A NOVEL MULTI-PUMP SYSTEM FOR HYDRAULIC ACTUATION IN ELECTRIC MOBILE MACHINERY

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ABSTRACT

An observable trend nowadays is the change in the prime movers of mobile heavy machinery to electric alternatives to achieve more eco-friendly equipment. These solutions often require large and heavy batteries with limited capacity, making the research of more efficient components and the development of different system architectures an important topic of study. Hydraulic actuation is still a relevant application for these vehicles because of its reliability, controllability, and high power density. The electrification and digitalization of mobile machinery allow for innovative designs and control strategies to be implemented that take advantage of electro-hydraulic systems and their characteristics. Similar research has shown that a higher number of degrees of freedom allow for the system to operate with higher total efficiency. This paper introduces a novel actuation architecture that combines multiple fixed displacement hydraulic pumps and on/off directional valves to control the position and force of two hydraulic actuators for the working functions of a mobile machine. Each pump is powered by a variable speed electric drive so that each one can be operated independently, and together with the set of directional valves, allows the selection of different combinations of pumps and flow sharing between the actuators' chambers to achieve the desired flow and pressure on each cylinder. The multi-pump system favours the use of smaller pumps, and the possibility of combining their flows reduces the need to operate the components at lower efficiency points such as partial displacement. At the same time, controlling the pumps' flow through the variable-speed electric motors means that throttling valves are not needed. The development of this architecture will allow for its use in mathematical models to analyse its behaviour and efficiency and to obtain insights regarding points of improvement in the system architecture.
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Keywords: *Electrification, digitalization, multi-pump system, control optimization*

INTRODUCTION

A traditional solution for the operation of loads in heavy machinery, such as excavators and wheel loaders, is hydraulic actuators because of their high power density, controllability, and reliability. Load-sensing systems have been traditionally used to control the system pressure so that multiple loads can be operated with the same pump [1]. This commonly involves one or more pumps connected to the internal combustion engine that adjust their displacement continuously to reach the required pressure [2]. To guarantee that the loads can achieve the desired speed, it is possible to combine pumps so that higher flows can be achieved. On the other hand, two or more actuators can be used at the same time, meaning that the flow of a pump might be distributed between them, resulting in what is called flow sharing. Although this process allows the operator to use different functions continuously to increase productivity, the loads often require different pressure levels, meaning that proportional valves are needed to limit the flow to each cylinder or motor, which often results in losses through pressure drop [3].

The load sensing system is well established in the industry for being a reliable solution that has seen constant improvement and is capable of adapting the system to different working conditions as needed by the operator, but the high losses encourage the search for different alternatives [4]. One option is the development of new pumps and motors, such as the Digital Displacement Pump® (DDP) [5]. Another research topic is reducing the system losses by modifying the conventional system [2, 4] or by exploring new architectures that aim at reducing the losses in hydraulic systems by changing the throttling valves to a series of on/off valves to operate the actuators [6, 7] and that take advantage of the higher control capabilities of a combined electric-hydraulic system by controlling the pump speed, and thus the flow [8].

The electrification and digitalization trend of heavy machinery supports the development of both these alternatives. The use of electric batteries with limited capacity requires more frequent and longer recharge times [9] or a complete battery exchange [10]. In this regard, having a hydraulic system with higher efficiency is advantageous, as the machine can operate for longer periods, but also reduce the overall energy cost even for newer or conventional fossil fuel equipment or hybrid solutions, thus also reducing emissions.

With a focus on the system architecture, this paper presents a novel solution for the hydraulic system in excavators. A multi-pump system is considered, where a series of fixed displacement pumps are used to provide the required flow. With a fully electric vehicle, it is possible to separate the pumps from the main engine and have each being operated by a different electric motor, thus granting operation independency to these components. Finally, a manifold block with on/off valves allows for the system to connect any number of pumps to any of the actuators as needed, as well as connect different chambers to regenerate energy.

The challenge in the development of such a system is finding a way to estimate its performance and possible benefits since the control strategy to be used is not clear because of the high number of control variables. This paper finishes with a discussion about dynamic programming, which has been used before to evaluate another highly complex system with a DDP [11]. This method aims at finding the optimal control strategy for a given operating cycle, thus offering insights on how to improve the system and develop an adequate controller.

ELECTRIFICATION AND DIGITALIZATION

Valve-controlled systems

A traditional valve-controlled system with actuators operating at different pressures always includes the loss of part of the total power [2, 12]. Figure 1.a) presents a simplified model of a load-sensing system with two cylinders, where the pressures in the actuators are compared and the higher one is used as a reference to control the displacement of the pump so that both pump flow and, consequently, pressure are adjusted as needed.

In Figure 1.b) the power consumption of the system is shown. One actuator consumes a total power of P_1 based on its flow and pressure while the second actuator needs flow at a lower pressure, thus consuming P_2. But since they share the same pump, the system must keep the pressure on a higher level, thus a large pressure drop is required on the proportional valve of the lower pressure cylinder, resulting in the previously mentioned power loss. The dashed line represents the extra power loss derived from internal losses in the system such as friction and leakage.

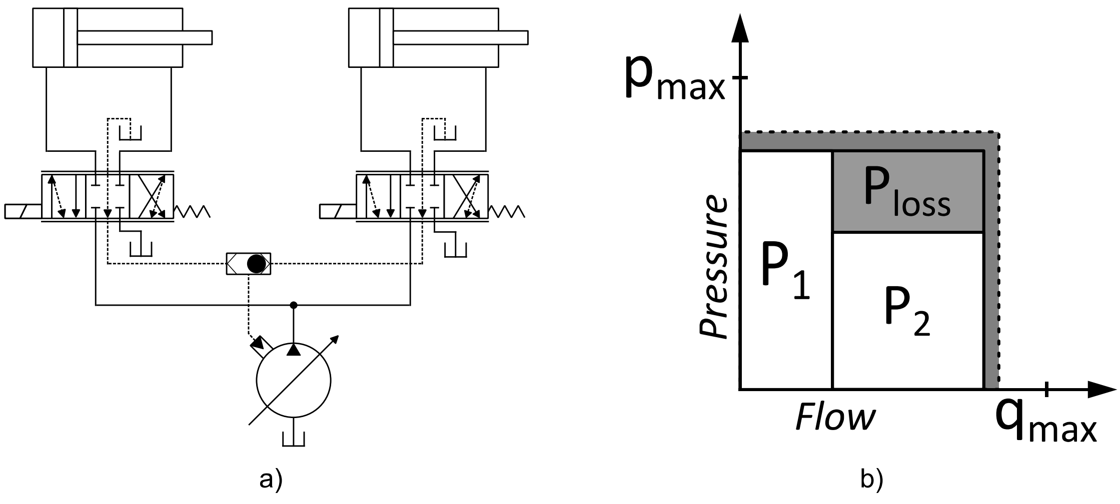

Figure 1 - Load-sensing system. a) Simplified hydraulic circuit for two actuators. b) Loads power consumption and losses

Although this system has been a successful change when compared to an open-centre valve circuit or a pressure-controlled system concerning system efficiency [1] and improvements have been proposed by combining, for example, load-sensing with open-centre solutions and controlling both the pressure and flow of the pump [3], the energy loss is still present through the load interference since a pump is always shared between actuators.

Current research on electrified systems

Different countries are instituting regulations with a focus on reducing the consumption of fossil fuels and emissions from vehicles. For companies that require heavy machinery, such as mining and civil construction, new laws and requirements should be followed, and OEMs are now searching for different ways to power the vehicles, such as battery, fuel cell and hydrogen combustion [13].

New challenges arise when sizing these vehicles regarding operation time, energy management and cost, but it also opens new possibilities for the design of the different systems in the machine. If a fully electric vehicle is considered, then having the hydraulic pumps connected directly to the prime mover is not a necessity anymore, since smaller electric motors and pumps can be installed on different spots of the machine and powered through electric cables. The hydraulic connections could also be done with shorter hoses, for example, since the pumps could be installed closer to the machine's actuators.

One topic nowadays is pump-controlled systems. When considering the flexibility provided by electric systems, one example is [14], which analyses a pump-controlled solution to operate differential cylinders. A single electric motor is used to power two fixed displacement pumps/motors and a control strategy is discussed. There are no throttling losses through valves and the flow is only provided to each of the chambers when needed. [15, 16] discuss different electro-hydraulic solutions regarding the number of pumps and utilization of hydraulic transformers or accumulators, while also comparing different architectures, benefits, and controllability challenges.

[11] discusses the application of the Digital Displacement Pump® in an electric scooptram. In this case, the electric motor speed is based on the operating cycle and the operator actions and two DDPs are used to provide flow to three actuators. Based on the design of the DDP, each one is modelled as a set of four small pumps with independent variable displacement connected to the same mechanical shaft, thus simulating an eight-pump system. The main advantages derive from the higher efficiency of the machines in a larger range of operating points and the fact that the valves can be used only to change the direction of the flow without acting as throttling components.

Another alternative for electric-powered hydraulic systems is presented in [17]. Here the discussion revolves around controlling two cylinders with multiple fixed pumps connected to different chambers of the actuators and powered by variable-speed electric motors, a system denominated as an electro-hydraulic variable-speed drive network. Different architectures are compared, considering how pumps can interconnect different chambers and how to size them, while completely removing the need for throttling valves.

A MULTI-PUMP ARCHITECTURE FOR MODULAR EXPANSION

The previous research shows the potential for electrification and digitalization and how those systems can improve overall efficiency by eliminating throttling losses. To expand on these ideas, a new architecture for two cylinders is proposed in Figure 2. The basic components considered are two actuators that should be operated by four fixed displacement pumps/motors plus four variable speed drives (VSD) for electric motors and thirty on/off valves. In the figure, A_n are the actuators, P_n are the pumps, P_{nm} are the pump ports connected to the valves and S_n refer to the service lines that connect the valves to each actuator chamber.

Another goal of this study is to evaluate how the system could benefit from using smaller fixed-displacement pumps. Smaller machines can normally operate at higher speeds to reach the same flow as a larger pump, which could reduce the overall weight and space required for installation. Scooptrams and excavators also commonly work under operating cycles that do not always require the maximum power at the actuators, thus having multiple pumps would allow the system to operate only the number of components needed at the adequate speed to reach maximum overall efficiency.

The considerations and ideas behind the proposed architecture can be summarized in the following points:

- The proposal considers identical-size pumps and valves, which can reduce the overall cost of production and allow for modularity,
- The system should operate by transferring fluid between the actuators directly through the valves, allowing for energy recuperation or through a pump if a higher pressure is needed,
- An auxiliary pump connected to the tank is available for use when extra flow is required or when excess flow should be returned to the reservoir. This extra pump allows the system to adjust the low-pressure level during operation,
- The variable speed drives also allow for energy recuperation by charging the vehicle batteries with the hydraulic machines operating as motors.

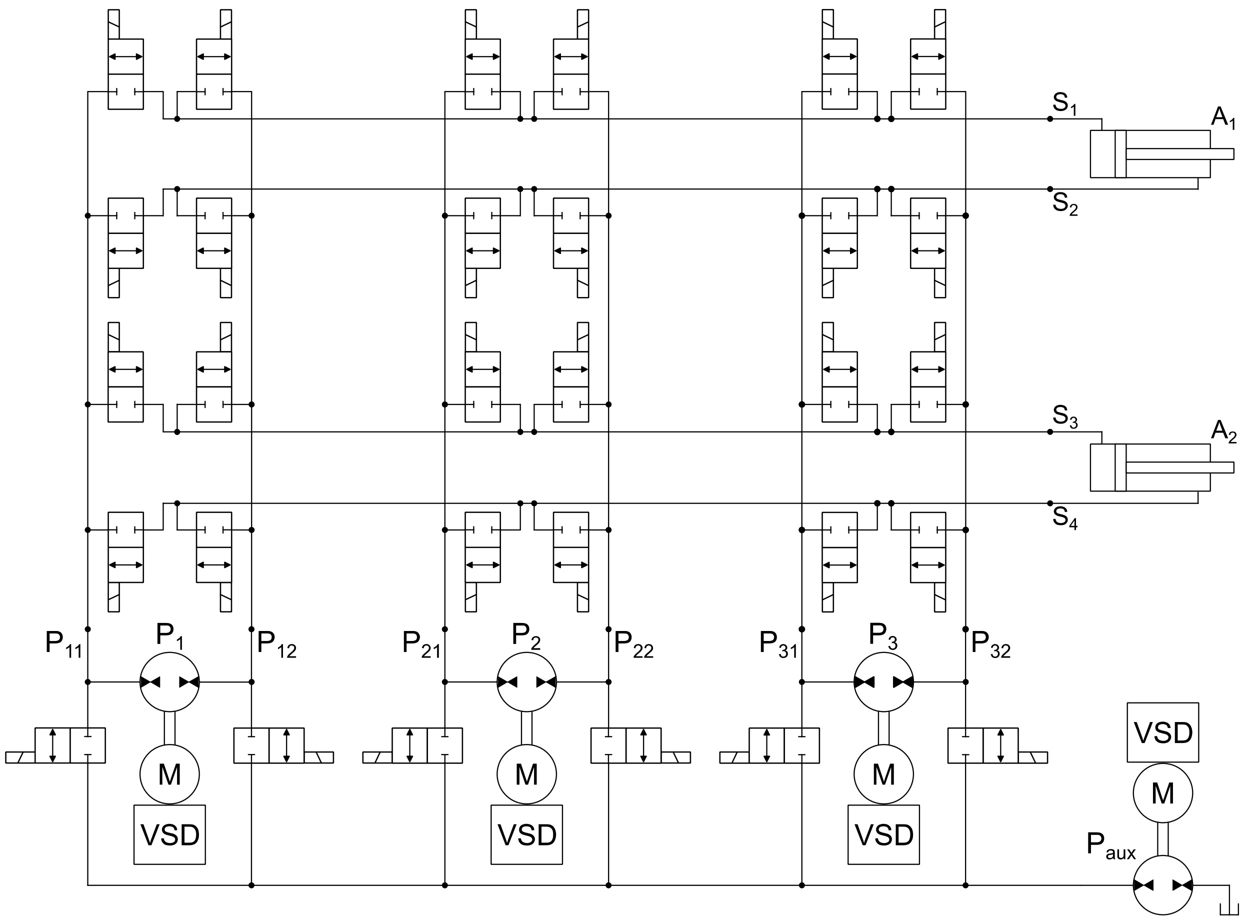

Figure 2 - System diagram for two actuators

The architecture shown allows for all possible interconnections between components. This means that each chamber from each actuator can be connected to any one of the pumps' inlets or outlets or the auxiliary pump. A single pump can be used if the required flow is low or multiple pumps can be activated simultaneously if a function requires a higher flow.

As an example, one could consider actuators A_1 returning and A_2 advancing. One possible operation could be connecting S_1 to S_4 through the valves on the pump P_3 column for direct energy recuperation, and if there is excess flow, it can be directed to the auxiliary line. At the same time, S_3 could be connected to P_{22} so that P_2 can set the pressure for P_{21} which would be connected to S_2. If extra flow is needed, then the system could add flow from the auxiliary line or send it back to the tank through the auxiliary pump if there is an excess flow.

The number of valves needed can be calculated based on the number of pumps that are connected to the actuators' services lines (connection points S_n) times the number of valves needed for each pump setup, which are two valves connected to the auxiliary line plus four valves for each actuator, thus

$$n_v = (n_p - 1)(2 + 4n_a), \quad (1)$$

where n_v is the total number of valves, n_p is the total number of pumps and n_a is the number of actuators. Increasing the number of actuators means adding an extra line of valves while adding an extra pump adds a column of valves connecting to the actuators and two extra valves to the auxiliary line.

This proposal also allows for some level of modularity. Figure 3 below represents how the system can be expanded to include any number of actuators and pumps for application on different machines. In this regard, having a standardized valve block solution would allow for the basic system to be adapted to an excavator, for example, that includes an arm, boom, bucket, and swing, totalling four actuators, while the number of pumps could be increased to achieve the maximum required flow instead of increasing the size of the components.

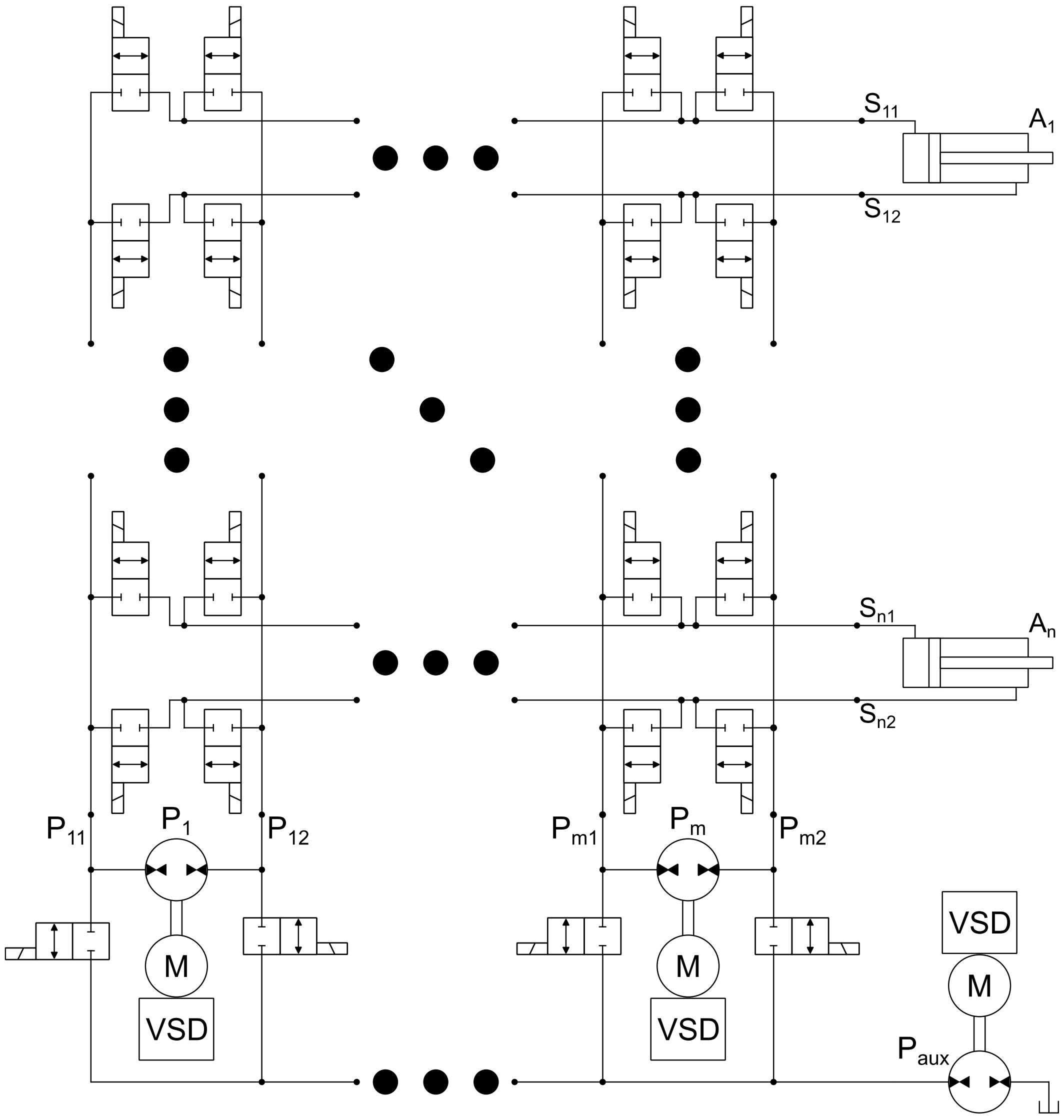

Figure 3 - General modular diagram for the multi-pump architecture

Evaluation proposal for the multi-pump system

The first step in evaluating this system will consist in analysing the possible gains of using multiple pumps. When the maximum flow is not needed, then a single pump operating at high speed could provide all the flow or multiple pumps could be active at the same time at a lower speed. The ideal solution could depend on the drive cycle considered and on the efficiency of the machines at the operating conditions. A sizing study and static evaluation with one or two actuators will provide insight into the system's behaviour and operating limitations.

The multi-pump system includes a high number of components that need to be operated. It also shows how to achieve a high degree of freedom, meaning that each pump can be connected to each actuator chamber at any moment. A system with four actuators and eight pumps (seven work pumps and one auxiliary pump) would require a total of 126 valves. A fair assumption is that the actual system would not need all these components to work adequately, but identifying what parts are redundant is a hard task to be done through an empirical analysis.

To tackle this problem, dynamic programming can be used to find the optimal solution. The system can be modelled as a discrete-time optimization problem where a target function, for example, minimizing the total energy consumption, is the main objective [18]. By setting the vehicle to work on a drive cycle, it is possible to estimate what would be the optimal selection of valves and pumps and when to activate them at each time step.

This method was applied before in [11] to find the optimal control strategy for the scooptram with DDPs and estimate the system's efficiency. For the current application, besides giving more information regarding the multi-pump solution capabilities and how it would operate, the results should also indicate which parts of the circuit are redundant. It would be possible, for example, to identify certain valves (or valves combination) that are never used because a more efficient alternative exists, which can be used as a basis for adapting the system architecture to a simpler alternative.

Finally, the results of the dynamic programming and the simplified architecture can then be analysed from the dynamic perspective to develop an adequate control strategy. Rule-based controllers tend to increase drastically in complexity as the number of control variables increases, in this case, pump speeds and valves, so alternative methods should be studied. Machine learning is one alternative that should be considered, where the system is trained with different drive cycles to define the ideal combination of valves and pumps that should be active based on, for example, pressure levels and operator commands.

CONCLUSIONS

This paper focuses on the broad research area of electrification and digitalization, more specifically on the integration of hydraulic systems into fully electric machines and how to make the hydraulic system more efficient. A discussion about the different subtopics is presented and which methods and approaches have been considered by different research groups, including component development, digital hydraulics, electro-hydraulic solutions, and multi-pump systems.

A novel multi-pump architecture is presented that combines a series of fixed displacement pumps with variable speed electric motors and a set of on/off valves that can be used to control different actuators. The system is presented at its most generic state with a high degree of freedom for controllability and a discussion about its modularity and how it can be adapted to different machines is presented.

Dynamic programming is then discussed as a mathematical algorithm that can be used to identify the optimal solution for a given drive cycle. The results would serve not only to estimate the capabilities of the system but also to identify redundant components that could be excluded from the system architecture since, for example, a more efficient combination of valves and pumps should be used. Another analysis could revolve around determining which parts of the system are unfrequently used, thus a compromise between the number of degrees of freedom and the overall cost of the system could be studied.

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