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The Control of Multiple Actuators using Single IEHEC Pump/Motor

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Abstract

The awareness and concern of our environment together with legislation have set more and more tightening demands for energy efficiency of non-road mobile machinery (NRMM). Integrated electro-hydraulic energy converter (IEHEC) has been developed in Lappeenranta University of Technology (LUT) /1/. The elimination of resistance flow, and the recuperation of energy makes it very efficient alternative. The difficulties of IEHEC machine to step to the market has been the requirement of one IEHEC machine per one actuator. The idea is to switch IEHEC between two actuators of log crane using fast on/off valves. The control system architecture is introduced. The system has been simulated in co-simulation using Simulink/Mevea. The simulated responses of pump-controlled system is compared to the responses of the conventional valve-controlled system.

KEYWORDS: IEHEC pump/motor, pump-controlled system, non-road mobile machinery, fast on/off valve.

1. Introduction

In hybrid technology it is possible to increase the efficiency of the vehicle power transmission system. It is often also possible to maintain the performance of the vehicle even when the original internal combustion engine is replaced by a remarkably smaller one /2/.Improvement of the efficiency of the working hydraulics has an important role when the target is to reduce working machine’s energy consumption /3/. The new control method for electro-hydraulic energy converter (IEHEC), (see Fig. 3) is introduced. This machine has a high power density and allows transformation of electrical energy into hydraulic energy and vice versa /1/.

There are three major features of IEHEC machine that makes it highly efficient over the traditional valve control system. The first one: the elimination of resistance flow apparent in throttle orifices which is known to be the basic problem of load sensing control system.

A number of modifications to load-sensing actuation have been proposed by researchers all over the world in order to minimize metering losses /4/, /5/, /6/, /7/, & /8/. It can be noted that the control for this specific system is complicated and large number of valves are required to realize every operating mode. All mentioned improvements on load sensing system reduces the metering losses but could not eliminate the losses.

Second: the replacement of hydraulic pipelines by electric cable. In non-road mobile machinery, the fluid power transmission lines are flexible hoses and pipes of small diameter which causes considerable power losses. In the electric cables the losses because of their internal resistances are apparent but negligible in comparison with the losses apparent in the hydraulic transmission lines /9/. In place of using long fluid power transmission lines, the end actuators can be supplied by the IEHEC, placed directly close to them.

Thirdly: the recuperation of energy in the form of electricity. Suitable place for this application in heavy mobile machines are all actuators that carry out work cycle in which the kinetic and potential energy is available for recovery e.g. lifting cylinders in cranes, grippers that tend to open by the payload mass and gravity /9/.

The prototype of IEHEC was tested by efficiency and characteristic measurements /10/. The testing of functionality of IEHEC as a component of working machine and finding of suitable application area has been the next step. Development of control interface for hardware-in-the-loop (HIL) simulation of IEHEC has been carried out /11/. Experiment has been done on applicability (functionality) and efficiency of IEHEC machine in single actuator /12/.

In this paper, design of the fluid power circuit has been done on the applicability of single IEHEC machine for multiple actuators. The actuators are separated by using fast on/off valves. Two different size of asymmetric differential cylinders of log crane have been used in the experimental set-up. To control the cylinder movement the direction of rotation and the rotational speed of the IEHEC pump/motor is alternated using the frequency converter. The experimental set-up has been designed and assembled as shown in **Fig. 1**. The circuit diagram of designed fluid power circuit is shown in **Fig. 3**. The experimental tests have not been carried out in the physical experimental set-up. Instead, the virtual prototypes modelled in Mevea software /23/ and in co-simulation Simulink/Mevea have been used to test the applicability. The attained results have been compared with the conventional valve controlled system that has been modelled using Mevea software.

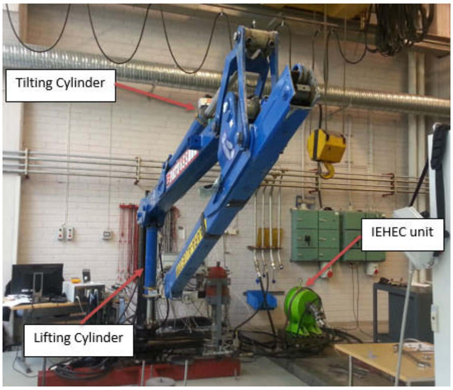

Figure 1: The Log Crane test setup

2. IEHEC

The integrated electro-hydraulic energy converter (IEHEC) is the principal component of the studied multiple actuator system. The designed IEHEC consists of a bent-axis piston hydraulic machine of 63 cm^3/rev and an integrated tooth-coil permanent magnet synchronous machine, which operates on the same shaft (see **Fig. 2**) /10/.

The designed solution of IEHEC allows considerably high space savings in the mobile environment. The compact design of the integrated electrical machine imposes the use of efficient liquid cooling. The working hydraulic fluid can be used as cooling media. The hydraulic cooling system increases the power density which allows to use less active electrical and magnetic materials in the construction of the electrical machine /10/.

Figure 2: prototype of IEHEC

The IEHEC of 26 kW has originally been designed for the power of 45 kW. It weighs only 43 % of a standard 45 kW induction motor coupled with the similar hydraulic machine and needs only 35 % of the installation length of standard setup. The maximum efficiency of the prototype is 90% in pumping mode and 86% in regenerating mode /10/.

Parameters	Value
nominal power	26kW
Flow rate	up to 180 l/min
pressure	up to 400 bar
voltage	400 V
nominal current	44 A
coolant flow	4 l/m @70º c

Table 1: Parameters of IEHEC /10/

3. Displacement Controlled Hybrid Actuator system

The studied circuit diagram shown in **Fig. 3**, is electro-hydraulic hybrid actuator system. The system in question is a pump controlled fluid power system using displacement control (DC). The control of actuator motion in DC actuation system uses the pump displacement.

Highly efficient displacement controlled actuation has been studied in /13/. The basis for the advantages of DC actuation reside in the complete elimination of resistance control.

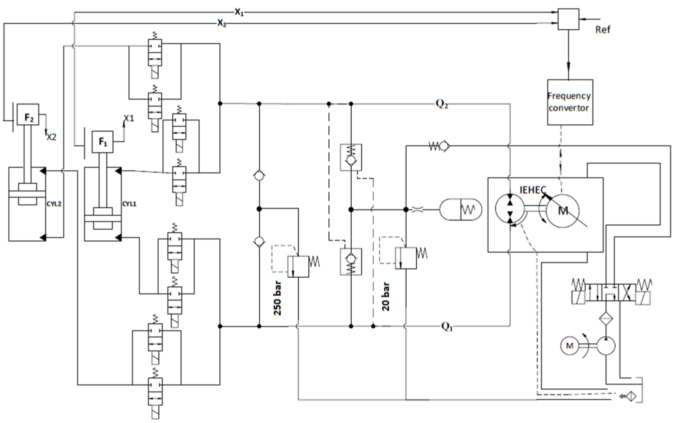

Figure 3: The studied system circuit diagram

In this system differential volume and volumetric losses are balanced on the low pressure side. Low pressure is given by the characteristics of low pressure source pump and accumulator and limited by the pressure relief valve. Two pilot operated check valves ensure that the low pressure level is always connected to the low pressure of the cylinder. This depends on the operating quadrant. The four quadrant operation of differential cylinder in DC solution for linear servo actuator has been proposed in /14/ and /15/. In this test the low pressure is set to p_{set}=20 bar.

The hydraulic pump-motor used in this system is directly driven by the electrical motor-generator controlled by a frequency convertor in reference to the actuators piston rod velocities. Hence, the system is capable to recover the energy released in motoring quadrants and stored into batteries.

The switching of the IEHEC machine between actuators (i.e. lifting and tilting actuators of log crane) as shown in the Fig.3 is managed by fast on/off solenoid valves. In the studied system the piston rods of two actuators are initially in fully retracted (lifting) and in fully extended (tilting) positions. The different position of the actuator piston rod would require different operating direction of the IEHEC machine which in turns the system cannot operate for two actuators at a time. This problem can be managed by reverting the tilting cylinder ports and, thus, the extension of lifting and retraction of tilting would operate in same direction of rotation of IEHEC. Thus the switching of the actuator can be managed easily by the fast on/off valves.

4. Modelling of the studied circuit

The opening of the fast on/off 2/2 directional valves are solved using first order dynamics, Eq. (1).

$$\dot{U} = \frac{U_{in} - U}{\tau_{valve}} \quad (1)$$

Similarly, for the angular speed of the electrical machine

$$\dot{\omega} = \frac{\omega_{in} - \omega}{\tau_{IEHEC}} \quad (2)$$

The pump volume flow is calculated using, Eq. (3)

$$Q_p = \omega \times V_p \times \eta_{vol} \quad (3)$$

And, the cylinder flow is

$$Q_{cyl} = \dot{X} \times A_{cyl} \quad (4)$$

The pressure build up in the volumes can be described by the continuity equations of Merritt, Eq. (5). /16/.

$$\dot{P} = \frac{Be}{V} \Delta Q \quad (5)$$

The compressional volume flow can be described by equation (6).

$$\Delta Q = \sum Q_{in} - \sum Q_{out} - \sum \dot{V} \quad (6)$$

, where $\dot{V}$ is externally supplied volume flow into and out of the volume (i.e. accumulator and actuator flow).

The volume flows in and out of each volume can be described in terms corresponding pressure drop by Eq. (7).

$$Q = f(\Delta p) \tag{7}$$

The volume flows of every orifices in the circuit is approximated by Eq. (7). The conditional statements and smoothening function have been used to avoid numerical problems in the simulation.

The force produced by the cylinder can be calculated using the chamber pressures and the cylinder and piston areas as shown in Eq. (8).

$$F = P_1 A_1 - P_2 A_2 - b\dot{x} \tag{8}$$

The oil volume V_{oil} of the pressure accumulator is described using Eq. (9).

$$V_{oil} = \int Q_{accu}\, dt + V_{oil0} \tag{9}$$

The volume of the gas V_{gas} is then the differential of maximum volume of pressure vessel V_{max} and oil volume.

$$V_{gas} = V_{max} - V_{oil} \tag{10}$$

The gas pressure is solved using energy balance equation, Eq. (11).

$$P_{gas} Vgas^k = P_{gas_0} Vgas^k \tag{11}$$

$H=1*10^{-5}$ s	Cd=0.6	g = 9.81 m/s^2	L_{lift} =0.53 m	L_{tilt}=0.78 m
Be=1.5*10^9 Pa	ρ=860 kg/m^3	*dcv*=20*10^{-3} m	*dp*-lift=0.1 m	*dp*-tilt=0.09 m
U_{in}=0…10 V	*b*=5000 Ns/m	*dpcv*=10*10^{-3} m	*dr*-lift=0.056 m	*dr*-tilt=0.056 m
C_v=4.12*10^{-8}	ω=78.5 rad/s	dpr=16*10^{-3} m	T=20 s	
Vp=1.003*10^{-5} m^3/rad	V_{max}=5*10^{-3} m^3			

Table 2: Parameters used in the simulation

5. The control of the system

The IEHEC machine is controlled by the ABB ACS800M1 frequency converter. This frequency controller works based on direct torque control (DTC) of the electrical motor. For DTC, a typical torque response is 1 to 2 ms when operating below 40 Hz /17/. In simulation time constant of $\tau = 32$ ms has been used to control the IEHEC machine. This value is valid for variable displacement axial piston pump /18/.

The direction of the rotation of the IEHEC machine has to be alternated in order to change the direction of the volume flow. Due to the combined inertia of rotor, pump shaft and piston block, the build-up of the angular speed takes longer however, the torque response is fast enough to build-up the angular speed. According to the design parameter of the IEHEC machine the machine can speed up at no load from 0 to 1500 rpm by 25 *ms*. Thus, the used time constant is valid /18/.

The volume flow from/to the IEHEC unit to/from the system actuators are guided by Rexroth 2/2 directional poppet valve of size NS6 with booster amplifier (fast on/off valves) with the response time of 10ms, /19/ and /20/. One fast on/off valve allow the maximum flow of 35 L/min at a pressure drop of 30 bar, and, thus, maximum Q=70 L/min by opening two valves at a time is possible per actuator.

6. Conventional valve-controlled system modelled using Mevea software

The 3D model of the log crane is created the same way as the model in co-simulation. The translational forces in the dummies are replaced by hydraulic pressure forces. All the hydraulic components shown in the conventional valve controlled fluid power circuit (see Fig. 6) are provided by Mevea software /23/. The forces (F1 and F2) are the external forces applied on the cylinder rods due to the inertia of the log crane links. The selected constant pressure pump builds-up 100 bar pressure in volume 1. The direction of the flow is controlled by 4/3 solenoid directional control valve /21/. The solenoids are working with a signal input of +/- 10 V. The pressure drop across the valve is 35 bar with nominal flowrate of 40 l/min. The semi-empirical volume flow coefficient (Cv) is calculated using Eq. 12. The time constant of a certain valve can be obtained from the Bode-diagram provided by the valve manufactures. Typically, the frequency from the Bode-diagram is chosen using the -45^{o} phase shift /22/. The time constant can be calculated using Eq. 13.

$$c_V = \frac{Q_N}{\sqrt{\Delta p_N/2}} \frac{1}{U_V} \quad (12)$$

$$\tau = \frac{1}{2\pi f_{-45^o}} \quad (13)$$

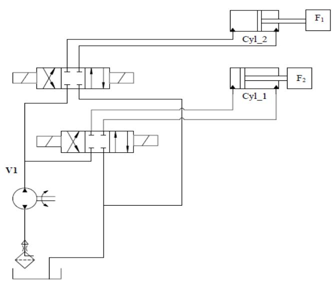

Figure 4: The conventional fluid power circuit of studied log crane

7. Result

In this Chapter, the simulation results are described. Simulations are carried out by solving mathematical model of proposed fluid power circuit (see Fig. 3). The maximum stroke for the lifting and the tilting cylinders are 0.53 m and 0.78 m, respectively. In the co-simulation Simulink/Mevea the virtual model of the log crane links weight of 495 kg are considered. The main challenge of the simulation was the transition point of the switching of the actuator, where there is frequent pressure drop in the opening and closing of the fast on/off switching valve which further leads to oscillation in the system.

The total simulation time is 20 s. The used input signal is sample based pulse generation for the IEHEC machine and fast on/off valves. The pulse generation input signal of the IEHEC machine works in a cycle time of 5 s to change the direction of rotation (see Fig. 50), whereas, the fast on/off valves works with sample time of 100 ms (see Fig. 5b). The first 5 s of the simulation time the IEHEC machine rotates in a clockwise direction, which provides a positive volume flow (Q1), which leads to defined positive movement of the cylinder piston. The next 5 s of the simulation time, the IEHEC machine rotates in counter-clockwise direction providing opposite volume flow (Q2), that leads to opposite of the defined positive movement of the cylinders piston. These cycle repeats for the total period of the simulation. The control signal inputs for the fast on/off valves of the two actuators are working exactly opposite to each other (i.e. both of them never open at the same time). The mathematical model of the IEHEC driven fluid power circuit has been simulated using co-simulation method in Simulink/Mevea, results and comparison are described in the following sub-chapters. Due to the different time steps used in the simulation of IEHEC driven system and conventional valve controlled system results are plotted independently.

Figure 6 shows the simulated rotational speed with respect to the reference rotational speed, (ω_{in}) direction of the IEHEC machine. The positive movement (extension) of the cylinders piston requires more volume flow than the negative movement (retraction). Thus, the positive movement requires higher rotational speed. Note that the ω_{in} is the reference for the PI controller that sets the simulated rotational speed of shaft. The vibration apparent in the graph is natural for this type of fast on/off control.

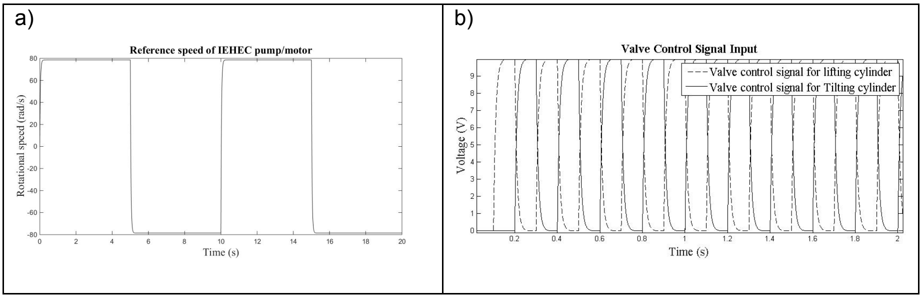

Figure 5: The control signal input: a) IEHEC machine b) Fast switching on/off valve zoom out the first 2 s

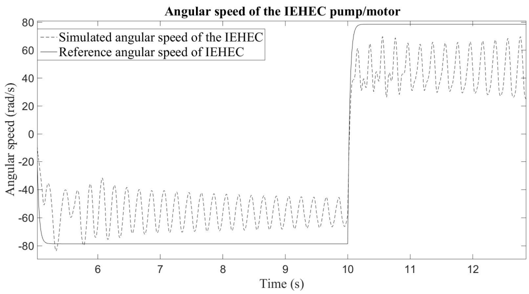

Figure 6: The simulated angular speed and reference angular speed of IEHEC machine.

7.1. Co-simulation Simulink/Mevea results

The control signal used for the IEHEC machine and fast on/off switch valves are shown in Fig. 5a and Fig. 5b. The inputs from Mevea simulation model of the log crane is used instead of constant mass-load used in the Simulink model. Figure 7a shows the piston position of the actuators. The switching of the IEHEC machine between the actuators can be seen from the step movement, when the lifting cylinder piston moves, the tilting cylinder piston stops and vice versa. The positive movement of the cylinders piston are the extension.

The velocities of the actuator pistons are shown in Fig. 8a. The reduced velocities of the piston apparent to the plot is because of the piston approaching the end of the cylinder, which starts to move back and forth due to lack of damping.

Figure 9a shows the power consumption of the IEHEC pump in the fluid power circuit. The different position of the log crane link (i.e. weight to be lifted or lowered) requires different amount of energy. This is due to different mass moment of inertia of the links at different lifting position. The maximum power consumption in the co-simulation result is 7 kW. The power consumption never reach's to zero, because either of the cylinders are moving in the entire period of the simulation.

7.2. Results of conventional valve-controlled system

The conventional valve controlled fluid power circuit (see Fig. 4). Figure 7b shows the cylinders piston position. The movement of the actuator pistons are controlled by the 4/3 directional valve. Depending on the valve spool position the negative and positive movement of the actuator piston can be controlled. The extension of the cylinders piston is positive movement.

Figure 8b shows the velocity of the actuator piston. The oscillation at the opening and closing of the valve is apparent to the valve controlled fluid power circuit. The power consumption of conventional valve controlled fluid power circuit is shown in Fig. 9b. The fluid power circuit maximum power consumption calculated from the pressure and flowrate is 9 kW.

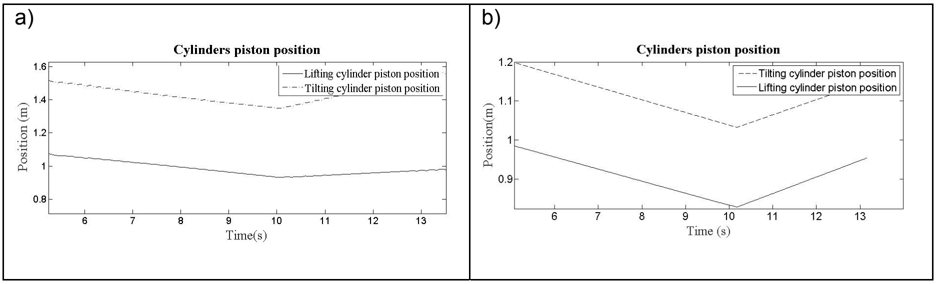

Figure 7: Cylinders piston positions: a) co-simulation b) conventional valve control

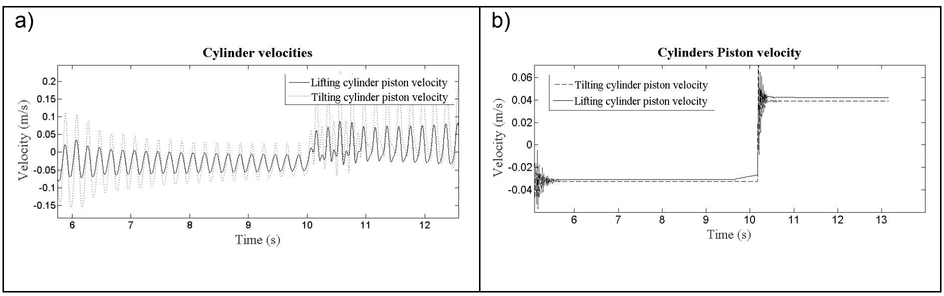

Figure 8: Cylinders piston velocities: a) co-simulation b) conventional valve control

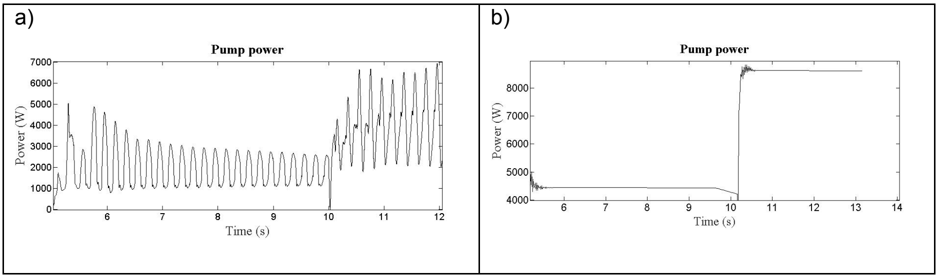

Figure 9: Power consumption of pump: a) co-simulation b) conventional valve control

7.3. Comparison of the IEHEC driven system and the conventional system

In comparison, the work cycle of the circuit driven by IEHEC and conventional valve controlled fluid power circuit has been considered. The work cycle can be defined as the cylinder piston travelled length within a certain working time. Figure 7 shows the position of the cylinders piston. In both cases the cylinders piston travels 0.2 m in retracting direction. This distance travelled by the cylinders piston is accomplished within 5 s working time.

The power consumption of the pumps within this working cycle (see Fig. 9). The power consumption of the pump in conventional valve controlled fluid power circuit is 4500 W in the lowering and 9000 W in the lifting whereas, the power consumption of the co-simulation IEHEC pump-motor is varying between 1000 W and 4000 W in the lowering, and between 2000 W and 7000 W in lifting. The high peak at the beginning is due to the friction resistance in the cylinders piston sealing and the mass of the boom at the start of piston movement.

8. Discussion and Future work

The main challenge of commercializing electro-hydraulic hybrid actuator system has been the requirement of one IEHEC unit per actuator, which leads to high investment costs. The concept of pump switching has been introduced in /13/. In this thesis, a fluid power circuit is implemented for switching the IEHEC unit between two actuators. The system has been simulated using co-simulation Simulink/Mevea. Attained results are compared to results of conventional valve-controlled system. During simulation, the main challenge has been the transition point of switching the actuators. The used fast on/off valve with booster amplifier have been tested by manufacturer with a promising time constant of 10 ms. In the co-simulation work the system response time of 100ms was sufficient to reach the stable movement of actuator piston. The control method has been tested using virtual model of the log crane.

The oscillations in the system is apparent to the fluid power circuit in which the fast on/off valves are used for guiding the volume flow. The fast opening and closing of the on/off valve causes pressure drops in the system which further increases the oscillations in the system. The other reason for the oscillation is due to lacking of damping in the system. In modelling of the studied fluid power circuit the viscous damping in the cylinders has been the only damping considered in the system. Thus, the PI controller with cylinder velocities feedback have been added in the modelling of the electrical machine control.

The designed fluid power circuit using IEHEC can operate with less power than the conventional valve controlled circuit even though, there is frequent opening and closing of switching valves of the actuators. The IEHEC driven fluid power circuit is 20 % more efficient than conventional valve controlled fluid power circuit.

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10. Nomenclature

x	Piston position [m]
$\dot{x}$	Piston velocity [m/s]
A	Area [m^2]
d	Diameter [mm]
ρ	Density [kg/m^3]
g	Gravity [m/s^2]
P	Pressure [Pa]
P	Power [W]
Be	Effective bulk modulus [Pa]
τ	Time constant [s]
ω	Angular speed [rad/s]
U_{in}	Reference signal [V]
T	Simulation time [s]
V_p	Radian volume [m^3/rad]
η	Efficiency [%]
L	Cylinder stroke [m]
b	Viscous friction coefficient [Ns/m]
H	Integrated time step [s]