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REVIEW OF ENERGY-SAVING TECHNOLOGIES IN MODERN HYDRAULIC DRIVES

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Abstract. This paper focuses on review of modern energy-saving technologies in hydraulic drives. Described main areas of energy conservation in hydraulic drive (which in turn are divided into many under the directions) and was established the popularity of them. Reviewed the comparative analysis of efficiency application of various strategies for energy saving in a hydraulic drive. Based on the review for further research a combined method of real-time control systems with energy-saving algorithms and regeneration unit – selected for maxing efficiency in hydraulic drive. Scientific papers (40 papers), what introduced in review, is not older than 15 years in the databases "Sciencedirect" and "Scopus".

Keywords: Energy-saving, hydraulic drive, energy regeneration, construction and road machines, liquid energy.

Introduction

Currently, a lot of different construction and road machines have been designed based on various design concepts and designs. According to Helbig (2002) the drive of their working equipment is provided by power transmission, which is able to consume in the working cycle from 30% to 100% of the energy of the primary combustion engine or electric motor. At the same time, Kanezawa *et al.* (2002), notes that the requirements for this technology are constantly growing, the main ones being: productivity, environmental friendliness, reliability and low energy intensity.

With regard to hydraulic drives, Takahashi *et al.* (2010), Zhao *et al.* (2015) marked that energy-saving technologies allow not only increasing efficiency and reducing energy consumption, but also to increase reliability, simplify the design, significantly increase the service life of components, working fluids and seals.

Review of main directions of energy saving in modern hydraulic drives

In order to understand the development of research in energy-saving area of hydraulic drive in the last years, it is important to conduct a literature review to understand the different ways of energy-saving which hydraulic drive has evolved as well as to identify research gaps.

The review was conducted on the basis of keywords "Energy-saving in hydraulic drive" in the databases – "Sciencedirect" and "Scopus". For analysis were taken scientific articles not older than 15 year.

Adachi *et al.* (2007), Wang *et al.* (2010) indicated that one of the most feasible ways to reduce power consumption in the hydraulic drive is to reduce the dynamic effects in a system. Stosiak (2015) in his work notes that periodically arising pressure fluctuations in hydraulic systems cause various problems, for example, excessive noise emission, decrease in the service life of components, violation of control loops, power loss (pressure) in the system, etc.

Pressure fluctuations can occur either in the hydraulic systems themselves (Fluid vibration) or due to external causes (Mechanical vibration), for example, due to periodic fluctuations in load on hydraulic cylinders or motors (classification of Chenxiao, Xushe 2012). It is also known that in hydraulic systems with high dynamics (for example, controlled electrically proportional or servo valve) and with hydraulic cylinder or engine, there may be too high pressure level of fluctuation what leading to energy losses (Stosiak 2015)

Solutions for this type of problem can be achieved by introducing some elastic-damping elements into the hydraulic drive (Ortwig 2005; Han, Wang 2010; Amirante *et al.* 2014), most often hydraulic accumulators and various fluid flow dampers. For example work of Makaryants *et al.* (2015) base on working fluid pressure pulsation at pipeline of punching machine with install damping element near pump, which produced for a reduction of hydraulic pulsations in the system about 38...40% of the initial, resulting in a decrease in pressure loss.

In test benches with harmonic vibrations, proposed by Yakushev (2005), of the executive hydraulic cylinder, the supply of the feed pump, defined as the product of the maximum instantaneous speed of movement to the area of the piston, can be reduced by 30% and reduce fluctuations by installing in the pressure line air-hydraulic accumulator. Also, the installation of a hydraulic accumulator, for example, in power cylinders of a loading manipulator with a payload capacity of 0.8 *t* allowed to reduce the energy costs by 7...12% due to the reduction of peak pressure spikes in the hydraulic system during the transient regimes and, accordingly, to reduce the dynamic effect on the hydraulic pump (Nesmiyanov, Khavronin 2007).

In the presence of short-term high-speed mechanisms (for example, ejectors) in the hydraulic system, good results of energy saving (Company HYDAC around 16...18% of energy saving) are provided by the batteries installed directly near the cylinders which excludes both vibrations in long pipelines. The weight had been downsized by 25%.

Shen *et al.* (2016) indicated that disadvantage of active vibration compensation systems is that energy is added to the hydraulic system via the actuator, which fundamentally worsens the stability of the entire system and, even with an inaccurately tuned regulator, can even lead to deterioration of the system's characteristics (under certain conditions, the amplitude of pressure fluctuations does not decrease, and even increases).

Energy recovery system (ERS) is not a new concept. Many ERS have been reported concerning different kinds of energy in modern machinery industry. The potential energy in these applications can be converted to many kinds of energy to restore.

The use of recovered energy in the working cycle will save considerable energy resources. Energy can be accumulated during the lowering of the load, idle movements of the working element or in another way, for example, when the entire unit brakes. As evidenced in a number of studies by scientists: Kagoshima *et al.* (2007); Ochiai, Rye (2008); Rohit *et al.* (2012); Wang, Wang (2012); Lin *et al.* (2017) and the leading companies of construction and road machinery in the world: Caterpillar, Manitou, Komatsu, John Deere, JCB, New Holland, Volvo, Hitachi and Kubota.

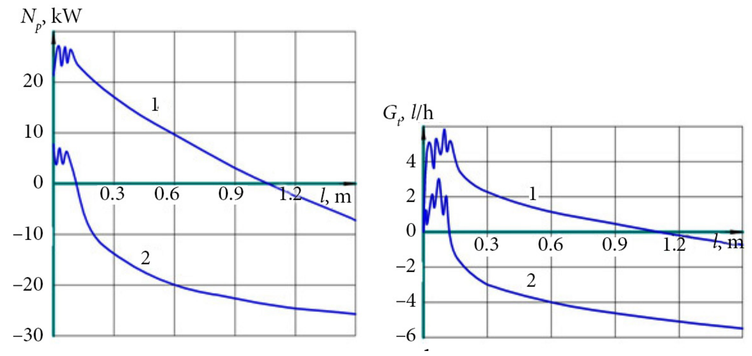
Recuperative braking – in the broadest sense it is the physical process of slowing or stopping the movement of a mass, for example, a moving front loader (can recover 18...22% of energy (Nesmiyanov, Lapynin 2011)), a rotating superstructure of an excavator or a descending arrow of an excavator, (Shen *et al.* 2015 – *ERS* could be reduced by more than 30%), and transforming the kinetic energy into another form of energy that can be accumulated or used immediately to perform useful work.

Karpenko *et al.* (2017) is considered to improve the efficiency of using a forklift class IV–VII (with an internal combustion engine) by introducing a hydraulic energy-saving system based on the potential energy of the working equipment. Using the proposed energy-saving system makes it possible to reduce power consumption by 32% and hourly fuel consumption by 3.1% of its initial value (Fig. 1).

Nyman *et al.* (2004) introduced an ERS in electric warehouse truck with a counter balance technique which integrated a hydraulic pump/motor (PM). 40–60% of the lifting energy can be saved with the combination of the counter balance and battery obtained from the simulation.

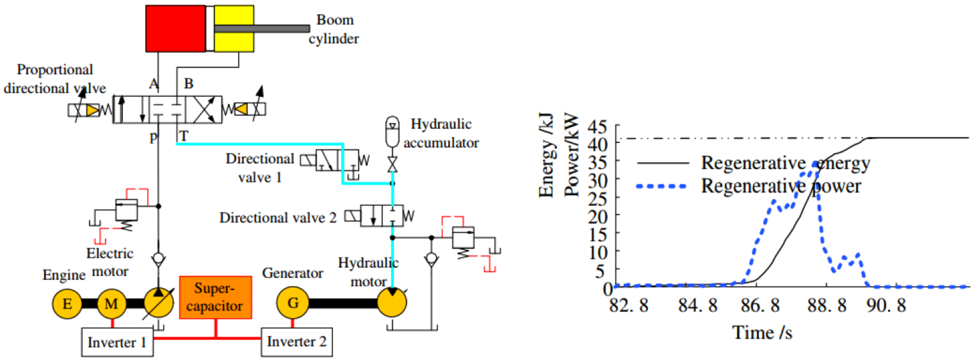
The inertia energy of mechanical motion is used to drive an electric motor running in the generator mode or a hydraulic motor (Fig. 2 by Tianliang *et al.* 2016) The potential energy could be converted into electricity and stored in an electric accumulator which can be a battery or capacitor for later use, it's produce more than 65% of the total regenerated energy and power.

Using hydraulic PM in hydraulic ERS is also suitable for the secondary unit. Triet, Kyoung (2012) presented a novel hydraulic ERS which was based on a hydrostatic transmission system and used a hydraulic accumulator to



a) b)

Fig. 1. Graphics of the research: a) Power consumption; b) Instantaneous fuel consumption: 1 – with ERS; 2 – without ERS. From Karpenko *et al.* 2017



a) b)

Fig. 2. Schematic of the ERC research from Tianliang *et al.* 2016: a) hydraulic scheme; b) graphics of regenerative power and energy

store energy. The novel configuration can regenerate the kinetic and potential energy without any fluid flowing. The experimental results showed that recovery efficiency changed between 22%...59%.

One of more popular method, in modern time, it's use the combined of two methods (ERS and reduce dynamic loads). The proposed power generation unit, by Karpenko, Bogdevičius (2017), can within a short period of time (about several tens of milliseconds), increase the fluid pressure several times (Fig. 3) as compared to the primary pressure and charge the hydraulic accumulator. Hydraulic accumulator used its recovery potential energy for smoothing pulsation in the pressure hydraulic lines, and also the compensation of volume and pressure during transient pump processes for energy saving in hydraulic drive.

Also in modern hydraulic drives used, throttle regulation, volumetric control or volumetric-throttle for energy-saving.

In the first, the change in the speed of the movement of hydraulic motors (cylinders or hydraulic motors) is realized by throttling the flow of the fluid (Li *et al.* 2015).

In the second – due to changes in the working volumes of pumps and hydraulic motors (Chen, Zhang 2011) research variable displacement of double action vane pump what can produce about 1/3 of energy saving.

From view the point of energy saving, throttle control is the least acceptable, in work of Yoshida *et al.* 2010, it's about 17%, however its design simplicity and high speed in drives of relatively low power (usually up to 3...5 kW) in many cases decisive.

In a number of throttle control systems, the reduction in energy losses is achieved by replacing the two-line flow regulators with three-linear regulators, since the latter change the pressure at the pump outlet depending on the acting load. However, three-linear regulators can be installed only at the entrance to the hydraulic motor, fed by an individual pump (Li *et al.* 2015).

Yuken's new frequency control system with pressure compensator provides energy savings by adding a pressure sensor and frequency converter to the asynchronous motor. By reducing the pump speed at zero feed rates from 1800 to 300 min^{-1}, power losses at a pressure of 15 MPa decrease from 1.5 to 0.5 kW.

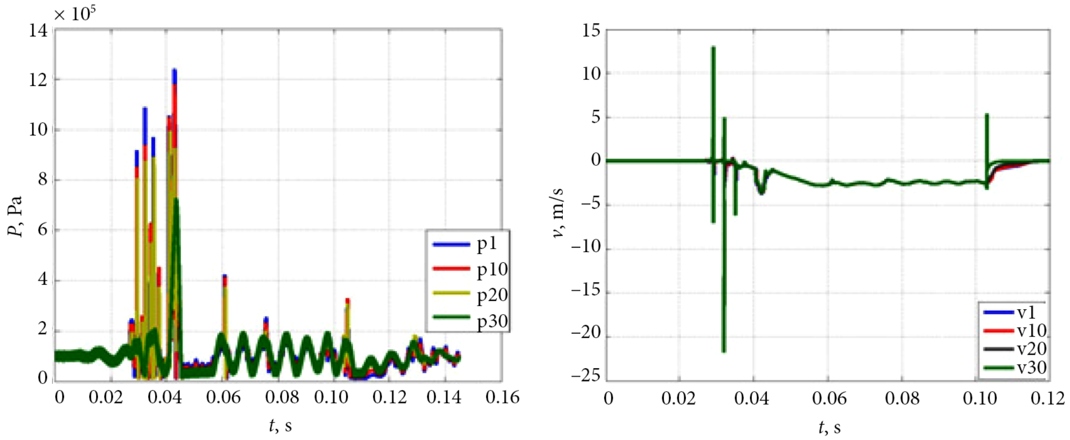


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Fig. 3. Graphs of research by Karpenko, Bogdevičius 2017: a) Graphs of the pressure of the fluid dependent on time in generation unit; b) Graphs of the speed of the fluid dependent on time in generation unit

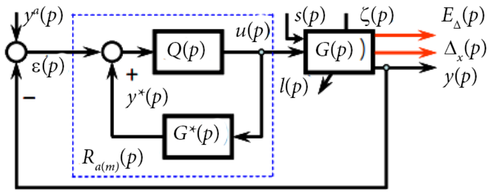

Fig. 4. R (M) – internal model control system from Nikolov 2003

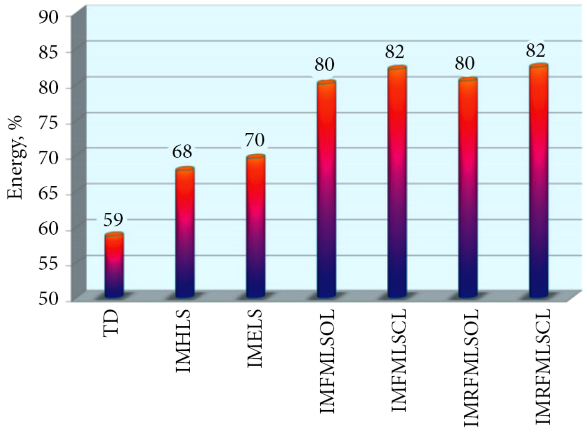

Fig. 5. Efficiency comparison for all the systems analyses by Borghia *et al.* 2014

An effective way is to install and power saving control multithreaded pumps, which can be individual unloading of individual sections, at the same time, the power consumed by the electric motor remains approximately constant it can produce energy saving about 30…50% (Huova *et al.* 2010).

Also, often, as energy saving in a hydraulic drive apply the newest systems of distribution of energy flows (control). The functioning of the flow of distribution systems allows ensuring the optimal technological process of the machine operation, to determine the efficiency up for about 20% of application and to reduce the costs of idle work of the hydraulic system (Pelevin, Karpenko 2016).

Proportional electric control of hydraulic devices significantly expands the possibilities of energy saving. Distributors, inductors and valves allow smoothly and accurately adjust the operating parameters of hydraulic drives in accordance with the signals coming from the control system at any time during the operation cycle of the equipment. At the same time, an optimal relationship between displacement, speed, pressure, flow and other parameters is provided to minimize energy losses (Gao *et al.* 2014).

Dexter (1981) introduse standard PID – control systems are designed, represented with the controllers PID and with the control signal. This method can produce energy-saving between 13…15%.

Nikolov (2003), introduce R (M) – internal model control system through the method of the "free parameter" (Fig. 4), shown with the control signal; this method can produce energy-saving between 21…25%.

R (F) – internal model control system and with conditional feedback through the method of "the balance sensitivity equation" (Real-time control). This method can produce energy-saving between 34…38% (Plummer 2016, Riccardo *et al.* 2016).

Of a particular interest are the possibilities of the presented method for comparison of the energy-saving properties of the control systems of same class. From the simulation results one with best energy-saving properties is the R(F) – system.

Comparison of energy-saving method

Borghia *et al.* (2014) in the paper and leaning on the work of Huova *et al.* (2010), Meyer *et al.* (2011) and Yao *et al.* (2014) comparison different strategy for energy-saving in hydraulic drive.

TD – traditional single spool distributor commonly.

IMHLS – independent control strategy with electro-hydraulic load sensing for traditional pump control.

IMELS – independent control strategy with electronic load sensing pump control.

IMFMLSOL – independent control strategy with open loop flow rate control and flow matching pump control. IMFMLSCL – independent control strategy with closed loop flow rate control and flow matching pump control.

IMRFMLSOL – independent control strategy with regeneration mode, open loop flow rate control and flow matching pump control.

IMRFMLSCL – independent control strategy with regeneration mode, closed loop flow rate control and flow matching pump control.

In Figure 5 all the systems efficiencies are reported and compared.

It is possible to observe step by step that the efficiency increases from 59% for the traditional system, to 82%, for an independent metering system with regeneration and direct pump displacement control.

Topic analysis of methods

In the hydraulic drive are still relevant the main areas of energy conservation (which in turn are divided into many under the directions):

Regulation and control of hydraulic drive and components (12 articles).

Increase the efficiency of hydraulic drives through the use of hybrid systems and the recovery of working fluid (15 articles).

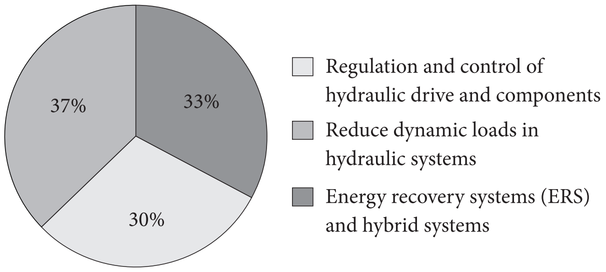

Fig. 6. Topic of energy-saving methods according review

Reduce dynamic loads in the system (13 articles).

Based on the review of scientific articles (40 of articles from databases "Sciencedirect" and "Scopus" basis of keywords "Energy-saving in hydraulic drive" in total) in this paper can say that each of the basic methods is equivalent. The popular way of energy saving in modern hydraulic drive (last 15 years) using ERS can be explained by the popularity of the hybrid system, but from 2015 control (real-time control with energy-saving algorithm) in hydraulic drive more popular Figure 6.

Conclusion

In the hydraulic drive are still relevant the three main areas of energy conservation (which in turn are divided into many under the directions).

One of the popular research directions in energy saving for hydraulic drive it's using hybrid systems and ERS (37% from review). In second place it's reduce the dynamic effects in a system (33% from review). In third place – control systems (30% from review), but this is due only to the beginning of work in this direction by the breakthrough in IT technologies.

Only the combined use of under the directions from each area can ultimately provide the greatest energy savings (up 82% of efficiency) in hydraulic drive than a single using each of them.

Based on the review, we can recommend, as a promising direction for further research, the combined use of energy saving methods in a hydraulic drive.

Based on the review for further research we selected a combined method of real-time control systems with energy-saving algorithms (MPC) and regeneration unit (ERS) for maxing efficiency in hydraulic drive. It will be one of the important research directions in the future.

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ENERGIJOS IŠSAUGOJIMO TECHNOLOGIJOS MODERNIOSE HIDRAULINĖSE PAVAROSE MOKSLINIŲ DARBŲ APŽVALGA

M. Karpenko, M. Bogdevičius

Santrauka

Šiame straipsnyje daugiausia dėmesio skiriama šiuolaikinių energijos taupymo technologijų apžvalgai hidraulinėse sistemose. Apibūdintos pagrindinės energijos taupymo kryptys hidraulinėje pavaroje (kurios savo ruožtu suskirstytos į daugelį pagal veikimo kryptį) ir nustatytas jų populiarumas. Peržiūrėta įvairių hidraulinių pavarų energijos taupymo strategijų efektyvumo taikymo lyginamoji analizė. Remiantis tolesnių tyrimų apžvalga, parinktas bendras realiojo laiko valdymo sistemų su energijos taupymo algoritmais ir regeneravimo įrenginiu metodas didinant hidraulinės pavaros efektyvumą. Peržiūrėti moksliniai straipsniai (40 darbų), ne senesni kaip 15 metų esantys *Sciencedirect* ir *Scopus* duomenų bazėse.

Reikšminiai žodžiai: energijos taupymas, hidraulinė pavara, energijos regeneravimas, statybos ir kelių mašinos, skysčio energija.