Latest Technology Advancements in Hydraulic Systems for Refuse Vehicle Applications: The Case of an Automated Side Loader

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Abstract

The present paper describes an innovative electro-hydraulic system developed for automated side loaders. The system is based on Intelligent Flow Control (IFC), a concept where open circuit electric displacement controlled pumps are coupled with EH directional control valves. IFC was selected in order to achieve the level of performance required, in terms of efficiency and productivity (i.e. cycle times), and also to provide the best possible control of the side loader arm. The paper describes the system layout and the basics of the controls: from the alghorithms of the arm actuators to the vehicle on board telemetry and diagnostic. The paper reports the comparison between the IFC system (implemented on the vehicle) and a more traditional approach based on a Load Sense Flow Sharing concept. The benefits of the IFC solution are highlighted focusing on the energy efficiency (very important especially in the case of CNG engines, where the torque available at idle is significantly lower than diesel engines), but also in terms of controlability and response (due to the lack of load sensing signal lines).

KEYWORDS: Automated Side Loader, Intelligent Flow Control, Fuel Efficiency, Productivity, Simplicity, Cost effectiveness

1. Introduction

The use of automated side loaders is becoming more and more popular for refuse collection in most of residential areas of the US. In fact, these machines are capable of loading garbage cans automatically, without the need of operators on the ground moving or handling the cans (which happens in the case of rear loaders). The collection of cans happens through an arm, equipped with a grabber. Once approached the can, the driver extends the arm until reaching the can, the grabber closes and the can is then lifted and dumped in the hopper. Afterwards, the empty can is returned on the ground. The truck hopper is also equipped with a packer compressing the loaded garbage. The arm and the packer control are realized through a hydraulic system, which is capable of realizing more than a thousand cycles per day; in fact an average can pick and dump cycle lasts approx. 10 seconds or less.

From a technical stand point, automated side loaders are very complex vehicles: beside the electro-hydraulic system, they are for example equipped with cameras, GPS, weight sensors. The arm design and hydraulic control are the key of the machine, being the element responsible the effectiveness and performance of the machine. Typical automated side loader arms have limited degrees of freedom because they are characterized by geometrical constraints. These can be a horizontal extension, a vertical lift on a rail or a parallel arm linkage: they make the control of the arm easier, but limits the performance of the arm. For example, can picks below grade are not possible or also the dump trajectory is fixed, and cannot be adapted to external obstacles, such as a tree or a power line.

Figure 1: The side loader object of the resent study

The Parker GMS engineering team was challenged to develop an electro-hydraulic system for a new side loader equipped with an innovative arm concept (Figure 1). This arm is characterized by no geometrical constrain in the X-Y plane and the function synchronization and control is purely achieved through the hydraulic system, based on the actuators’ position feedback.

The arm control had to be capable of:

- Moving following the trajectory imposed by the operator joystick, as well of achieving different possible trajectories when executing the can dump.
- Automating the dump cycle returning the empty can in the same exact location it was picked
- Achieving cycle times below 7 sec minimizing the shake of the vehicle cab.
- Maximizing the energy efficiency, making it possible to run a full cycle even on CNG powered trucks at low idle.
- Estimating the can weight (thus the truck estimated load) and realizing a slower dump cycle for heavier cans.
- Providing real-time system diagnostics broadcasted via an on-board modem.
- Being simple and cost effective.

2. System architectures comparison

Historically, in the last decades, the development of hydraulic systems has been characterized by a constantly increasing degree of intelligence and automation. However, this development has mostly involved the directional elements and the control valves, leaving the pumps to a lower technology stage. Even in electro-hydraulic load sensing (LS) systems, which represent the finest current technology, the variable displacement pump is controlled by a hydro-mechanical compensator, which is controlled by the pressure signals coming from the valves. Left of Figure 2 represents a simplified layout and operation of a traditional LS system with a variable pump: when the operator commands a function, the command first reaches valve spool; the valve shifts accordingly, detecting the load pressures and communicating the highest load to the pump through the LS line. The pump control then adjusts the displacement in order to set the pump delivery pressure p_p as:

$$p_p = p_{LS} + s \tag{1}$$

where p_{LS} is the load sensing pressure and s is the margin pressure. This allows the flow to reach the actuator, which finally moves. The advantages of the LS system compared to other predecessor is the controllability intended as the independence of the actuator speed as a function of the load, at least in most of the condition. Flow-sharing solution came out in order to solve controllability in event of saturation as described in /1/ and /2/.

In the past years, the Parker Global Mobile Systems team has focused on the research and development of new hydraulic systems. These researches culminated with the Intelligent Flow Control (/3/), an architecture based on open circuit electric displacement controlled pumps (EDC) and directional control valves.

The IFC system concept allows introducing a new level of intelligence in the system improving the performance of mobile equipment. The use of the IFC also introduces new degrees of freedom in the system design and therefore the possibility of simplifying the parts of the system without penalizing the performance level.

A simplified IFC system can be observed from Figure 2, here the operator's command is directly sent from the Control Unit in parallel to the pump and the valves.

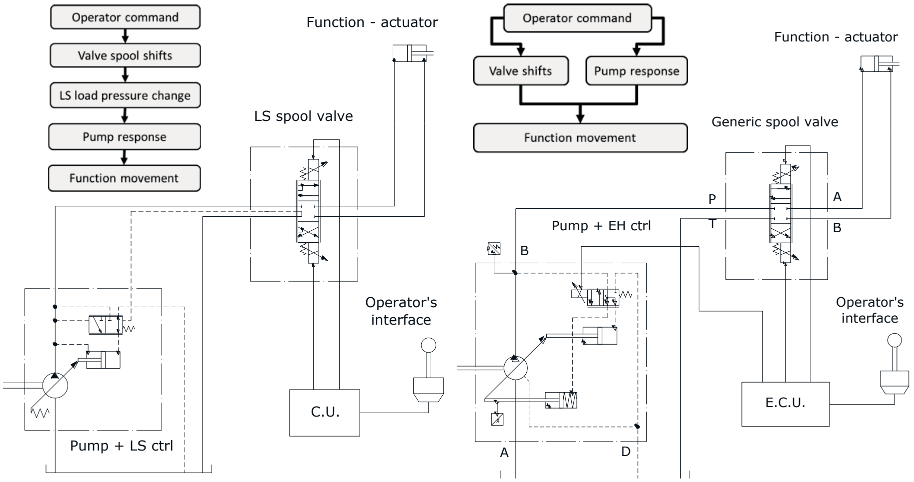

Figure 2: Simplified schematic of a generic IFC system and operating principle when responding to an operator command

This implies a much faster response time as visible Figure 3 where a LS systems is compared with IFC. IFC does not need any connection between load pressure signal and pump displacement, which is also responsible of response delays as visible in the step response in Figure 3 and also potential system instabilities. Figure 3 also shows the Bode plot of an IFC controlled function: the low dB decay up to 3Hz.

Having a stable and controllable system allows simplifying the spools design and reducing meter out restrictions that are usually introduced in order to dampen the functions and make them more stable. Moreover the use of electronics in order to control the pumps allows better power management. In fact the engine CAN bus information (such as engine load and engine speed) can be matched with the pump controls in order to maximize the power output at every engine condition. All these benefits result in significant productivity improvements.

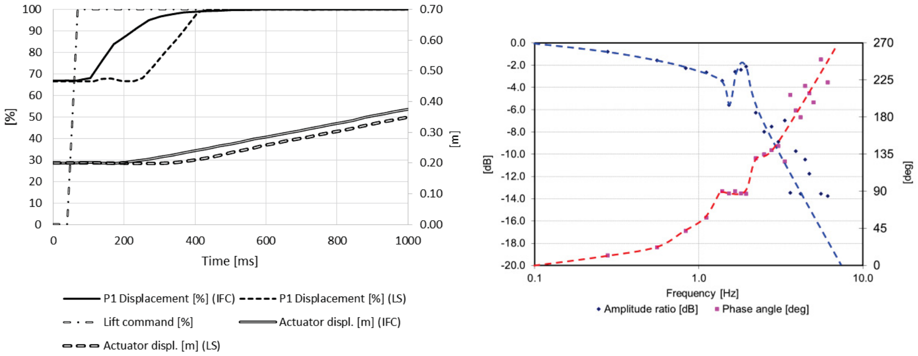

Figure 3: Response comparison between IFC and LS for two fork lift systems (left), Bode diagram for IFC controlled actuator.

2.1. Hydraulic Schematic

With reference to Figure 1 and looking at the arm operation, only three of the functions need to be controlled simultaneously. In addition, the requirement (by law) of actuator mounted counterbalance valves implies that the spools may not need to work as meter-out control elements. By combining these considerations with the IFC design concept, it is possible to adapt a triple IFC pump and simple ON-OFF valves architecture (Figure 4) for achieving a very precise control of the arm and eliminating any metering loss. The control of the function’s flow is managed by the pumps (P1 – grabber/extension, P2 – lift, P3 - rotation), while the valves are just used for directional control. Between the pumps and the “arm manifold”, the three flows pass through a “combiner manifold” with three check valves and an “isolation valve”. When the packer is activated, the flow of all three pumps is combined to the packer valve. It is also noticeable that the extension function runs in regenerative mode thanks to the check and pilot-to-close check valves in the counterbalance block. The body functions are controlled by a 3 section valve. When these are activated, only the flow of the smaller pump P3 is used, while P1 and P2 are left at standby.

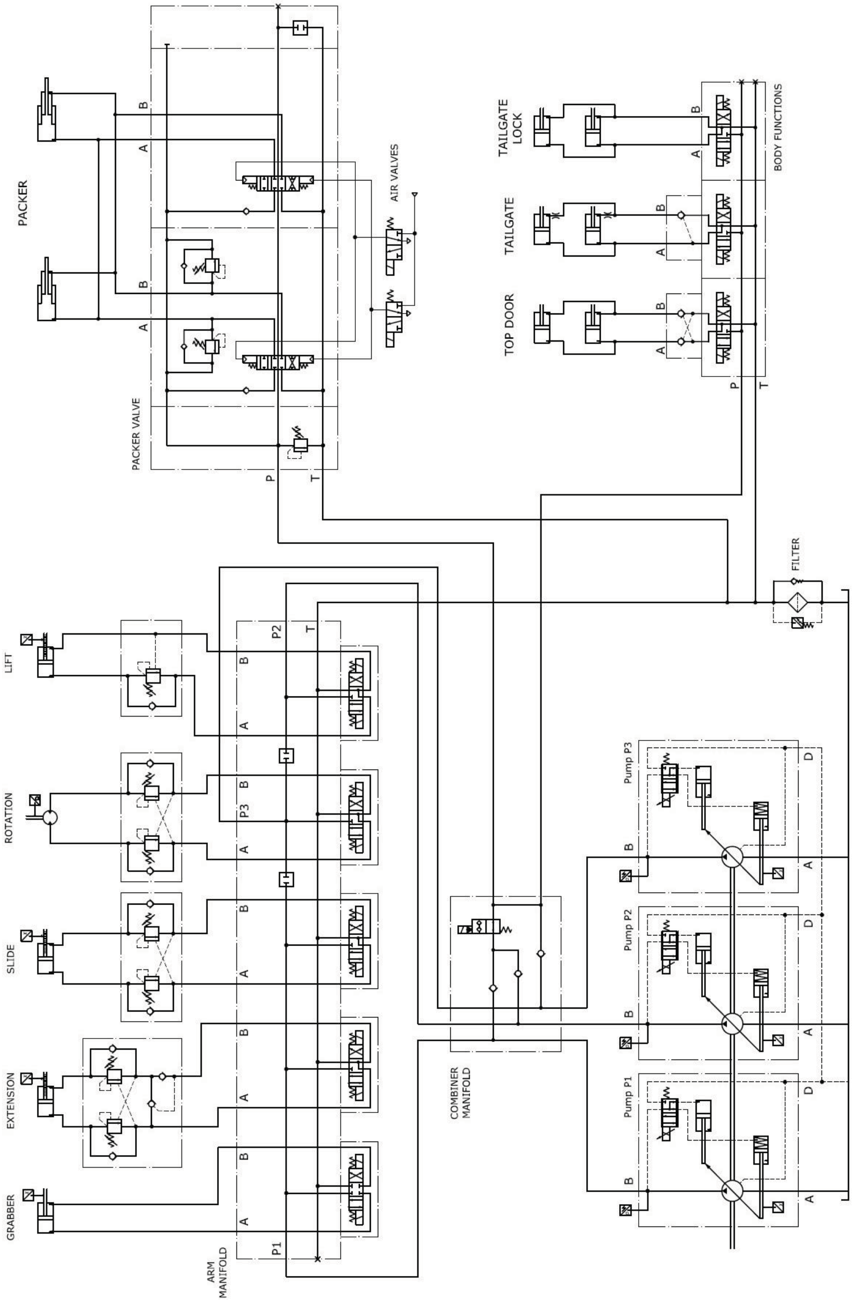

Figure 4: Schematic of the IFC system for the automated side loader.

The body functions are never run simultaneously with the arm. Normally, also the packer function runs stand alone, but some particular cases might require packing while the arm is being moved. In these cases the isolation valve in the combiner manifold is actuated, so that P1 and P2 are used for the arm, while P3 keeps moving the packer at a reduced speed.

3. The Control Concept

Electronics is heavily used in this system. In particular, the position feedback information of the arm functions is the key for meeting the required specifications. The system comprises of three Parker Intellinders, used for the lift, extension and slide functions. In this particular case the Intellinder has a unique advantage, allowing the use of small rod and bore diameters, compared to other traditional solutions (magnetostrictive sensors, which use would increase cylinder sizes resulting in larger pumps and valves). Figure 5 shows the control logic of the system that is implemented using IQAN modules. The MD4 and XA2 includes the control logic of the valves, reads the sensors and Intellinders, interfaces with the operator’s commands and communicates with engine and transmission. The MC2 works at a higher processing frequency and it is dedicated just to the pumps, implementing both displacement and pressure control. The MD4 communicates to the MC2 via CANbus the desired pump displacement for each of the three units and the MC2 drives the pumps accordingly based on displacement and pressure feedback. Both modules are connected to a G3 modem for remote diagnostics allowing the operation centre of the fleet management to understand real-time which are the problems on the truck and therefore send the proper assistance in case of failure.

The other important part of the system is the control concept implemented in order to achieve the desired motion of the arm. Figure 6 represents the control concept architecture: the operator’s input (whether is a coordinated motion or an automated cycle) enters the inverse kinematics model of the arm. This block translates the inputs into current commands to the valves and the pumps. As said, the valve command is on/off type, while the metering is realized in the pumps. The amount of flow delivered by each pump allows following the desired motion paths.

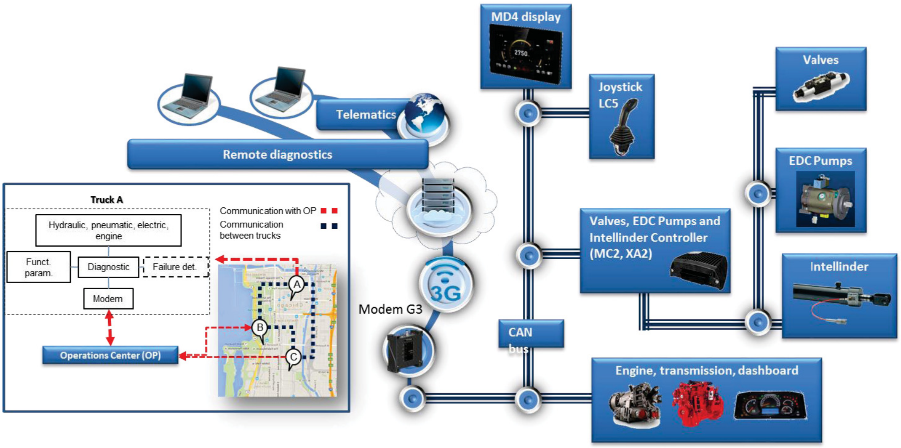

Figure 5: Control logic of schematic of the Parker IFC system

The pump commands generated by the inverse kinematics block consist of the Feed Forward portion (marked as FF in the figure), which is added to the closed loop PID control output, in order to achieve a high level of precision and compensate for the dynamic motion effects (e.g. some functions accelerate faster than others). The PID block reads the difference between the actual position feedback readings and the target position (also generated by the kinematics model).

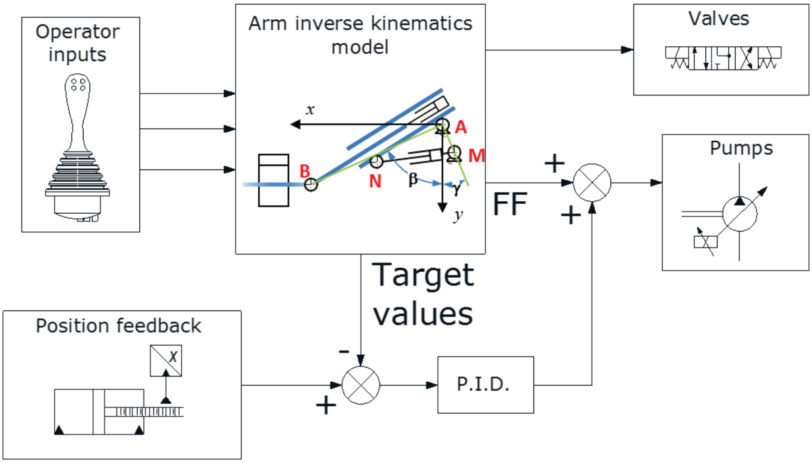

Figure 6: Simplified representation of the control concept layout.

From the control point of view, the direct control of the pump and the displacement feedback information allows a very accurate control of the flow delivery. Therefore, known the cylinder bore and rod sizes, the system can deliver the right amount of oil to move each function to the desired target in the desired amount of time. Vice-versa, a system that meters the flow across valve spools cannot have exact information about the flow delivery.

3.1. Inverse kinematics model

The inverse kinematic model allows to use of FF control and to maintain a straight trajectory of the arm during the picking operation. In order to accomplish this objective it is necessary to correlate the command of the operator to the speed of the actuator and to the flow rate generated by the pumps.

With reference to Figure 7, the length of the lift and extension actuators have been indicated as $\overline{MN}$ and $\overline{AB}$[1] respectively. The flow rate to each of the two functions (Q_l and Q_e) is then expressed as follows:

$$\begin{cases} Q_l = \dot{\overline{MN}} \cdot A_l \\ Q_e = \dot{\overline{AB}} \cdot A_e \end{cases} \tag{2}$$

Where A_l and A_e are the bore areas respectively for the lift and extension cylinder (their value is different for actuator extension and retraction).

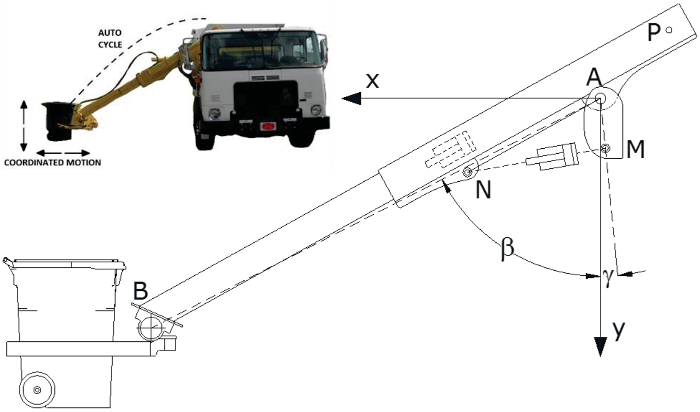

Figure 7: Arm layout and reference coordinates

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[1] The lenght of the extension can be very well approximated with the lenght of the segment $\overline{AB}$[1]

Point B is representative of the position of the grabber and can be expressed, as:

$$\begin{cases} x_B = \overline{AB}\, sin(\beta) \\ y_B = \overline{AB}\, cos(\beta) \end{cases} \tag{3}$$

With $\beta = acos(\Psi) - \gamma$ and $\Psi = \frac{(\overline{AM}^2 + \overline{AN}^2) - \overline{MN}^2}{2\overline{AM} \cdot \overline{AN}}$. Being $(x_B\, ;\, y_B)$ the position of the can, the *x* and *y* components of the speed of the can, expressed as a function of cylinder speeds are:

$$\begin{cases} \dot{x}_B = \dot{\overline{AB}}\, sin(\beta) + \overline{AB}\, \dot{\beta}\, cos(\beta) \\ \dot{y}_B = \dot{\overline{AB}}\, cos(\beta) - \overline{AB}\, \dot{\beta}\, sin(\beta) \end{cases} \tag{4}$$

Keeping in mind that: $\dot{\Psi} = -\frac{\overline{MN}}{\overline{AM} \cdot \overline{AN}} \dot{\overline{MN}}$, and $\dot{\beta} = -\dot{\Psi} \frac{1}{\sqrt{1-\Psi^2}} = \frac{\overline{MN}}{\overline{AM} \cdot \overline{AN}} \cdot \frac{\dot{\overline{MN}}}{\sqrt{1-\Psi^2}}$, the horizontal and vertical speed of point B are:

$$\begin{cases} \dot{x}_B = \dot{\overline{AB}}\, sin(\beta) + \dot{\overline{MN}} \left(\frac{1}{\sqrt{1-\Psi^2}}\ \frac{\overline{AB} \cdot \overline{MN}}{\overline{AM} \cdot \overline{AN}} \right) cos(\beta) \\ \dot{y}_B = \dot{\overline{AB}}\, cos(\beta) - \dot{\overline{MN}} \left(\frac{1}{\sqrt{1-\Psi^2}}\ \frac{\overline{AB} \cdot \overline{MN}}{\overline{AM} \cdot \overline{AN}} \right) sin(\beta) \end{cases} \tag{5}$$

By grouping $\frac{1}{\sqrt{1-\Psi^2}}\ \frac{\overline{AB} \cdot \overline{MN}}{\overline{AM} \cdot \overline{AN}} = \frac{1}{\sqrt{1 - \left(\frac{(\overline{AM}^2 + \overline{AN}^2) - \overline{NM}^2}{2\overline{AM} \cdot \overline{AN}} \right)^2}} \frac{\overline{AB}\ \overline{MN}}{\overline{AM} \cdot \overline{AN}} = K$ the actuators' speed is therefore:

$$\begin{cases} \dot{\overline{MN}} = \frac{1}{K} \left(\dot{x}_B\, cos(\beta) - \dot{y}_B sin(\beta) \right) \\ \dot{\overline{AB}} = \dot{x}_B\, sin(\beta) + \dot{y}_B\, cos(\beta) \end{cases} \tag{6}$$

In order to move the arm horizontally, then $\dot{y}_B = 0$, therefore:

$$\begin{cases} \dot{\overline{MN}} = \frac{1}{K} \dot{x}_B\, cos(\beta) \\ \dot{\overline{AB}} = \dot{x}_B\, sin(\beta) \end{cases} \tag{7}$$

If the operator wants to run the arm vertically, then $\dot{x}_B = 0$, therefore:

$$\begin{cases} \dot{\overline{MN}} = -\frac{1}{K} \dot{y}_B sin(\beta) \\ \dot{\overline{AB}} = \dot{y}_B\, cos(\beta) \end{cases} \tag{8}$$

If the control wants to keep a straight line, then $\dot{y} = \vartheta \dot{x}$, where ϑ is a constant value, therefore:

$$\begin{cases} \dot{\overline{MN}} = \frac{\dot{x}}{K} \left(cos(\beta) - \vartheta\, sin(\beta) \right) \\ \dot{\overline{AB}} = \dot{x} \left(sin(\beta) + \vartheta\, cos(\beta) \right) \end{cases} \tag{9}$$

It is important to remind that the value of $\dot{x}_B$ is proportional to the *x* axis joystick, while $\dot{y}_B$ is connected to the y joystick position. In other words Eq. (6,7,8,9) express the relationship between the pump flow rate, actuator speed and joystick command through the inverse kinematic model. The same consideration can be done for the retraction and lowering by considering the rod side area of the actuators.

4. Performance comparison with LS system

The IFC system has been compared to an alternative more conventional solution, based on a single pump Load Sensing flow sharing approach, which schematic is shown in Figure 8.

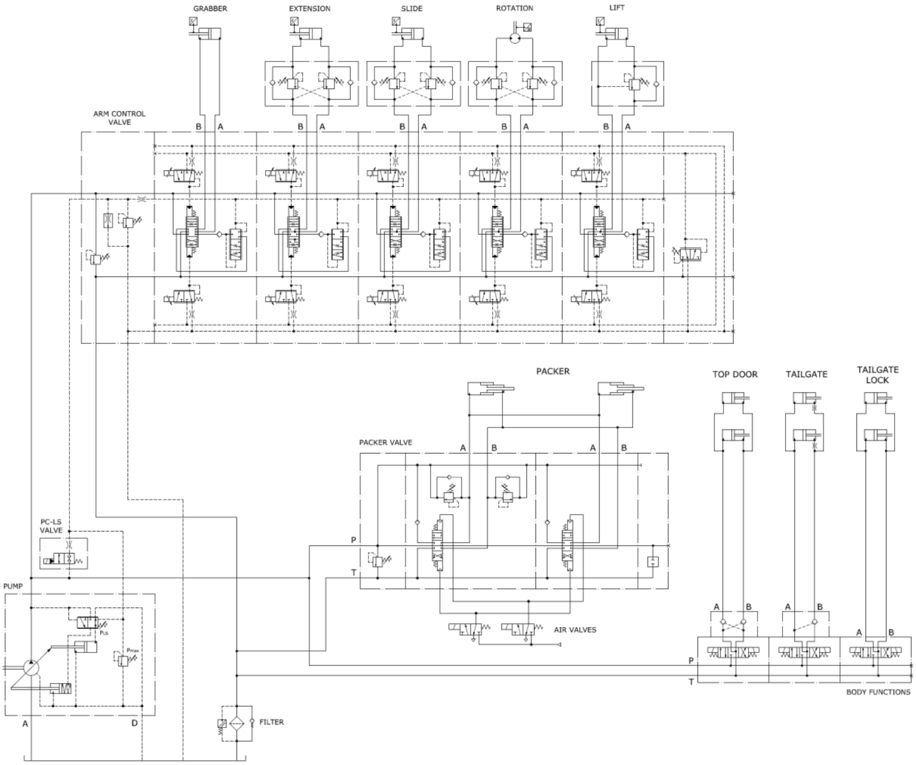

Figure 8: LS system for side loader

In order to perform a correct energy analysis, the following duty cycle has been considered:

1. The truck reaches a complete stop; the operator extends the arm following a horizontal straight line until he reaches the can. An average situation of a 6ft pickup (distance from the chassis) has been considered.
2. The operator performs the automated cycle: the can is grabbed and lift and extension are operated following a straight line connecting the grab point to the dump point. Rotation is activated and the garbage is dumped in the truck. Afterwards, rotation, lift and extension are run simultaneously and the can is returned to the initial position following a straight line path. The grabber is opened and the can is released.
3. The arm is then stowed in the transport position using the “auto stowe” function.

This cycle has been performed with the real truck and the system data were acquired (positions, flows and pressures). By analysing the pumps pressure it is noticeable how the three functions operate at significantly different pressure levels, in particular during the lift phase, the extension function is at very high pressure, when the can is dumped, rotation has the highest pressure and during the return, extension is at high pressure (regen function) while lift is at very low pressure. The data recorded were used as input for the LS model within AMESim, where measured pump pressures were used as load pressures (lift, extend, etc.), while the margin pressure and the compensator losses were calculated by the model. The losses in the hydraulic units were estimated based on the pump efficiencies lookup tables. Figure 9 shows a summary of power demand and the energy consumed by the two systems during a single cycle. From the power curves it is possible to observe how the instantaneous power consumption of the IFC system is always below the LS system. The energy chart shows instead how the energy consumption develops along the cycle time. In particular, it is possible to notice how the IFC system requires (at the engine shaft) 102 kWs to complete the cycle. Instead the LS system requires 137 kWs to complete the same operation. Therefore the energy consumed by the IFC system is 26% lower than the LS system. Figure 9 shows also the contribution of the different losses in the LS system: the compensator losses and the margin pressure losses. In the cycle 23 kWs are wasted on the compensators and 12 kWs are wasted due to the margin pressure.

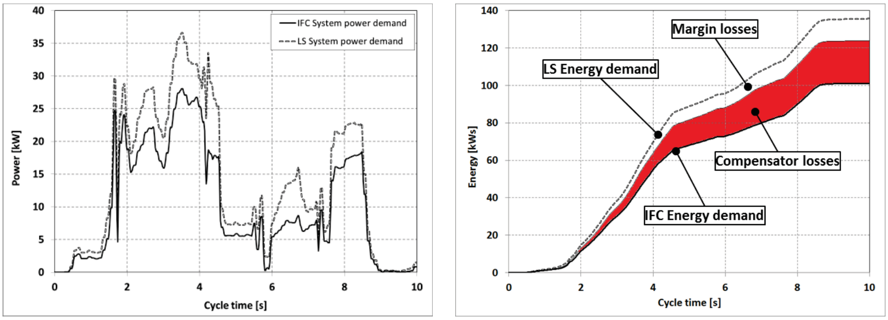

Figure 9: Power demand (left) and Energy consumption (right) during the automated cycle for the IFC and LS system

Side loaders execute between 1000 and 1500 pick-ups per day, the amount of energy saved per pick-up is 35 kWs, which correspond to 9.7 kWh per day in the case of 1000 operations. Beside the automated cycle, the IFC system shows energy savings also during the phases of “reach out” and “auto stowe”, previously mentioned as phases 1 and 3. Those phases were not considered in the above mentioned simulations; however, the full cycle inclusive of these phases increases the savings of approx. 20%. Therefore the energy saved per pick-up is 42 kWs, which correspond to 11.7 kWh per day.

The energy saved can be translated into fuel saving by using a consumption map of a common diesel engine. In the case of the refuse truck analysed in this paper, the cycle is operated at engine idle, i.e. 750 r/min and medium load. Assuming an average fuel consumption of 280 g/kWh, the IFC system saves to the operator approx. 1.1 gallons of fuel per day. If the truck is used 200 days/yr, the savings to the user are approx. $880/yr, considering an average diesel price at the pump of $1/liter.

Another advantage of the IFC system is the lower heat rejection. In fact, the LS system creates additional losses for 42 kWs at each cycle, which turn into heat. Therefore, the LS system probably needs a cooler in order to keep the oil temperature within the acceptable limits. On the other hand, the IFC system has been implemented and successfully operated without any hydraulic cooler. Last but not least, the IFC system has another important advantage: within the refuse market many end user request the installation of CNG powered engines on their trucks. These engines have a different torque vs. speed characteristic, which leads to less available power (approx. 10 hp) at idle than diesel engines. The IFC system draws less power from the prime mover, and it works effectively also on CNG engines. In addition, the use of IFC pumps allows very easily limiting the power demand using the J1939 engine load feedback (antistall feature). Vice versa, the LS system exceeds the power at idle on the CNG engines, therefore it needs a power limiting or antistall device with the result of running the arm at a reduced speed under load.

5. Conclusions

In this paper the IFC concept has been analysed from an application-focused point of view. In particular, the author explained how IFC is not only an opportunity to improve systems performance, but also a possibility to open up innovative and original system concepts with smart control strategy.

This is the differentiating key from other system where electronics is not or partially implemented: smarter pumps can allow using simpler valves and significantly improve the system efficiency. The less energetic requirement during idle condition permit the use of the system on new truck with CNG engine that provide less torque in idle conditions. Antistall feature can be implemented depending on the operating conditions not limiting the use of the engine. Fuel efficiency is also increased by using a hot-shift PTO that can be disengaged (detaching the pump from the transmission) when the hydraulic circuit is not used. Real-time diagnostic is also possible, increasing the reliability of the machine reducing the downtime.

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