pressure 1.013 bar	Flow rate 20 l/min	Cracking Pressure 250 bar
Diameter 10 mm	Pressure drop (ΔP) 5 bar	
Length 1 m		
Hydraulic pipe	Directional valve (2/4)	Hydraulic Cylinder
Diameter 10 mm	Flow rate 50 l/min	Piston diameter 100mm
Length 0.1 m	Pressure drop (ΔP) 5 bar	Length of stroke 1,5 m

The hydraulic pipes are modeled with the HL0000 sub-models, and the hoses are modeled with the HL0001R sub-model. The configured parameters for pipes and hoses are the nominal diameter and length. The system simulation sketch is presented in figure 5.

There are four electrohydraulic directional valve 3/2 type that control the output of each pump and 4/2 types electrohydraulic directional valve that controls the direction of the hydraulic cylinder. The electrohydraulic directional valves in the simulation have proportional valve sub-models, but in this case, they are controlled with maximum on/off signal. Static models have been adopted for electrohydraulic directional valves. The system safety relief valve has been set to 250 bar.

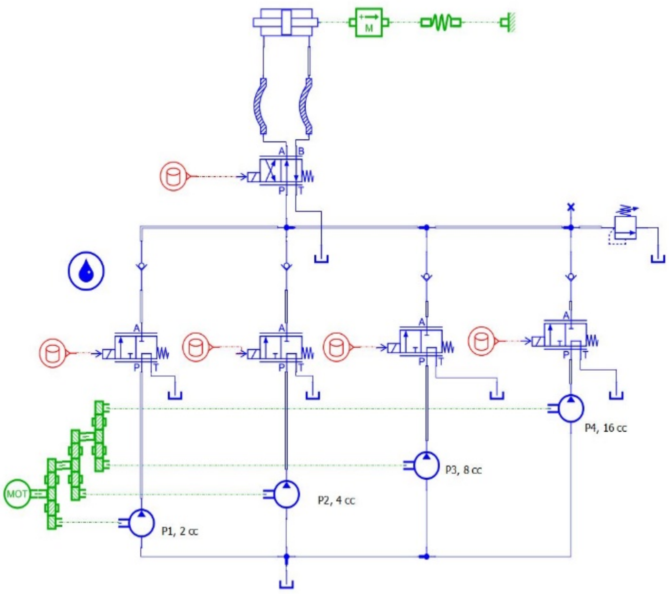

Figure 5 - DHPS system simulation scheme

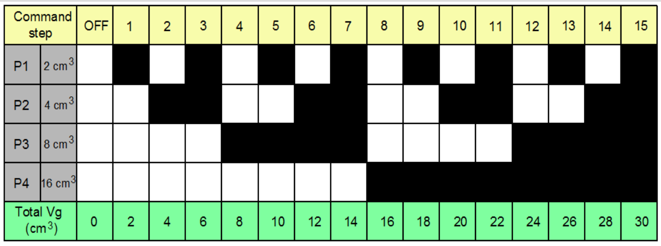

Figure 6 - Variations of the total capacity of the geometric capacity of the pumps, for the 15 control stages

Dynamic time table blocks were used to control the pumps, which simulated the binary code for controlling type 3/2 electrohydraulic directional valves, to achieve the 15 flow steps.

DFCU system

The second system DFCU consists of: internal combustion engine marked M, Fixed Flow Pump (HP), Hydro accumulator (HA), electrohydraulic directional valve 2/2 (DV6), 5 electrohydraulic directional valves (on/off) DV1- DV5 type 2/2 which are transited by different flows in binary progression. DV7 electrohydraulic directional valve type 4/2 that changes the direction of rotation of the hydraulic motor. HM hydraulic motor, FM flow transducer, PT pressure transducer, Filter F. The PLC that controls the operation of the entire system.

This system is designed for applications where continuous operation such as adjusting the combine head is not required.

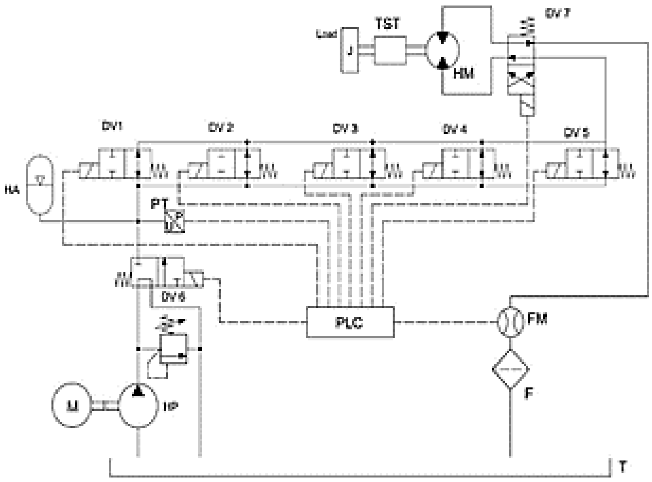

Figure 7 – Hydraulic diagram of the DFCU system with 4 binary coded electrohydraulic directional valves

The operation of the system is the following: the fixed flow hydraulic pump is a small capacity one and charges the hydro accumulator. When it is necessary to operate the system, depending on the speed desired by the operator, the PLC sends an order to one or more DV1-DV5 electrohydraulic directional valves. When the pressure in the hydro accumulator decreases, the PT transducer sends a signal to the PLC, so that the DV 6 electrohydraulic directional valve is actuated so that the pump sends flow into the system and implicitly into the hydro accumulator. When the pressure value has reached the set threshold, the

PLC takes control of the DV 6 electrohydraulic directional valve, and it moves to the main position, sending the flow supplied by the pump to the tank, with low energy loss.

Due to the hydraulic accumulator, the pump can be small, so that the energy loss is reduced, implicitly the consumption of the machine.

DFCU simulation

Figure 8 shows the simplified DFCU simulation scheme. A simplified simulation was performed in order to initially validate the principle of this DFCU. SC-1 to SC-3 are super components created to be able to operate the directional valves according to the actuation scheme presented in table 3.

Table 3. The condition of each electrohydraulic directional valve and the flow obtained for each of the 31 adjustment stages

Q State	q=2 [l/min]	q=4 [l/min]	q=8 [l/min]	q=16 [l/min]	q=32 [l/min]	Qt [l/min]
0	-	-	-	-	-	0
1	+	-	-	-	-	2
2	-	+	-	-	-	4
3	+	+	-	-	-	6
4	-	-	+	-	-	8
5	+	-	+	-	-	10
6	-	+	+	-	-	12
7	+	+	+	-	-	14
8	-	-	-	+	-	16
9	+	-	-	+	-	18
10	-	+	-	+	-	20
11	+	+	-	+	-	22
12	-	-	+	+	-	24
13	+	-	+	+	-	26
14	-	+	+	+	-	28
15	+	+	+	+	-	30
16	-	-	-	-	+	32
17	+	-	-	-	+	34
18	-	+	-	-	+	36
19	+	+	-	-	+	38
20	-	-	+	-	+	40
21	+	-	+	-	+	42
22	-	+	+	-	+	44
23	+	+	+	-	+	46
24	-	-	-	+	+	48
25	+	-	-	+	+	50
26	-	+	-	+	+	52
27	+	+	-	+	+	54
28	-	-	+	+	+	56
29	+	-	+	+	+	58
30	-	+	+	+	+	60
31	+	+	+	+	+	62

In order to be able to see the flow adjustment, a flow transducer was introduced at the exit of the five directional electrohydraulic valves.

In the simulation of this DFCU system, a constant pressure and flow source was taken into account in order to validate the operating principle of this system, and according to the simulation, it can operate in the system described in figure 5.

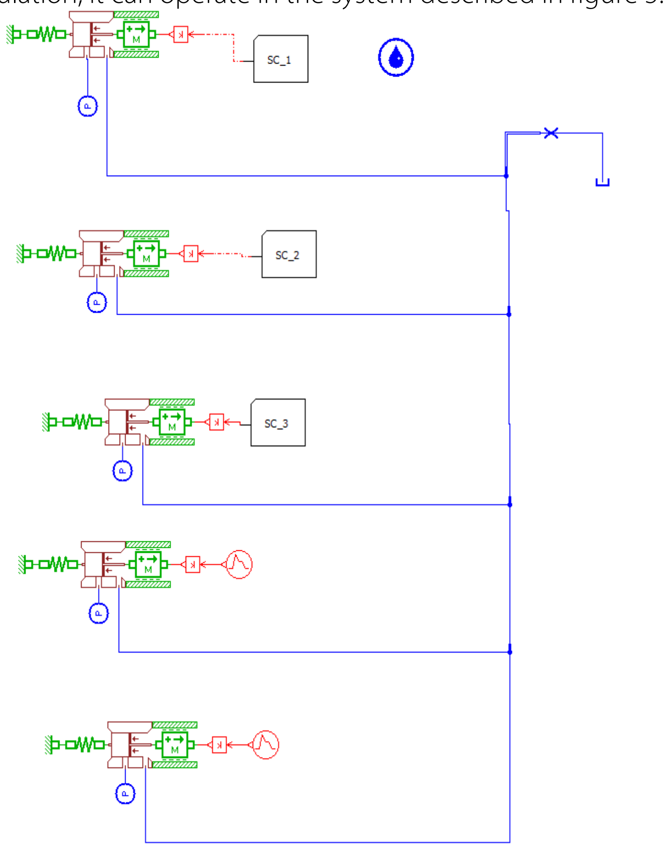

Figure 8 – DFCU system simulation scheme

RESULTS

The simulation result for the 4-pump digital system is presented in the following figures.

The directional control valves are ordered at an interval of 4 seconds. After the maximum capacity of the pumping system is dyed, the direction of movement of the hydraulic cylinder is reversed, using the 4/2 electrohydraulic directional valve.

For the DHPS system, as one can see from the figure below, a discrete flow adjustment in 15 points is obtained.

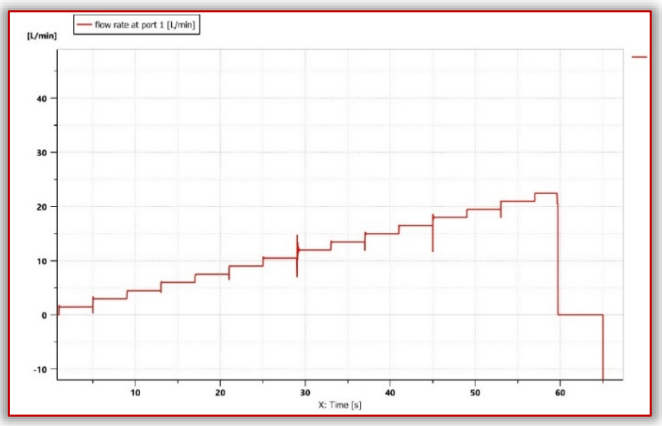

Figure 9 – Pressure and flow at the inlet to the hydraulic motor for the DHPS system

Following the simulation of the DFCU system with five binary coded distributors, a flow variation in 31 discrete points is obtained, as shown in table 3

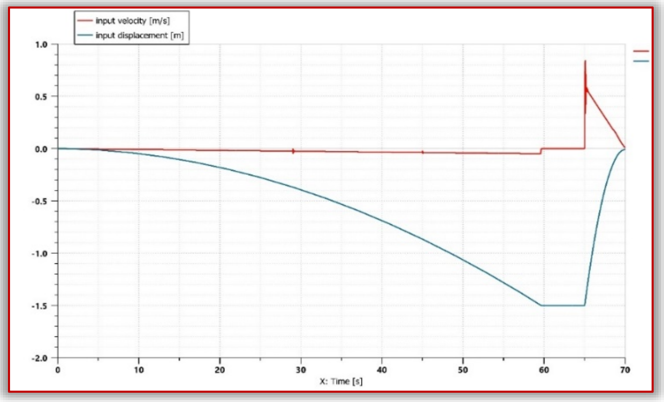

Figure 10 - Input velocity and displacement for the DHPS system

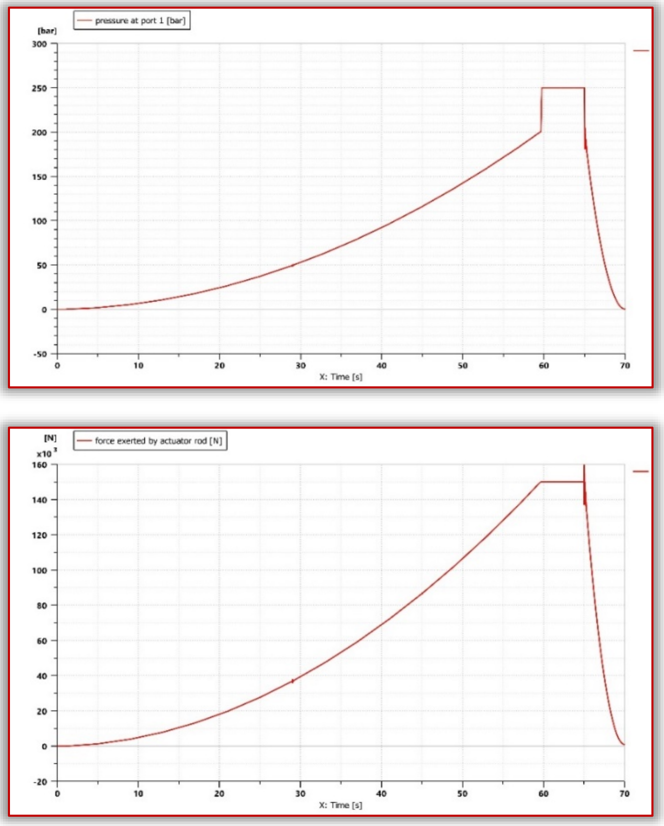

Figure 11 – Hydraulic cylinder pressure and force on the rod for the DHPS system.

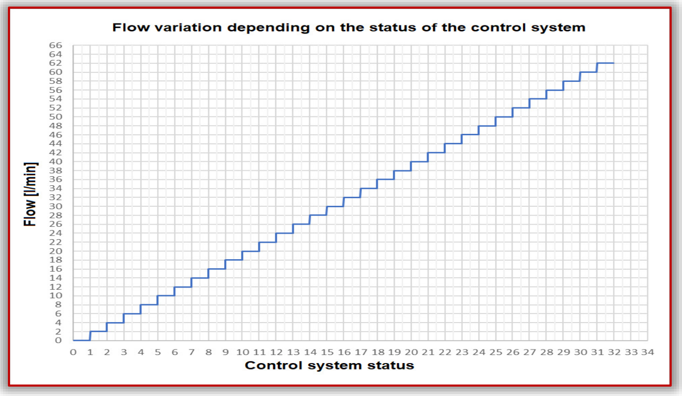

Figure 12 - Variation of the system depending on the status of the control system for the DFCU system

CONCLUSIONS

DHPS and DFCU systems are two systems that use simple components that can be easily replaced and with reduced working fluid requirements.

By using the two systems, discrete flow adjustments are obtained with lower energy losses than in the case of proportional or servo devices, where the flow in addition to the system requirements is sent to the tank through the high-pressure valve.

The world trends are to develop these simple and efficient systems as widely as possible, which makes the subject of ascending interest.

The two digital systems presented above are developed within INOE 2000-IHP and are part of the doctoral theses of two of the authors, therefore based on these results we will move to the next stage that will be the realization of these two digital hydraulic systems and subjecting them to various tests.

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