Electro-Hydraulic Hybrid Actuator System using Integrated Power Unit

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Abstract

Electro-hydraulic hybrid power transmission system can save fuel while maintaining the same performance in comparison to the conventional fluid power system driven by the combustion engine in mobile working machine applications. This paper introduces the electro-hydraulic hybrid actuator system specially developed for compact assembly. In this assembly all the components are located near each other to avoid the long fluid power transmission lines which quite commonly appear in big mobile working machines. Normally, in this type of machinery the transmission lines are flexible hoses and pipes of small diameter which cause remarkable power losses. Proposed actuator design allows the replacement of long flexible pipe lines by electrical cables. In the cables the losses due to their internal resistances are apparent but negligible in comparison to the losses apparent in the hydraulic transmission lines. The present paper introduces the electro-hydraulic hybrid actuator system and the integrated electro-hydraulic power unit. The actuator system is simulated.

KEYWORDS: Electro-Hydraulic, Hybrid, Power Unit, Pump-motor, Energy converter

1. Introduction

Electro-hydraulic hybrid system as an actuator system can save fuel while maintaining the same performance in comparison to the conventional fluid power system driven by the combustion engine in mobile working machine applications. This paper introduces the electro-hydraulic hybrid actuator system specially developed for compact assembly. In this assembly all the components are located close to each other to avoid the long fluid power transmission lines which quite commonly appear in heavy mobile working machines. Normally, in this type of machinery the transmission lines are flexible hoses and pipes of small diameter which cause remarkable power losses. Proposed actuator design allows the replacement of long pipe lines by electrical cables. In the cables the losses due to their internal resistances are apparent but negligible in comparison to the losses apparent in the hydraulic transmission lines.

The principal component of the proposed hybrid actuator system is the compact integrated electro-hydraulic power unit (see **Figure 1**) which consists of a hydraulic pump-motor and an electrical permanent magnet synchronous motor-generator. Integrated electro-hydraulic power unit can be driven in both operating directions to produce the mechanical power required from the actuator or to recover the energy released by the actuator mechanism.

One of the essential aspects in designing the energy recovery system in the form of electrical energy is efficient electrical generator. The compact design of integrated electrical machine imposes the use of efficient liquid cooling. The cooling of electrical machine requires a container for coolant and heat exchangers which would increase the weight and dimensions of the power unit. This is undesired because the power unit will be placed near the actuator. For this reason the electrical machine is specially designed to use the working hydraulic fluid as the cooling media.

The system in question is a pump-controlled fluid power system. The hydraulic pump is directly driven by the electrical motor. The pump-controlled fluid power systems have many advantages. The biggest advantage is the reduction of hydraulic losses in comparison to the conventional directional valve operated systems. But, unfortunately, these systems have also disadvantages which have limited the commissioning of the pump-controlled fluid power systems.

Asymmetric differential cylinder is a typical component in producing the force and movements of mechanisms. When it is used together with the pump-controlled fluid power system it can cause problems due to the differential volumes in cylinder chambers. The pump-controlled system is commonly operated in closed loop where it is essential to maintain the even volume flow in input and output ports of the pump. In case of the differential cylinder the difference in volume flows must be equalized, e.g. by using pressure accumulators.

The present paper introduces the electro-hydraulic hybrid actuator system and the integrated electro-hydraulic power unit. The actuator system is simulated.

2. EHEC

Electro-hydraulic energy converter (EHEC) is the principal component of the proposed hybrid power transmission system (see Figure 1). The energy converter consists of a hydraulic pump-motor and an integrated electrical permanent magnet synchronous motor-generator. Integrated energy converter can be driven in both operating directions to produce the mechanical power required from the actuator or to recover the energy released by the actuator mechanism.

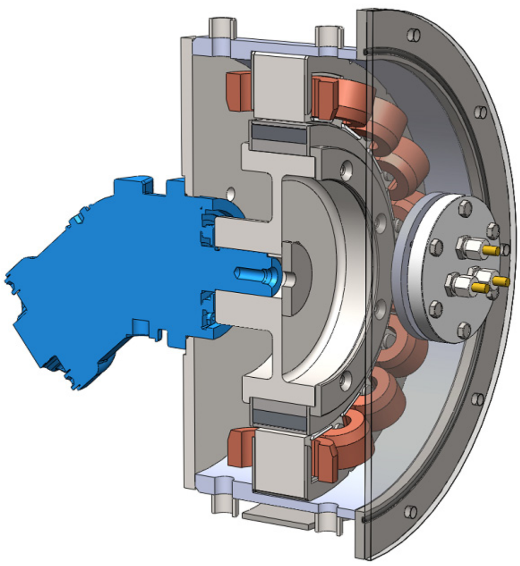

Figure 1: Cross-sectional cut of the integrated electro-hydraulic power unit

2.1. Hybridization

With hybrid technology it is possible to increase efficiency of the transmission. It is also possible to increase mechanical efficiency of the internal combustion engine if smaller engine is used /1/. Improvement of the efficiency of the working hydraulics has an important role when target is to reduce working machine energy consumption /8/. Many heavy working machines use load sensing hydraulic system. In multiple actuator systems, load sensing hydraulic systems suffer from poor efficiency if in the system different pressure levels and flow rates are required /9/.

During the latest years more and more attention has been focused on the developing of energy saving technologies for mobile working machines. Both hydraulic systems with hydraulic flywheels and electrical drives with energy storages are developed for working machines. Such technologies allow increasing the energy efficiency and minimizing CO_2-emissions. Novel solutions for recovering potential and kinetic energy in mobile working machines have lead to producing environmentally friendlier systems. Serial and parallel operating hybrid systems are promising for kinetic and potential energy restoration in heavy working machines.

One of the possible choices for hybridization is the application of serial hybrid architecture to a mobile working machine. This architecture is implemented by directly connecting a powerful enough electrical generator to a diesel engine. The only direct load of the diesel is the generator. When correctly selected according to the average work load the diesel engine can most of the time work in its optimum point at the highest efficiency in a series hybrid system. When direct power feeding is smaller than the generator output, the generator charges an electrical battery. When the battery is fully charged the generator can be stopped and the mobile working machine can operate fully electrically without CO_2-emissions at all. This, of course, necessitates a high power density battery, such as lithium-titanate battery, or a super capacitor. Depending on the hybrid architecture all or some of the working actuators in a mobile working machine are supplied with the electrical motors. Actuators are in work only when it is required by the operator. In electrical drives stand-by is achieved practically with minimal losses – the no load power of the converter. A series hybrid solution implies the presence of many electrically driven actuators in the system. /7/

2.2. Power density and energy recuperation

Most of the actuators in mobile working machines are hydraulic as electrical drives do not produce large enough force densities. Therefore, there is a clear need for efficient electro-hydraulic power units - sets of electrical motors and hydraulic pumps which could supply hydraulic components of mobile working machines with minimal losses. In cranes, excavators, reach machines and different stackers the potential energy could be recycled if the hydraulic machine could work as a hydraulic motor taking its power from the hydraulic circuit and driving the electrical machine in generating mode.

Recuperation is possible, for example, when lowering a telescopic boom. In case of a series hybrid hydraulic system it is clever to move to direct pump control both in lifting and lowering. In such a case the electric drive via the hydraulic machine works as a position controller for the hydraulic system /3 - 6/.

In principle, hydraulic machines work both as motors and pumps, but in practice only few machines are fully ready to be operated in both modes. Bent-axis piston machines are often applicable in both modes and offer very high efficiency, too. Very few of these machines, however, are ready to operate as a pump without pre-pressure in the pump inlet. A suitable hydraulic machine that can be operated in pumping mode up to 1500 rpm with ambient charging pressure is selected among the freely available standard components.

Ponomarev *et al.* have designed an integrated high power density concentrated non-overlapping tooth winding IPM synchronous electrical machine targeted to directly operate on a shaft of a bent-axis piston-type hydraulic machine. Such a design solution of an electro-hydraulic power unit increases the compactness in comparison with traditional in-line configuration (see **Figure 2**) and brings great possibilities to load the electrical machine heavily using working hydraulic fluid as a coolant. This, in turn, further increases the power density of the device allowing using less active electrical and magnetic materials in the construction of the electrical machine. /7/

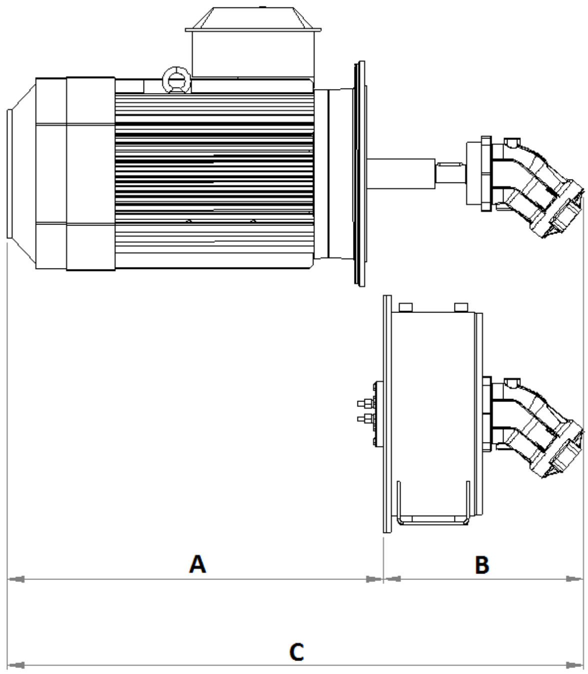

Figure 2: Comparison of dimensions of two configurations. Top: in-line configuration with stand-alone standard 45 kW industrial induction motor with bent-type axial-piston hydraulic motor/pump; Bottom: integrated directly oil cooled 45 kW PMSM.

The hydraulic unit can also operate as a hydraulic motor. Hence, the electrical machine can be used to transform excessive hydraulic energy – such as potential energy – into electrical energy. This electrical energy can be consumed by other actuators of the mobile working machine or, stored in a battery or super capacitor for future use.

2.3. Direct oil cooling

The use of working hydraulic oil in direct cooling of electrical motors which are used in mobile working machines brings several benefits: /7/

- Motor electrical loadability can be increased with efficient cooling
- Cooling circuit with separate fluid (e.g. water/glycol) is eliminated from the system
- Flow of the fluid is obtained from the working hydraulic circuit (there is no need for an additional cooling pump)
- The availability of high volume of coolant allows heavy loading of the machine for a long time
- Presence of oil in the machine chamber helps to damp the noise produced by the electrical machine.

The influence of oil friction has been studied by Ponomarev *et al.* and as a future work the CFD analysis has to be performed to refine the possibilities of oil cooling in the system.

3. Electro-Hydraulic Hybrid Actuator System

Figure 3 shows the circuit diagram of an electro-hydraulic hybrid actuator system. The system in question is a pump-controlled fluid power system. The hydraulic pump is directly driven by the electrical motor as introduced in Section 2. The pump-controlled fluid power systems have many advantages of which the biggest is the reduction of hydraulic losses in comparison to the conventional directional valve operated systems. But, unfortunately, these systems have also disadvantages which have limited the commissioning of the pump-controlled fluid power systems.

Asymmetric differential cylinder is a typical component in producing the force and movements of mechanisms. When it is used together with the pump-controlled fluid power system it can cause problems due to the differential volumes in cylinder chambers. The pump-controlled system is commonly operated in closed loop where it is essential to maintain the even volume flow in input and output ports of the pump. In case of the differential cylinder the difference in volume flows must be equalized, e.g. by using pressure accumulators.

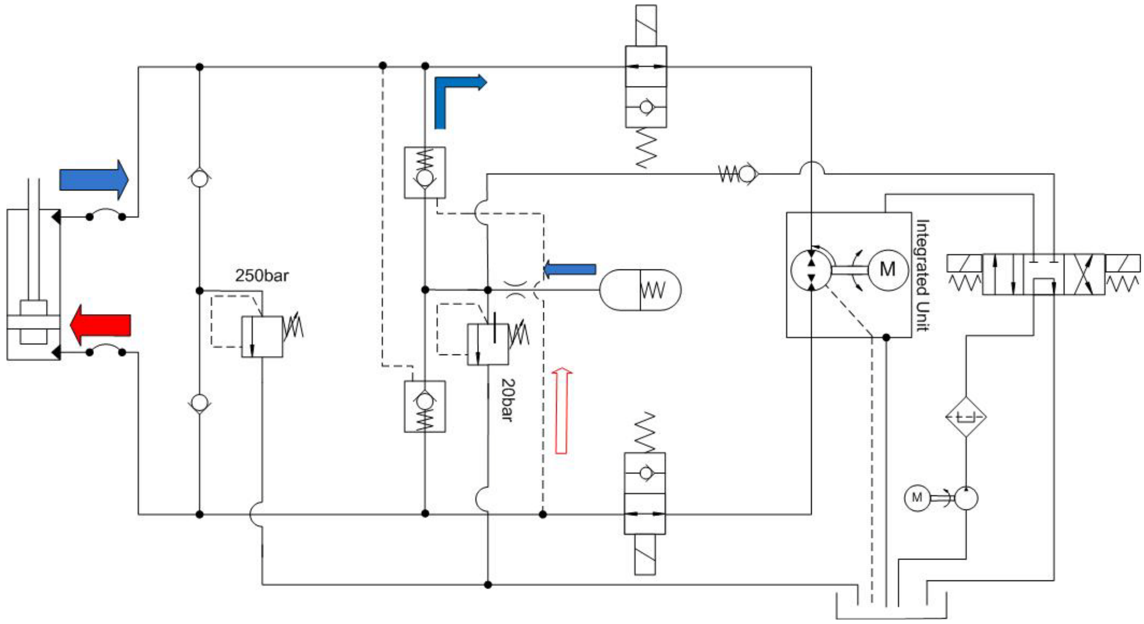

Figure 3: Electro-hydraulic hybrid actuator system.

The system shown in the Figure 3 consist of EHEC, asymmetric differential cylinder, pressure accumulator, separate power unit for the cooling and charging the pressure accumulator and pressure relief and check valves.

The arrows in the Figure 3 show the operation principle of the system at the operation point at which the actuator is performing the extension movement. At the time less oil flows out of the cylinder piston rod side due to the different areas and this loss needs to be replaced. The actuating pressure on the piston side forces the check valve to open, which enables the pressure accumulator to bleed out to lower pressure side.

In reversed function the excess oil from the piston side would flow to the accumulator after the check valve is opened due the higher pressure on the piston rod side.

3.1. Simulation of the electro-hydraulic hybrid actuator system

The hydraulic pump-motor selected for this study is commonly available bent-axis piston machine which is ready to operate as a pump without pre-pressure in the pump inlet and which can be loaded on the inlet port with sufficiently high pressures.

One of the main goals of this study is to determine the control properties of EHEC. The fluctuation in volume flow due to the finite number of pistons in hydraulic pump and the oscillation in rotation due to the finite number of poles in electrical machine can meet each other at the same frequency. This is very harmful phenomena and it should be removed from the system by means of the phase shift optimization or control.

Ivantysyn and Ivantysynova have proposed simulation model for the bent axis axial piston pump which takes the fluctuation in volume flow into account /2/. Instantaneous value of flow rate in bent axis pump with an odd number of pistons Equation (1) is applicable in the interval of $0 < \varphi \leq \frac{\pi}{z}$. .

$$\mathrm{Q_{aU}} = \omega A_K R_2 \sin\beta \sum_{i=1}^{k_1}\left[\varphi + (i-1)\frac{2\pi}{\mathrm{z}}\right] \tag{1}$$

, while in the interval $\frac{\pi}{z} < \varphi \leq \frac{2\pi}{z}$ Equation (2) is applicable

$$\mathrm{Q_{aU}} = \omega A_K R_2 \sin\beta \sum_{i=1}^{k_2}\left[\varphi + (i-1)\frac{2\pi}{\mathrm{z}}\right] \tag{2}$$

Terms k_1 and k_2 take the following values as per the intervals stated as follows

$$0 < \varphi \leq \frac{\pi}{z} \quad ,k_1 = z/2 + 0.5$$
$$\frac{\pi}{z} < \varphi \leq \frac{2\pi}{z} \quad ,k_2 = z/2 - 0.5$$

And the angular position φ is directly integrated out of angular velocity ω.

$$\varphi = \int_0^{2\pi/z} \omega\, dt \tag{3}$$

3.2. Simulation results

The simulation model was created and solved in Matlab Simulink. The initial values used in simulation are presented in the Table 1.

d_p = 80 x 10^{-3} m	d_{pr} = 30 x 10^{-3} m	V_{BP} = 36 x 10^{-6} m^3
H = 1 x 10^{-5} s	V_{accu} = 20 x 10^{-3} m^3	β = 40°
R_2, A_k – From manufacturer		ω = 157 rad/s

Table 1: Initial values used in simulation

Figure 4 shows the pulsation that appears in the pump volume flow due to the finite number of pump pistons. In this simulation the pump flow was kept constant. The resistive load impulse that was used to excite the vibrations in the system is shown in **Figure 5**.

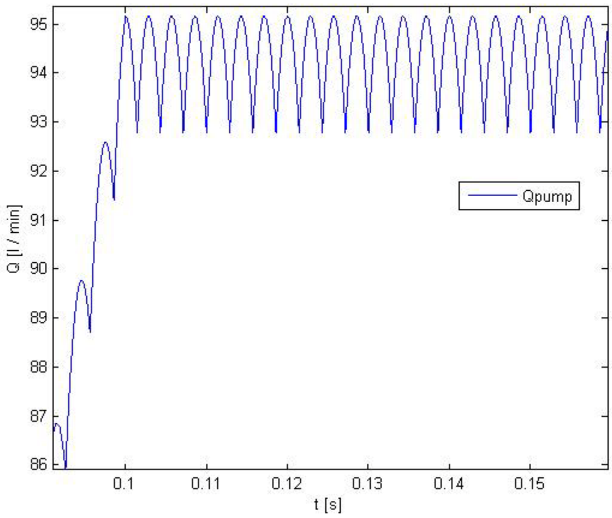

Figure 4: The pulsation of the pump flow

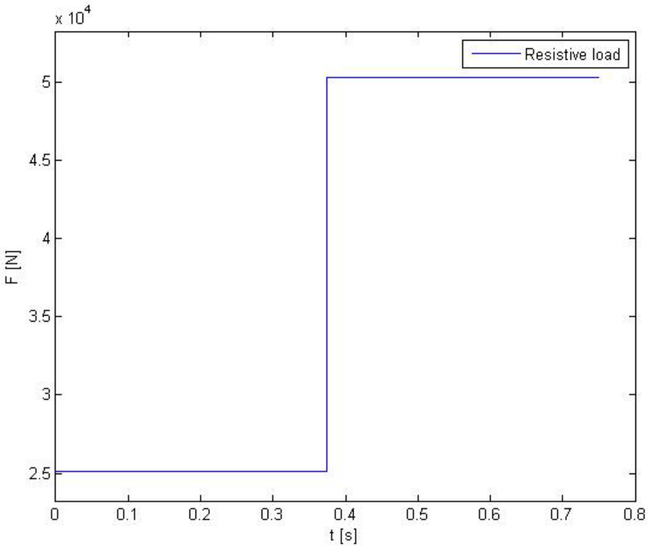

Figure 5: The resistive load impulse

Figure 6 shows the difference in cylinder volume flows due to the differential cylinder used. This difference needs to be compensated to the piston rod side using the pressure accumulator. The volume flow through the check valve is the compensative volume flow that consists not only of accumulator volume flow but also of the possible excess volume flow from the piston side and the boost pump volume flow. The accumulator volume flow is the flow through damping orifice assembled to separate the accumulator from check valves and pressure relief valve. The accumulator volume flow is sufficient to compensate the difference in cylinder volume flows.

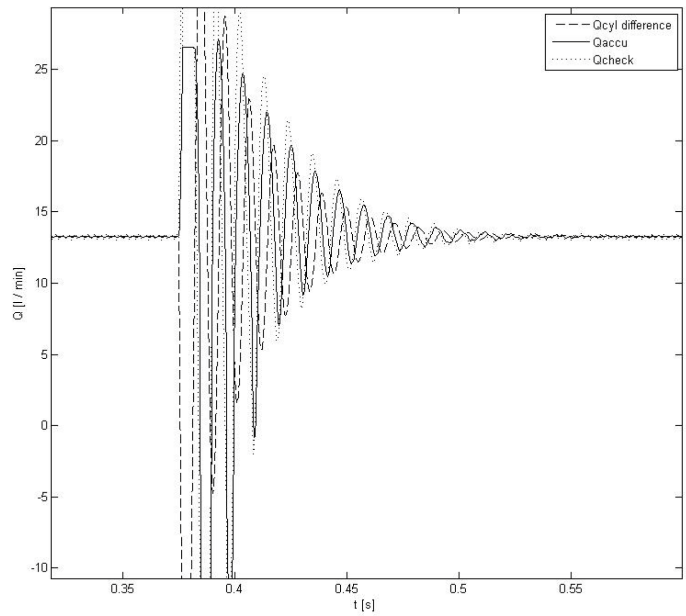

Figure 6: The compensation of unequal cylinder flows

4. Future work

Simulated results are to be verified using the test rig specially developed for verification of simulated responses of the system. Proposed test rig allows the experimental testing of behavior of real power transmission system in both modes while using simulated loads.

5. Conclusions

The simulation model which describes the pulsation in pump volume flow is implemented. This model is used in conjunction with the electro-hydraulic hybrid actuator system model. The complete system model is utilized to study the compensation of difference in cylinder flows caused by the differential cylinder.

6. Acknowledgement

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8. Nomenclature

A_K	piston displacement area	m^2
d_p, d_{pr}	diameter of cylinder piston and piston rod, respectively	m
H	simulation time step length	s
k_1, k_2	parameters defining pistons in delivery stroke	
R_2	reference radius of piston installation	m
V_{accu}	volume of the pressure accumulator	m^3
V_{BP}	revolution volume of the boost pump	m^3 / rev
z	number of pistons	
φ	angular position of the driving flange	rad
β	angle between the input shaft and the valve block	rad