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A Review Article Based on Energy-Saving Measures on Power Hydraulic System

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Abstract:

This article examines various ways for increasing the energy efficiency of a power hydraulic system. System design, improving components or product functionalities, and loss reduction are the three kinds of energy-saving schemes. The several types of energy-saving measures are briefly explored. In addition, numerous energy-saving potentials of power hydraulic systems are tabulated for a clear comprehension of the chronological progress toward an energy-efficient fluid power system. The energy efficiency of the hydraulic system is increased in the plan of system design by changing the configuration of the system. This goal can be achieved by using cutting-edge system design and advanced control strategies on the equipment/system, or by selecting the right equipment. Furthermore, decreasing energy losses in the hydraulic system can save a significant amount of energy. Hydraulic systems are generally less energy efficient than other systems such as electrical or mechanical. This article provides a quick overview of several energy-saving measures utilized in hydraulic power systems.

Keywords: A regenerative system, hybrid system, waste energy recovery, energy savings, throttling energy loss

1. Introduction:

Due to the continued depletion of natural fuel supplies in the universe, constant increases in fuel prices, and amplification of environmental pollutants, energy conservation is a growing research subject. Electrical, mechanical, and hydraulic transmission systems are the three basic categories of power transmission systems.

A battery is commonly used as an energy storage device in electrical systems, whilst fly-wheels & accumulators are used as energy storage devices in mechanical and hydraulic systems, respectively.[1,2,3] High energy density is a benefit of electric energy storage devices (such as batteries). However, because of its reduced power density, it is only suited for the limited recovery of brake energy. The flywheel in a mechanical system stores the extra energy as kinetic energy and releases it as needed by the system.[4] Its moment of inertia resists changes in rotational speed. The flywheel results in a larger mechanical system. System design, upgrading components or product functionality, and reducing system losses are all examples of ways to save energy in a hydraulic system.

The energy efficiency of the hydraulic system is increased in the plan of system design by changing the configuration of the system. This goal can be achieved by using cutting-edge system design and advanced control strategies on the equipment/system, or by selecting the right equipment. Control techniques are mostly used on mobile hydraulic equipment that includes a hydraulic pump/motor, a control valve, and an actuator. A variable displacement hydraulic pump with a fixed displacement hydraulic motor; a fixed displacement hydraulic pump and a fixed displacement hydraulic motor connected with a speed-controlled electric drive; a fixed displacement hydraulic pump–motor unit connected to flow and direction control valves, and so on are some of the different efficient hydraulic system combinations available.[5,6]

Furthermore, decreasing energy losses in the hydraulic system can save a significant amount of energy. Hydraulic systems are generally less energy efficient than other systems such as electrical or mechanical. Frictional and leakage losses occur in hydraulic moving elements such as the hydraulic motor, pump, controlled valves, and cylinders, lowering system efficiency. Moreover, the energy loss from the system is aided by pressure decreases through the fittings and pipes.[7] Aside from that, energy is lost owing to hydraulic system regulation. A control valve or throttle valve is usually used to regulate the flow of a hydraulic system. During the movement of the valve spool, these valves lose throttling energy. In comparison to other losses in the hydraulic realm, the throttling energy loss is significant, accounting for 60% of the total loss.

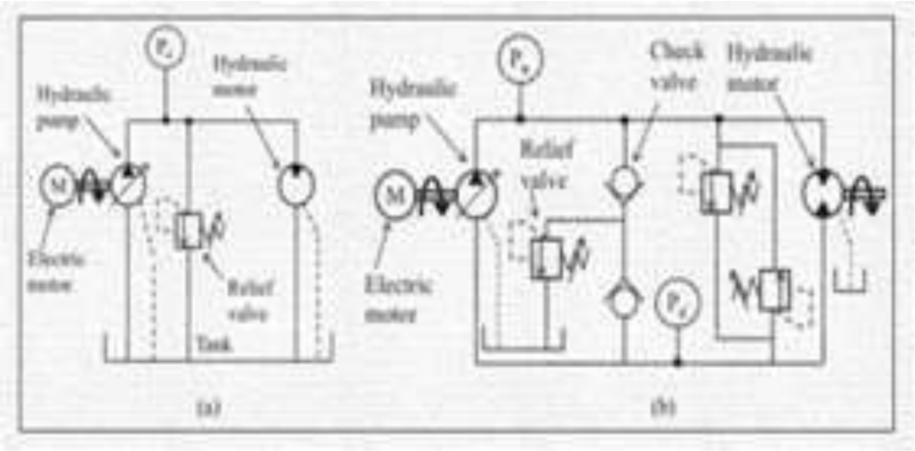

Fig.1 (a) Open-loop hydraulic system and (b) closed-loop hydraulic system.

The review presents multiple methods of energy conservation, such as system design, upgrading components or product functionality, and loss reduction, which are briefly reviewed. Each of the energy-saving methods is divided into several categories. Finally, by taking into account various parameters for energy-saving potential, a summary of energy-saving potential for each sub-category has been generated and given in a tabular format.

2. Different strategies for energy savings

2.1 Energy savings by system design

A significant method for improving the energy efficiency of a power hydraulic system is system design. Various hydraulic system designs,[8,9] such as open and closed-loop circuits, and control approaches, such as central or distributed system, displacement control or speed control, load-sensing system, common pressure rail system, and system hybridization, are described successively under this strategy.

Circuits with open and closed loops. As illustrated in Figure 1, the pump-controlled hydraulic system is divided into two types: open-loop circuit type and closed-loop circuit type. The hydraulic pump can draw its flow from a reservoir and return it directly to the reservoir after performing its duty using an open-loop arrangement. In a closed-loop system, however, the return flow line is directly connected to the pump inlet.[10] Only the leakage flow returns to the reservoir, which requires a booster or charge pump to replenish. The pump's swash plate angle, which can be regulated by a compensator, determines the pump's displacement (hydraulic valve). The hydraulic pump's swash plate control also reduces the system's noise. As a result, the pump remains in great condition, which has an indirect impact on system efficiency. The layout of open-loop hydraulic systems is straightforward. Because of its simplicity, it is cost-effective and reliable. A feedback mechanism is not present in an open-loop hydraulic system.[11] As a result, the answer obtained from an open-loop system is not very exact; thus, this system is unreliable. In contrast to its open-loop equivalent, closed-loop technology is more reliable. The closed-loop system, on the other hand, is difficult to build.

2.2 Improvements to the hydraulic system's function save energy

The energy savings of a mobile power hydraulic system are directly tied to the hydraulic system's operation or function. Under this subsection, energy recovery, storage, regeneration, individual metering, and control algorithm are the various techniques for improving the energy efficiency of the mobile hydraulic system. All of these energy-saving techniques are discussed in order.

2.3 Energy recovery, storage, and regeneration system

Tractors, trucks, excavators, earthmoving machinery, and city buses are heavy commercial vehicles with a tendency to change modes (start/stop) frequently. There are three different modes of operation for hydraulic systems used in commercial vehicles: driving mode, cruising mode, and braking mode. In driving mode, the principal energy source (hydraulic motor, high-pressure accumulator, or flywheel) is employed to power the other machine elements. The hydraulic power source (accumulator) is cut-off in cruising mode, and only the flywheel or prime mover supplies power to the driving member.

There are several methods for recovering energy from a power hydraulic system. A constant pressure system (CPS) is one of the most important and widely used methods for recovering the system's braking energy.

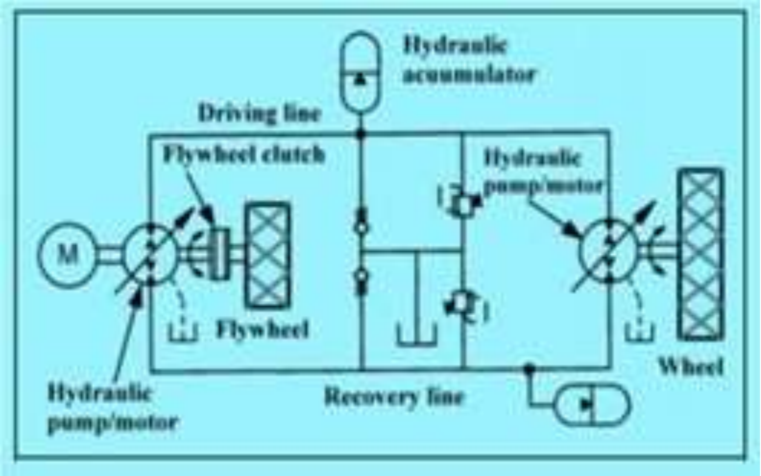

Fig.2 switching type closed-loop CPS system

This system comprises an auxiliary hydraulic pump/motor and a prime over or flywheel, which allows it to collect the load's braking kinetic energy and then reuse it to meet the energy demand. During braking, the flywheel's kinetic energy is transferred to the hydraulic pump via the hydraulic motor and load. Many researchers have previously investigated how to improve system performance or efficiency by including CPS configuration in the system. Triet and Ahn have presented a CPS hydraulic model (shown in Figure) for further development, which eliminates several unnecessary hydraulic machines from the traditional CPS system.[12] Their method is not only cost-effective, but it also improves the system's total round-trip efficiency. In a mobile application, the CPS system includes a greater specific energy–based flywheel and a hydraulic connection structure from the primary power source to the load, which provides superior driver comfort. It also eliminates hydraulic shock problems due to its ability to solely flow fluid in one direction.

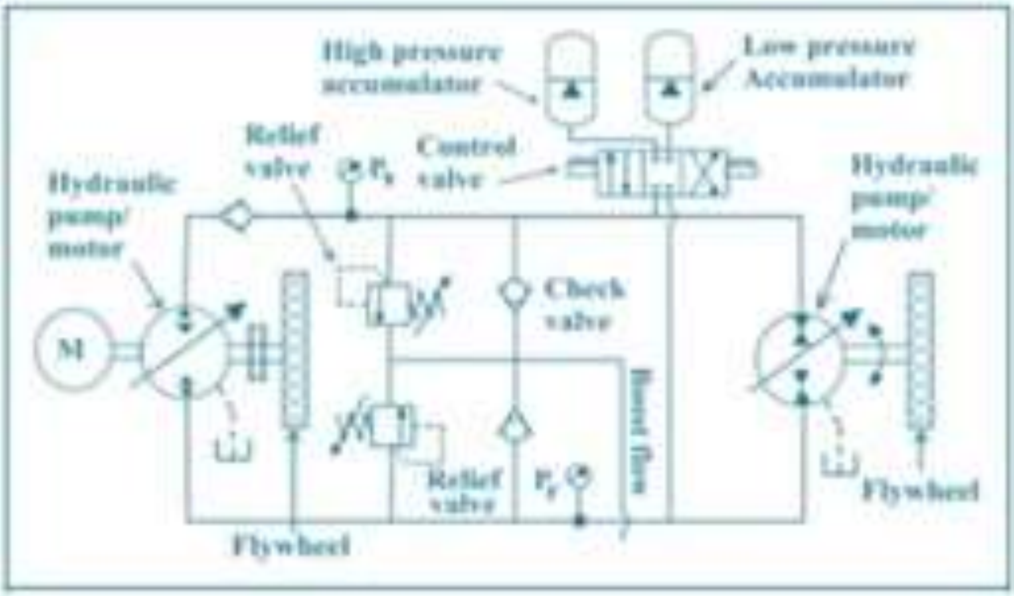

Fig.3 CPS hydraulic model

2.4 Individual metering

A mechanically operated valve controls the hydraulic actuators in a traditional hydraulic system. This design is difficult to control, and its energy consumption is considerable, especially when it is over-running. The figure depicts a typical hydraulic system with a 4/3 (four-way three-position) proportional valve (a). The meter-in and meter-out principles are used to increase the hydraulic circuit's controllability. The flow control valve and the check valve are placed in the meter of the hydraulic circuit so that the actuator flow can be controlled. The cylinder extension operation is controlled in the meter-in circuit.

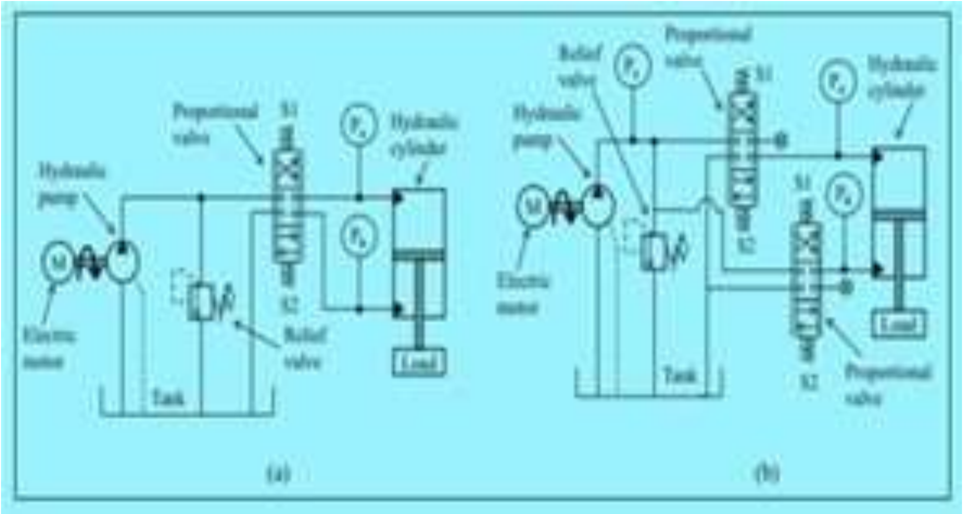

Fig.4 (a) Typical 4/3 proportional directional valve controlled hydraulic system and (b) meter-in and meter-out controlled hydraulic system.

The check valve, on the other hand, ensures that the return flow escapes the flow control valve during the cylinder's return operation. On the contrary, in the meter-out hydraulic system, the flow control valve is incorporated in the output line of the cylinder. The valve is controlled electronically and is embedded with electronic control algorithms in this technology. The pressure loss across the meter-in and meter-out orifices of the valve is significant in that system. Liang et al. altered the configuration of the same system without changing its function to minimize the loss, as shown in Figure. (b). It enhances system efficiency by allowing the meter-in or meter-out orifices of the valve to be controlled.

2.5 Control algorithms

PID, fuzzy logic, generalized super-twisting algorithm, and fuzzy-PID position are all well-known control algorithms that are used in real-world situations. Electro-Hydraulic Actuators (EHA) control and Digital Displacement Technology have evolved in recent years, both of which are directly related to increasing the energy efficiency of a power hydraulic system.[13,14] The following subsections go through these two control techniques.

3. Digital displacement technology

In full displacement situations, conventional hydraulic machines are effective. However, performance suffers dramatically when partial displacement is used. Digital displacement technology was used to increase machine performance under partial load scenarios. It is a promising technology in fluid power hydraulic machines that deal with advanced level control technology, and it delivers improved energy efficiency over a wide range of conditions, including part-load conditions. The radial piston arrangement is used in these machines, with the piston drives in the center and the valving radially outboard. The reciprocating mechanism underpins the operation of reciprocating hydraulic equipment such as pumps and motors. The pistons of the cylinder oscillate in volume when the shaft of the hydraulic equipment starts to rotate. For filling or emptying the cylinder chamber, a control valve or a flow-regulated device is required. This technology not only increases part-load efficiency but also improves dynamic response time.[15] This technique was previously used to provide sustainable energy benefits in wind and wave energy power transmission systems. Furthermore, when the same technology is used in an excavator, it has a fuel-saving potential of up to 20% and a productivity increase of approximately 30%.

4. Energy savings by reduction of energy losses

The most promising study in the subject of power hydraulics is the energy savings of a hydraulic system by lowering energy losses from various sources. In comparison to other power transmission systems such as mechanical and electrical systems, the power hydraulic system has lower energy efficiency. Energy losses from various sources contribute to lower efficiency. Fluid frictional and leakage losses occur in the movable elements of the hydraulic system, which are one of the principal sources of energy loss. Hydraulic drive systems also experience fluid compressibility loss, accumulator hysteresis loss, valve transition loss, and head loss. Fluid compressibility loss is proportional to the bulk modulus of the working fluid and is small in comparison to other losses.

However, in the vast majority of situations, it is overlooked. During the fluid movement through the hydraulic system's pipes and fittings, a large amount of pressure drop or head loss occurs.

5. Improving component performance by improving the current design

Nowadays, the majority of hydraulic system equipment is powered by electricity and controlled digitally. The hydraulic technology's flexibility has substantially expanded as a result of the high-level engagement of electronic control. It may present a once-in-a-lifetime opportunity to design an energy-efficient, controllable power hydraulic system. The control valve is responsible for the throttling energy loss, which is a substantial loss contributor in the valve-controlled hydraulic system. Because the proportional directional control valve can be regulated more effectively and switches from one position to another in less time, the directional control valve accumulates more energy losses than the proportional directional control valve. The pressure drop loss during the flow via the directional control valve was studied using computational fluid dynamics (CFD) by Lisowski and Rajda. A redesigned directional control valve with four logic valves on the body replaces a 4-way directional control valve with pilot-operated check valves in this study. ANSYS/FLUENT is also used to build and verify the system flow routes inside the body.[16] A newly created directional control valve has been discovered to reduce pressure drop loss into the system by 35 percent. Rannow and Li also proposed a novel soft switching idea for the power hydraulic On/Off valve-controlled system. When the On/Off valve is in transition mode, the soft switch keeps the high-pressure throttle fluid in its cylindrical chamber and releases it when the valve is fully open.[17] The figure depicts the proposed soft switch with a valve-controlled hydraulic system.

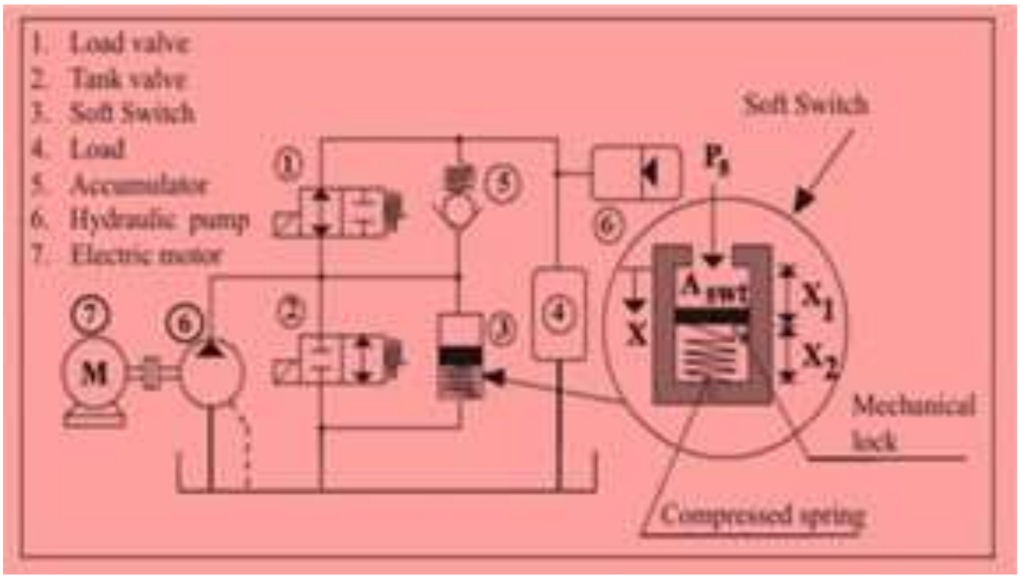

Fig.5 Soft switch with valve-controlled hydraulic system

In addition, Mahato et al. looked examined the impact of different soft switch characteristics on energy savings.

The hydraulic pump is usually driven by an electric motor in most hydraulic drive systems. In industrial applications, the configuration of the fixed-speed electric motor drive hydraulic pump remains critical. The introduction of variable-speed electric motors and digital control systems in recent years has resulted in a considerable improvement in hydraulic system performance.

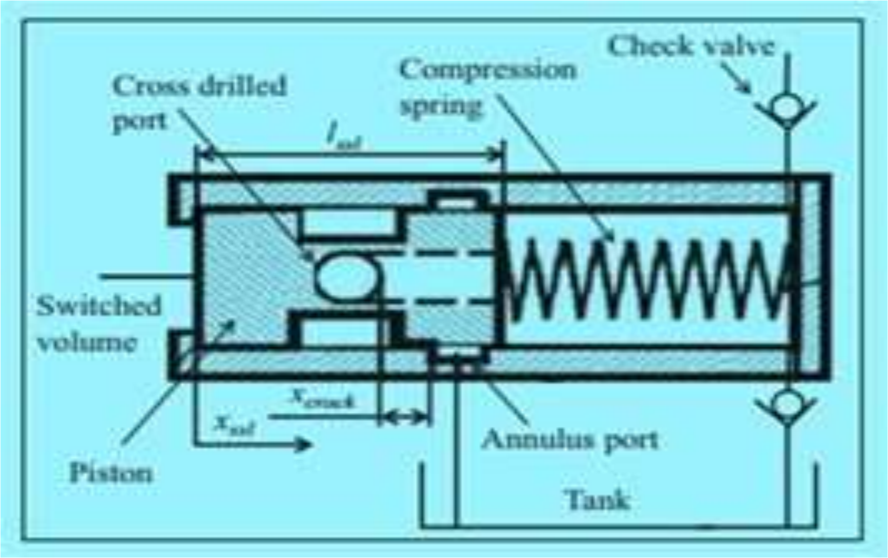

Fig 6. Schematic diagram of the locking soft switch

This advancement also makes the hydraulic system more cost-effective. As a result, the most cost-effective alternative is to combine a speed-controlled electric motor with fixed displacement hydraulic pumps. In comparison to the variable displacement-controlled hydraulic arrangement, the variable speed controlled with fixed displacement pump hydraulic configuration has superior energy efficiency, especially at part-load conditions.

6. Efficiency improvement of individual components

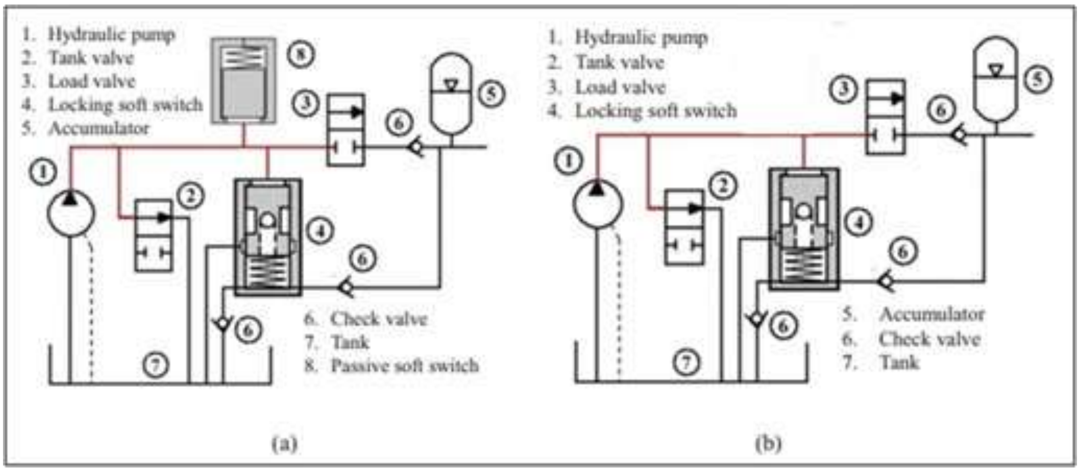

Fig7b. (a) Hydraulic system with both soft switches, that is, locking and passive, and (b) hydraulic system with locking soft switch only

Beckstrand et al. have confirmed this. The results were validated in that study by merely inserting the locking soft switch into the system (see Figure (b)). The effect of the passive soft switch, on the other hand, has not been studied in the literature. Following that, Mahato et al. investigated the effect of including both passive and locking soft switches in a basic.[18,19,20]

switched-mode power hydraulic system (see Figure (b)). The bond graph technique is used to create dynamic models of the hydraulic system with and without a passive soft switch. The system's bond graph models are also simulated, and the results are compared. If the passive soft switch is removed from the system, an extra 3.25 percent of throttling energy can be saved. A multi-run simulation of the bond graph model is also used to optimize the soft switch parameters. The bond graph is a graphical depiction of a physical dynamical system that can interact with several different energy domains. A multi-run simulation technique is also employed to optimize the soft switch characteristics, which aids in the effective fabrication of the soft switch.

7. An overview of various energy-saving measures

Energy-saving options for a power hydraulic system in terms of energy-saving potential. This research gives a basic grasp of the energy-saving potential of a power hydraulics system. Distinct energy-saving solutions have different characteristics to identify their potentiality (energy recovery efficiency, fuel-saving potential, breaking energy recovery potential, throttling energy saving, etc.). The fuel-saving capabilities of a displacement-controlled excavator system are about 40%, and the maximum energy recovery efficiency of a CPR HST system is about 66 percent, according to the system design strategy. In addition, an electric hybrid system and a hydraulic hybrid system have energy recovery efficiency of 53 percent and 69 percent, respectively. Furthermore, the PHH and SHH systems have a fuel-saving potential of 10%–25% and 20%–40%, respectively. Similarly, the following technique, which involves increasing the hydraulic system's operation, can recover up to 50% of the load's kinetic energy in the CPS system. The hydromechanical hybrid CPS system (CPS) with a flywheel has a brake energy recovery potential of 78 percent. Furthermore, when digital displacement technology is used on an excavator, fuel savings of up to 20% are possible. Using a gentle switching idea, 56 percent–66.1 percent of throttle energy-saving potential is observed in the reduction of energy loss (REL) strategy.

8. Limitations of power hydraulics system

Because the power hydraulics system has inherent drawbacks, its applicability is limited in certain fields. Due to fluid flow resistance and leakages, the power hydraulic system's efficiency is low. Internal and external leakages are the most common problems in hydraulic power systems. Internal leakage takes place inside the equipment and is not visible from the outside, yet it adds to system power loss. Furthermore, the handling of the power transmission medium, namely hydraulic liquid, is untidy and leakage-prone. The hydraulic fluid should be pure; any contaminants could cause serious damage to the apparatus.[21] As a result, it must be fitted with an appropriate filter. Because the liquid used to transport the power is not completely incompressible, this system should be avoided if the transmission ratio is a highly sensitive parameter. The problem can be solved by using hydraulic equipment that was designed ahead of time. It may, however, raise component or total system costs. Leaks and other faults in the power hydraulic system can be reduced or eliminated with regular inspection and maintenance.

Conclusion

This article presents a complete analysis of a hydraulic system's energy-saving potential using several tactics such as process optimization, equipment performance enhancement, waste energy recovery, and energy loss reduction. Each method is divided into distinct types based on the system configuration, control prospects, hydraulic equipment availability, and other system losses. All tactics and their subcategories are briefly discussed.

Following that, their benefits and drawbacks are briefly discussed. Following that, the energy-saving potential in several areas is assessed and contrasted, including energy regeneration, fuel-saving, brake energy recovery, and throttling energy savings. The following are the results of this research;

1. The process optimization strategy's maximum energy recovery efficiency is 53%, and the fuel savings potential is between 20% and 40%.
2. Under the energy-saving approach of equipment performance improvement, a displacement-controlled excavator system has a fuel-saving capability of roughly 40%.
3. In the CPS, the highest brake energy recovery capacity is around 78 percent of the waste energy recovery.
4. Using a soft switching idea, the maximum throttling energy-saving potential of the reduction of energy loss strategy is around 56 percent – 66.1 percent.

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