Global Fluid Power Society PhD Symposium 2022| Naples, Italy - 2022

Different Solutions for the Achievement of Variable Margin Load Sensing Systems: Energy Saving and Increased Performance

Davide Mesturini[1], Mattia Scolari[1], Francesco De Martino[1], Ulderico Busani[1]

[1] *Walvoil SpA (Interpump Group), Reggio Emilia (RE), Italy*

Abstract

Load Sensing system is one of the most common types of hydraulic circuit; its relative simplicity, the high level of controllability and the energy savings achievable in combination with a variable pump have made it commercially successful over the last few decades. However, in order to ensure good control, a certain amount of energy is usually dissipated in the so-called "LS-margin".

A greater opportunity for improvement is now guaranteed by electronic integration; in particular, the management of a variable LS-margin allows further savings, also guaranteeing interesting control strategies that can increase productivity, precision and working comfort in the off-highway machineries.

The paper presents two different solutions for the management of variable stand-by margin.

The first one, known under the commercial name ALS (Adaptive Load Sensing) is an electrohydraulic device integrated in the directional control valve and provided with an ECU that defines its control strategy. The system has been simulated and tested on a telehandler with significant improvements in terms of consumption and performance.

The second one consists of an electronically controlled variable piston pump, where the displacement is defined by a closed loop control. In this case as well, an external ECU is providing the best logic to match with the directional control valve actuation.

The paper provides the results of the simulations, the case studies and the experimental data, comparing benefits and drawbacks of both solutions.

A specific focus is provided on the management software developed in Codesys environment and on the specific implemented working functions. A complete system approach in the work allows for the definition of a complete system, provided with Piston Pump, Directional Control Valve, ECU and HMI devices.

Keywords. Load Sensing, Electronic Control, Variable Margin, Energy saving.

1. INTRODUCTION

Load Sensing (LS) systems are still today one of the most widespread and most appreciated solutions on the Non-Road Mobile Machinery (NRMM) market, despite the fact that the solution is now several decades old and has not significantly changed over time [1].

The strengths of the LS systems are the relative simplicity of the components, the good controllability achieved and the reasonable energy consumption resulting from the use of a Variable Displacement Pump (VDP) in combination with an LS Directional Control Valve (DCV).

One of the limits of traditional LS system is represented by the LS-margin, that is the additional pressure drop needed by the system to perform the control, as illustrated by Bedotti [2].

Already many years ago an upgraded version of LS concept integrating electronic control was theorized [3, 4]. In this system, the physical connection between the DCV and the VDP is not present, as the LS pressure is read by a pressure transducer on the DCV and elaborated by the Electronic Controls Unit (ECU) to pilot the VDP. The concept was developed and improved by various researchers [5, 6], especially regarding the software control stability [7, 8] and showing some specific machineries application cases [9, 10], but it took many years to find a widespread application on the market.

Only in the last decade, the larger availability of electro-hydraulic components and the spread of ECUs have opened up new possibilities for improvement both in terms of efficiency and in terms of functionality, giving rise to Electronic Load Sensing (ELS) systems.

The potential of ELS systems lies in the ability to optimize the interaction of multiple components, providing a holistic approach and the optimal whole system logic.

This paper presents two different configurations of an ELS system and their practical application in two different types of machines:

- the Adaptive Load Sensing (ALS): an additional electro-hydraulic device interposed between the DCV and the pump and its application to a 79.5 kW Telehandler;
- the electro-hydraulic operated VDP and its application to a 5t Mini-excavator.

2. ADAPTIVE LOAD SENSING DEVICE

Under the name of ALS, Walvoil SpA introduces a new electro-hydraulic device that can be interposed between the VDP and the DCV to realize specific system logic and allow an energy saving.

The electro-hydraulic device can be a stand-alone manifold or can be integrated into a traditional LS DCV to create an ELS in combination with a traditional VDP equipped with a common hydromechanical LS controller: this feature makes it particularly interesting for the after-sales market, since it can be easily installed to upgrade machines, introducing an important benefit even on already operational fleets.

A very interesting aspect of the ALS device is the possibility of creating an ELS also in fixed displacement systems; there are still many applications on the market that, for cost or simplicity reasons, require the use of a fixed displacement pump, although much less efficient than a variable displacement pump. Thanks to the ALS system interfaced to the DCV main compensator, it is possible to anyway increase the efficiency, as well as benefit from the functional advantages of ELS systems.

2.1. Adaptive Load Sensing System Description

Figure 2.1.1 shows the ISO1219 scheme of the ALS manifold. The system receives as input the LS signal from the DCV and outputs a modified LS signal (LSC) that is supplied to the VDP or to the inlet compensator of the DCV in case of fixed pump systems. The main stage of the device is represented by a 3/2 spool valve, which, feeding from the high-pressure line P and discharging any overpressures in the exhaust line T, adjusts the modified pressure LSC by reference to the LS signal itself and a pair of proportional signals pil1 and pil2 generated by a couple of electrically operated proportional pressure reducing valves. When no control is provided at the pilot stages, the device copies the LS signal in LSC without any modification; increasing the current I1 or I2 to the pilot stages, the value of LSC is consequently modified comparing to the original LS value.

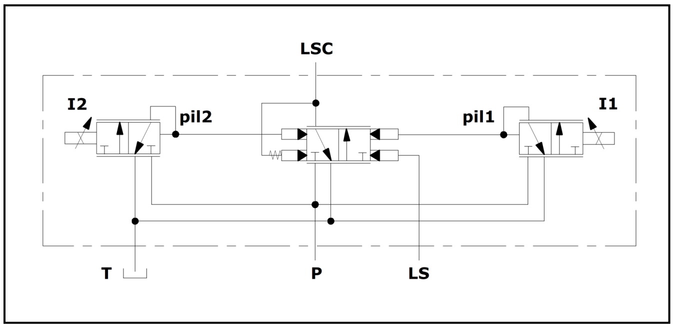

Figure 2.1.1. Adaptive Load Sensing manifold ISO1219 scheme

It is clear that the modification of the LS signal through the pressures imposed by the pilot stages allows to vary the pressure margin (PM) across the metering areas of the DCV. In the following equation, PPM is the mechanical pressure margin set by the standard Load Sensing pump regulator (or by the DCV main compensator in case of fixed displacement pumps): it imposes a constant margin between LS and P. In case we provide LSC as reference instead of LS, the value of PM is consequently modified:

$$\mathrm{PM} = \mathrm{P} - \mathrm{LS} = \mathrm{LSC} + \mathrm{PPM} - \mathrm{LS} = \mathrm{PPM} + (\mathrm{LSC} - \mathrm{LS}) \qquad (2.1.1)$$

Referring to Figure 2.1.1, the pil1 signal acts in the direction of increasing the pressure margin, while the pil2 signal in the direction of reducing it. As a final result, the following operative conditions are possible:

- I1 = I2: LS = LSC: PM = PPM (2.1.2)
- I1 < I2: LSC < LS: PM < PPM (2.1.3)

- I1 > I2: LSC > LS: PM > PPM (2.1.4)

Figure 2.1.2 shows a cut view of the 3/2 spool, main stage of the ALS. The spool is realized by means of internal coupled pins that allows the influence of four different pressures (LS, LSC, pil1, pil2) on the two piloting faces.

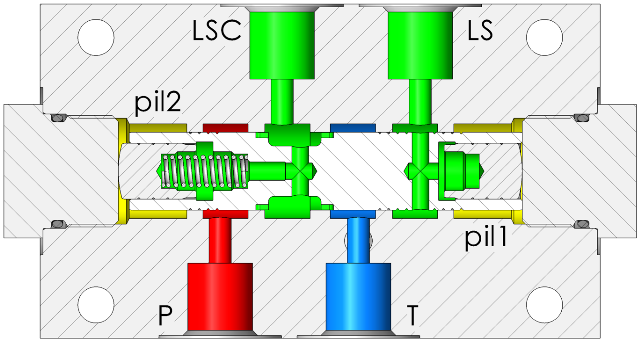

Figure 2.1.2. ALS 3/2 main stage spool design

Other versions of the ALS are available, including alternatively only the pil1 or only the pil2 pilot stage; in these specific versions the device is built to only increase or only reducing the PM from an original value imposed by the spring. The design and the different possible configurations are described in [11].

2.2. ALS Software Structure and the Implemented Functions

Various types of logic implemented in the ECU, allow to realize various modes of operation; the most simple and intuitive gives the operator the possibility of selecting different working modes: typically, a fast/dynamic mode (using a high PM) and a high-precision/efficient mode (using a low PM).

For all the tests described in this paper, a different logic has been used, varying the LS pressure margin according and proportionally to the control signals of the DCV. The flow demand required by the operator is detected directly through the signals generated in the human-machine interfaces (HMIs) and defines an increasing PM, proportionally to the DCV spools displacement: this allows to modify and shape the flow delivery characteristic, improving the fine control at low speed and minimizing the consumption, while maintaining the actuator maximum speed. In case of simultaneous actuations, a specific priority logic is applied, in order to set a common and appropriate PM.

The software has been developed in the Walvoil PHC Studio® environment, with a combination of Structure Texts and Function Block Diagrams. The ECU communicates through SAEJ1939 protocol with the HMIs and directly generates the PWM control of the DCV.

The PM control has been tested in both open and closed loop logic; in the second case the P and LS pressure feedback allows a more precise and responsive control.

An additional feature of the ALS software is the capability of the torque/power limitation. The function can be implemented by adding a pressure sensor on the pump delivery and an angle sensor on the pump swash plate, to evaluate the actual torque. A dedicated logic block has been developed to reduce the PM when a specific torque level (given as the product of pump displacement and pump pressure) is reached. The function has been successfully tested on the bench, but it has not been implemented in the application yet.

2.3. 3D Map-based ALS Control Logic

As a final stage of the development, a further logic has been tested: it consists in a 3D map-based algorithm that autonomously selects, depending on the flow required by the operator, the best and most energy-efficient combination of PM and DCV metering area. Compared to the linear logic applied during the tests, there is no more a direct proportionality between HMIs signals and the spools displacement: the DCV meter-in areas are adjusted by the ECU, depending on the actual PM. Figure 2.3.1 shows the different PM strategies compared to the standard LS: in the 3D map-based case the choice of larger metering areas in the spools allows to reach the target iso-flow curve at a lower PM, giving an additional efficiency improvement. The results of this control strategy have been investigated in a dedicated work [12].

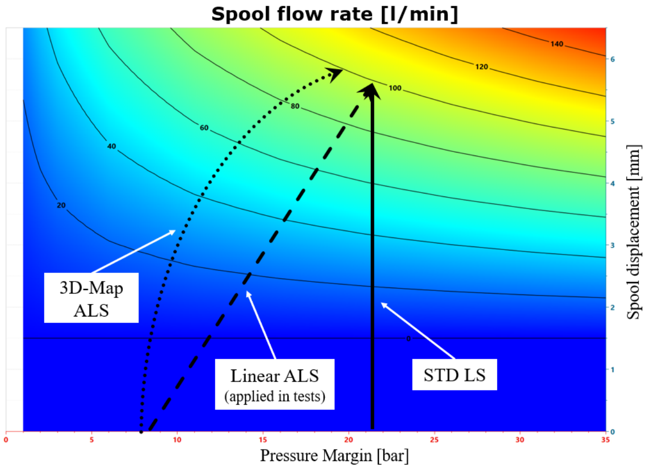

Figure 2.3.1. Linear and 3D map-based algorythms compared to standard LS system

2.4. Application of Adaptive Load Sensing to a Telehandler

The development of the ALS system went through a detailed simulation analysis by means of a lumped parameters model in AMESim© software; [13] and [14] illustrate some use modes and applications of the system and estimate a good consumption save, especially interesting on electrified agricultural tractors. After a performance test activity on the hydraulic bench, the ALS system has been installed on a Dieci Agri Farmer 34.7 GD® Telehandler, shown in Figure 2.4.1.

Figure 2.4.1. Dieci Agri Farmer 34.7 GD® Telehandler

The Dieci Agri Farmer has a tandem gear pump and represents a significant example of use of ALS in combination with fixed displacement pump. The machine has been equipped with the following components:

- Electronic joysticks DJW®, with electronic multifunction MTH® grips;
- CED400® ECU dedicated to ALS management and interfaced to the machine system with SAEJ1939 protocol;
- Tandem Gear Pump (43cc/rev+17cc/rev);
- ALS Manifold;
- Flow Sharing DPX100® DCV, 4 working sections, with electro-hydraulic control.

2.5. Test on the Dieci Agri Farmer® Telehandler

The tests of the machine were performed at Dieci R&D Center and were based on a combination of functional and efficiency checks.

The direct feedback from the operators made it possible to optimize some aspects relating to the controllability and driving comfort; additionally, four tests were carried out on the track to assess the consumption of a vehicle equipped with the original system compared to one equipped with ALS system:

- Positioning test: loading and unloading two different loads at a defined distance;

- Fine positioning test: precision loading and unloading of a load in narrow and critical space;
- On road test: vehicle drive in various conditions;
- Track test: constant speed vehicle driving with load.

The following table summarizes the results of the tests.

	Consumption reduction with ALS [%]
Positioning test	6,3
Fine positioning test	5,9
On road test	5,0
Track test	5,4

Table 2.5.1. Dieci Agri Farmer Tests Results

Beyond the excellent energy results, with the use of ALS, the vehicle also reported numerous additional advantages; a series of augmented functionalities have allowed the drivers to carry out more operating cycles in the same time, especially in precision movements, experiencing a greater productivity of the machine.

Some instabilities and jerking present in the system have been eliminated by introducing dynamic effects in the control of the PM, significantly improving the driver comfort.

3. ELECTRONIC CONTROL PUMP-BASED ELS SYSTEM

The second practical application applies the ELS to a 5t mini-excavator (Figure 3.1) and involves the use of a variable displacement axial piston pump equipped with an electro-proportional controller, according to the most usual way of building an ELS system.

Figure 3.1. 5t mini-excavator equipped with Walvoil ALS

3.1. Variable Pump Eletromechanical Control

According to the peculiarities of each application, different layouts and control strategies are needed to maximize the working cycle and minimize the energy consumption. Various types of electro-proportional regulators have been developed and studied by the research team, aiming to reduce the number of components on the system, while maintaining a comfortable feeling by the operator and a high level of safety.

For this test a Walvoil PWLS53® axial piston variable displacement pump has been used, with an electro-hydraulic controller including pressure control and flow control capabilities. It incorporates a 3/2 spool proportionally operated by a coil and an electro-proportional relief valve, according to Figure 3.1.1 ISO1219 scheme; it also comprehends an angle Hall effect-sensor, to detect the swash plate position.

An in-depth experimental activity was preliminarily carried out to optimize the pump regulator performance and to finalize the control software. This substantial part of the development has retraced many of the theories and solutions illustrated in past works [15, 16] regarding both physical layout and control algorithms. The mechanical-hydraulic tuning mainly focused on the definition of the 3/2 spool metering areas and its overlaps. Both the pressure and the flow stages control have been improved in terms of hysteresis, thanks to an accurate proportional electric control.

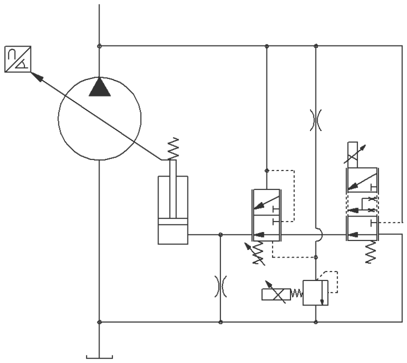

Figure 3.1.1. Electro-hydraulic control for the pump displacement

In order to keep a direct comparability with previous experiences on ALS system, a simple pressure control mode has been chosen, mainly operating on the proportional relief valve to achieve the PM target imposed by the ECU. The PM logic applied is the linear one described in § *2.2*: PM increase from 8 to 16 bar is directly proportional to the spool displacement, defined by the HMIs signals.

Figure 3.1.2 shows the synoptic layout of the excavator system, including the HMIs, the pump and the LS pressure transducers to provide a closed loop controlled PM.

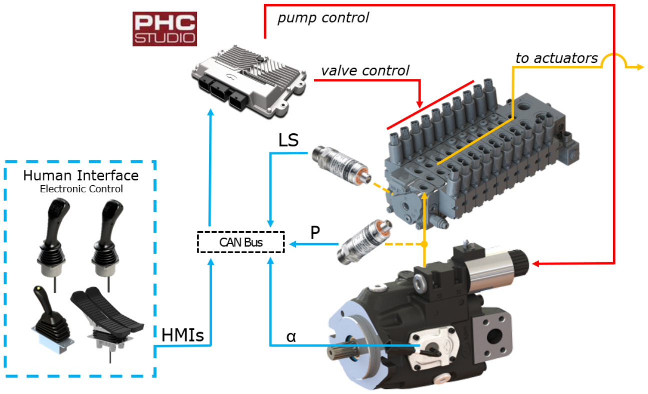

Figure 3.1.2. Mini-excavator components layout

3.2. Excavator System Simulation in AMESim©

Before approaching the experimental activity, the system has been simulated by means of the AMESim© software. A typical "digging and unloading" cycle has been performed on the excavator by an average expert operator; pressures and flows of all actuators' ports have been logged and used as input parameters for the model.

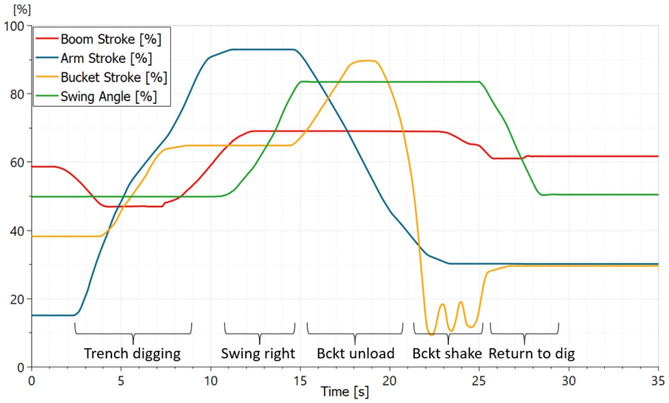

Figure 3.2.1. Main actuators' displacement performed in the simulation cycle

The cycle involves boom, arm, bucket and swing functions, whose actuator displacement is shown in Figure 3.2.1.

The spools' displacement is calculated backward from the input flows and the input pressures are superimposed to the actuators' ports. The variable PM is consequently defined.

Figure 3.2.2 shows the value of the PM imposed by the control during the whole simulated cycle, expressed as a percentage of the regulation range (8-16 bar). Figure 3.2.3 shows the developed AMESim© model with special focus on DCV block.
The total consumed energy along the cycle at pump level is calculated:

- Traditional LS (constant 15 bar PM): 140,1 kJ;
- ELS (variable PM): 132,4 kJ.

The reduction in hydraulic energy consumption settles on 5,5%; it is reasonable to expect that a similar reduction is also present at fuel level.
This outcome is very similar to the one obtained with the application of ALS to the telehandler: the contribution of the variable margin seems to settle indicatively in the same range, regardless of the application case and the method of use. As a confirmation, analogous results have been found also in previous works [12, 13, 14].

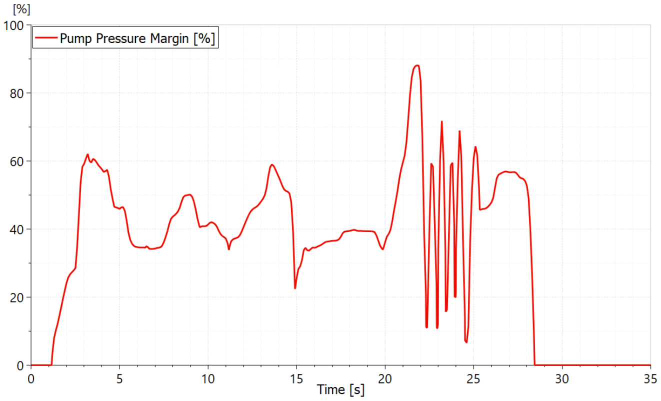

Figure 3.2.2. Variable pump pressure margin during the simulated cycle

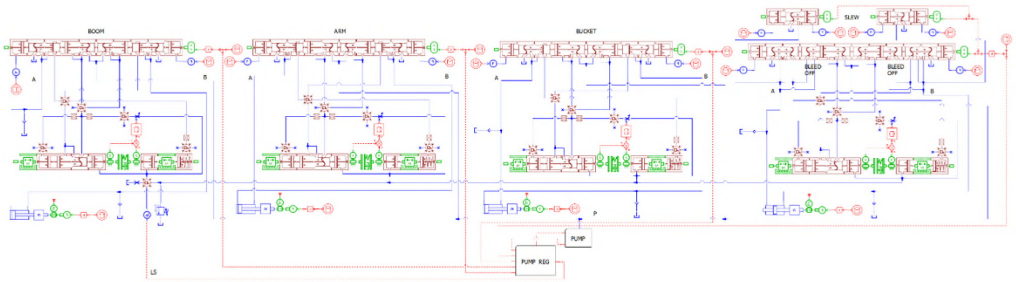

Figure 3.2.3. AMESim© model of the excavator’s DCV block

3.3. Experimental Layout built on the 5t Mini-excavator

The ELS system simulated in AMESim© has been eventually installed on the mini-excavator. The system is composed by following components:

- Electronic joysticks HJW®, with electronic multifunction XMH® grips;
- Electronic pedals CPW® for tracks control;
- N°5 CED400® ECUs interconnected with SAEJ1939 protocol and dedicated to the system logic, to the PWM outputs and to the various sensors log for a complete analysis of the machine performance;
- Variable axial piston pump PWLS53® with electro-hydraulic controller;
- Flow Sharing DPX100® DCV, 10 working sections, with electro-hydraulic control;
- Fan Drive system.

As a first stage, an accurate tuning of the DCV has been made in order to guarantee the best machine controllability. Secondarily the ELS control has been applied and checked in its performance in the machine operating cycle. In this case as well, as already experienced in the telehandler, the adjustable PM over the spool displacement helps significantly to smooth the operations and to make the machine dynamic more sensitive.

An additional development phase has integrated the electronic torque/power control, that was previously realised in the mini-excavator by means of a mechanical torque limiter in the VDP.

The linear PM logic described in § 2.2 has been eventually applied and verified to work properly. Figure 3.3.1 shows a log of the digging cycle performed on the mini-excavator with the ELS system working. The red line is the actual modified PM applied to the system, while the black dotted line represents the dimensionless PID controller output.

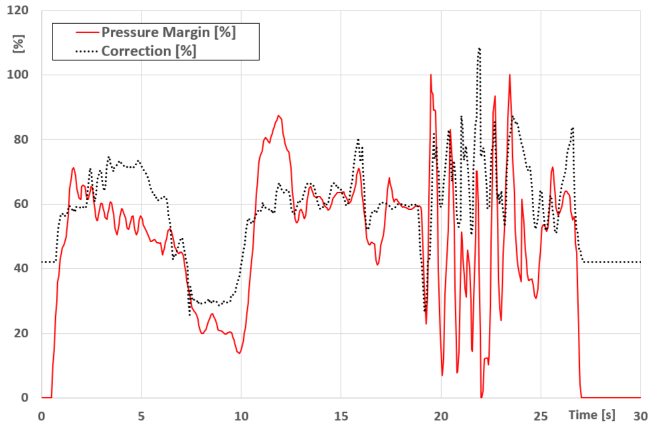

Figure 3.3.1. PM and PID correction gain data acquired during the mini-excavator test

The simulation model has been compared and optimised according to the experimental results by means of simple and directly comparable operations (as for example single movement step response).

Regarding the whole cycle, diagram in Figure 3.3.1 is not perfectly comparable to the simulation diagram in Figure 3.2.2, due to the unavoidable differences in the time scale and in the actuation sequence; nevertheless, the two diagrams are similar on a qualitative base and show analogous dynamic and behaviour. The PM is continuously varying according to the joystick actuation and to the power limiting control. The PM is dynamically adjusted between 8 and 16 bar and the PID controller correction gain is monitored.

A first approximate evaluation of the consumption is confirming the saving values estimated in the simulation, but the machine will be soon equipped with a more accurate fuel consumption measurement system for a more reliable data collection.

4. CONCLUSIONS AND OUTLOOK

Two different configurations of ELS have been studied and compared; the unprecedented Adaptive Load Sensing system has been practically applied on a Dieci telehandler in a fixed displacement circuit, while the classical solution using an electro-hydraulic pump regulator has been studied on the bench, simulated and eventually applied to a 5t mini-excavator.

Both technologies have proven the capability to perform a variable pressure margin logic, allowing an average 5% reduction in fuel consumption. The practical application on the Dieci telehandler and on the mini-excavator has furthermore shown some augmented control capabilities and improved drive comfort. The direct comparison of the two possible approaches has highlighted the following aspects:

- The ALS system integrated in the DCV, represents an immediate and easy solution to benefit of the ELS opportunities. The simple and stand-alone installation makes it an interesting way for the retrofit market and for the enhancement of existing machine models;
- The ALS system integrated in the DCV makes it possible to benefit of ELS opportunities even on fixed displacement circuits that still represents a significant percentage of the market applications;
- The ALS system integrated in the DCV results to be more stable and easier to set comparing to the ELS realized by means of the pump electronic control. The proportional control of the ALS guarantees a higher definition and resolution of the electronic proportional control;
- The electronic control pump-based ELS, offers a multitude of additional opportunities thanks to a more sophisticated software. Especially the capability to switch from flow control to pressure control, opens to various strategies of coordinated control of the DCV and of the VDP.

Next activities will be focused on the development of mixed control strategies to improve the match of DCV and VDP, exploiting especially the beneficial effect of flow control on the pump-based ELS, capable of significantly reducing the oscillations and instabilities typical of pressure controls.

5. ACKNOWLEDGMENT

We thank the company Dieci for the continuous collaboration and the shared effort in applying the ALS system. We also thank Prof. Casoli from University of Parma and prof. Zardin from the University of Modena and Reggio Emilia for the supportive activities within the TASC project.

6. REFERENCES

[1] H.C. Pedersen, T.O. Andersen, M. Hansen, "Load sensing systems - A review of the research contributions throughout the last decades", Proceedings of the 4th IFK Workshop, Dresden, Germany, 24–26 March 2004.

[2] A. Bedotti, F. Campanini, M. Pastori. L. Riccò, P. Casoli, "Energy saving solutions for a hydraulic excavator", 72nd Conference of the Italian Thermal Machines Engineering Association, ATI 2017, Lecce, Italy.

[3] B. Zähe, R. Schmidt, M. Eschweiler, "Elektrohydraulisches Loadsensing", Ölhydraulik und Pneumatik, 34, 1990.

[4] W. Backé, B. Zähe, "Electrohydraulic load-sensing", SAE Technical Paper Series, nr. 911814, 1991.

[5] H. Esders, "Elektrohydraulisches Load Sensing für mobile Anwendungen", PhD thesis, Technischen Universität Braunschweig, Germany, 1995.

[6] M. Hansen, T.O. Andersen, H.C. Pedersen, F. Conrad, "Feasibility study of electronic load sensing concept for hydraulic variable", Proceedings of the 7th International Conference in Education and Mechatronics (REM06).

[7] A. Langen, "Experimentelle und analytische Untersuchungen an vergesteuerten hydraulisch-mechanischen und elektro-hydraulischen pumpenregulungen", PhD thesis, Rheinisch-Westfälischen Technischen Hochschule Aachen, Germany.

[8] G. Tewes, H.H. Harms, "Fuzzy control for an electrohydraulic load-sensing system", Proc. 9th Bath International Fluid Power Workshop, September 1996.

[9] T.O. Andersen, M. Hansen, H.C. Pedersen, "Experimenting with electrical load sensing on a backhoe loader", Proceedings of the 6th International Conference on Fluid Power Transmission and Control (ICFP 2005).

[10] R.H. Hansen, A.M. Iversen, M.S. Jensen, T.O. Andersen, H.C. Pedersen, "Modeling and control of a teletruck using electronic load sensing", Proceedings of the ASME 2010 10th Conference on Engineering System Design and Analysis, ESDA 2010, July 12-14, 2010, Istanbul, Turkey.

[11] Patent application EP3667103 Applicant Walvoil s.p.a.

[12] P. Casoli, F. Scolari, C.M. Vescovini, D. Mesturini, F. Zannoni, “Excavator hydraulic circuit solution to reduce dissipations and fuel consumption”, 76th Conference of the Italian Thermal Machines Engineering Association, ATI 2021, Roma, Italy.

[13] A. Gaiola, B. Zardin, P. Casoli, M. Borghi, F. Mazzali, F. Pintore, S. Fiorati, “The hydraulic power generation and transmission on agricultural tractors: feasible architectures to reduce dissipation and fuel consumption - Part 1”, 75th Conference of the Italian Thermal Machines Engineering Association, ATI 2020, Roma, Italy.

[14] P. Casoli, B. Zardin, S. Ardizio, M. Borghi, F. Pintore, D. Mesturini, “The hydraulic power generation and transmission on agricultural tractors: feasible architectures to reduce dissipation and fuel consumption - Part 2”, 75th Conference of the Italian Thermal Machines Engineering Association, ATI 2020, Roma, Italy.

[15] M. Scherer, M. Geimer, B. Weiss, “Contribution on Control Strategies of Flow-On-Demand Hydraulic Circuits”, The 13th Scandinavian International Conference on Fluid Power, SICFP2013.

[16] M. Axin, “Mobile Working Hydraulic System Dynamics”, Linköping Studies in Science and Technology, Dissertations No. 1697, 20.