ELECTRIC ENERGY RECOVERY SYSTEM EFFICIENCY IN A HYDRAULIC FORKLIFT

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Abstract: **The purpose of this research is to find possibilities to recover electric energy in a hydraulic forklift system. The drive consists of a DTC controlled electric servo motor directly running a reversible hydraulic pump. A real system was built and tested, especially, from the energy recovery point of view. Results of the system were analyzed and compared and according to them, energy can be recovered efficiently from the hydraulic forklift system. Also new ideas and directions of further research were obtained during the research.**

***Index Terms*: Electric energy recovery, forklift, electric servo drive, hydraulics**

I. INTRODUCTION

Energy efficiency is the theme of all engineering fields nowadays. Due to the large number of forklifts used in the world even a small energy saving in one device would mean a large energy saving in total. Electric forklifts usually use accumulators as a source of electric energy, and therefore, they have a need to be frequently recharged. A forklift cannot be used for working during a recharge period unless the battery is replaced. Extending the time of usage can be done in two different ways, either by developing new accumulator technologies [1] or by recovering energy from as many functions as possible, for instance from braking [2], to make the accumulator charge last longer. The best solution would be a combination of these two ways. In this way it is possible to make a forklift work more efficiently and longer and also make it more ecological.

Traditional forklifts use lead-acid accumulators to supply electric energy to an electric motor drive to rotate a hydraulic pump. The control of hydraulics is realized with directional, servo and flow control valves. Energy is used for all movements, but none is recovered back to accumulators except maybe the braking energy of driving. [3]

The experimental test setup uses a speed controlled motor, drive and a hydraulic pump to control the hydraulics instead of a directional or a servo valve. An application program was made for the electric drive ACSM1 to control both the electrical and hydraulic side of the forklift system. The purpose of this program was to make a system that can be controlled easily with different speeds up and down and at the same time recover energy as much as possible in the lowering. This testing was done using a hydraulic internal gear pump capable of operating both as a pump and as a motor. The pump construction seems to be one of the main issues in the electric energy recovery system. Some of the internal gear pumps are suitable for operating as a motor but not all of them. It is also known that piston type pumps are more energy efficient but they are also more expensive.[4]

From the electric drive point of view the efficiency of such an energy recovery system may be improved by selecting as energy efficient electric drive types as possible. Permanent magnet synchronous motors offer the best possible performance from the efficiency point of view. In the power range of few kilowatts the permanent magnet servo motors may give about 94 % efficiency. As frequency converters offer rated efficiency of 98.5 % the energy efficiency of an electric forklift mostly depends on the hydraulic system – especially the pump – and the accumulator.

II. General Overview of the Test Setup

The structure of the hydraulic and electric system for testing the forklift is presented in Fig.1.

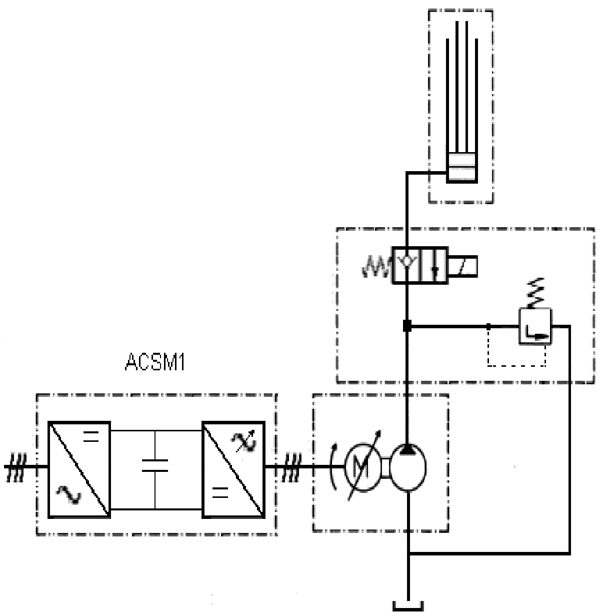

Fig.1 - Structure of hydraulic and electric system for testing. The electric motor drive operates directly the pump and is, hence in principle, capable of position control of the fork.

For the test setup, electricity is supplied to ABB-manufactured ACSM1 servo drive converter from network and it is connected to the servomotor with phase connections and a cable for a resolver.

The motor is mechanically connected to the hydraulic pump and these two act either as an electric motor-hydraulic pump or electric generator-hydraulic motor combination.

To control the upwards and downwards movements and to stop the load from falling down on its own, a hydraulic valve is used. This valve is a poppet type 2-way normally closed valve and it contains a check valve in its closed position. The valve is controlled with solenoids and a spring to switch it to default position. This valve is in further texts referred to as a control valve even though it is not used for the actual control purposes.

The pump takes its oil from the tank and pumps the oil through the control valve to the cylinder to move the piston and forks upwards. If the pressure before the control valve becomes too high, a pressure relief valve will direct the flow of oil straight to the tank, thereby limiting the maximum system pressure to appr. 200 bars. The control valve is used only to choose between the movements directions of the cylinder piston to either upwards or downwards. In upwards movement and when the movement is stopped, the oil can flow through the control valve only to the cylinder. With this, the pressure can be kept in the cylinder and the load in a stable position, without having to use the pump all the time. When the control valve is used in downwards movement, oil flow from cylinder to the pump is now allowed by a control command. As oil goes back to the tank through the pump, the pump acts as a motor and rotates the servomotor in generating mode. When working as a generator the motor returns electricity to the DC-link of the ACSM1 frequency converter. The control valve position is controlled by the ACSM1. [5]

The control principle of the ACSM1 is based on the direct torque control method (DTC). The main features of DTC are: The motor torque is controlled by directly controlling its stator flux linkage. In principle only two simple vector equations are needed in the control

$$\boldsymbol{\psi}_{\mathrm{s,est}} = \int \left(\boldsymbol{u}_{\mathrm{s}} - \boldsymbol{i}_{\mathrm{s,meas}} R_{\mathrm{s}} \right) \mathrm{d}t, \quad (1)$$

$$\boldsymbol{T}_{\mathrm{s,est}} = \frac{3}{2} p \left(\boldsymbol{\psi}_{\mathrm{s,est}} \times \boldsymbol{i}_{\mathrm{s,meas}} \right). \quad (2)$$

The stator flux linkage vector $\boldsymbol{\psi}_{\mathrm{s,est}}$ is estimated by integrating the stator voltage $\boldsymbol{u}_{\mathrm{s}}$ of which the resistive stator voltage loss is subtracted. The torque is found as a cross product of the stator flux linkage and the measured current vectors. DTC provides the following advantages: minimum torque response time, accurate torque control at low frequency, torque linearity and dynamic speed accuracy. [6] As a DTC converter is equipped with position control features it should be possible to control the hydraulic system so that the position of the piston is directly controlled by the driving motor rotor position. This is, however, complicated by the leakage of the hydraulic pump. Especially, internal gear pumps leak so that we could compare a synchronous motor driven internal gear pump drive to an induction motor drive with a slip. In a piston type pump the leak is small and the position of the cylinder can be controlled relatively accurately with the servo motor drive position control. This study, however concentrates on the efficiency of the energy recovery system.

III. Experimental tests

Internal gear pumps are cheaper than piston type pumps and despite their lower efficiency the internal gear pump was first tested. The forklift system was equipped with a hydraulic internal gear pump, which can also be rotated to the other direction as a hydraulic motor. Fig.1 shows efficiency curves an internal gear pump. [7]

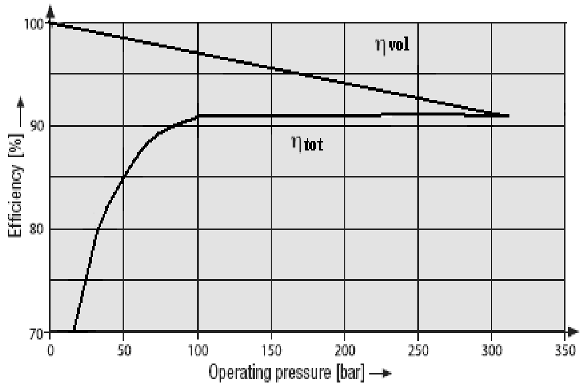

Fig.1-Efficiency curves of internal gear pump

Internal gear pump is operating well at higher speeds. When operating at low pressure and low speed an internal gear pump has a lot of leakages, and its operation is not efficient. The higher the pressure differential across the pump is the lower the volumetric efficiency is. Optimum working operation pressure is approximately 100 bar in this case.

The pump was tested with different rotation speeds of the servomotor. For the internal gear pump tests were made with a gross of 750 kg, 940 kg. The fork system tare is 250kg. The masses were lifted to heights of 1.0 m, 2.0 m, 3.0 m, 4.0 m and 5.0 m. The values measured from ACSM1 were the rotation speed of the motor, current in the drive, torque in per cent of the nominal torque of the motor, the dc-voltage in the intermediate circuit of ACSM1 and the relay signal that marks the changing of the control valve position to move forks downwards or to stop the movement.

A. *Measurement of efficiency for upwards and downwards movements for different masses*

The efficiency of the upwards movement is defined as

$$\eta_{\mathrm{up}} = \frac{W_{\mathrm{pot,up}}}{W_{\mathrm{e,in}}}, \quad (3)$$

where $W_{\mathrm{pot,up}}$ describes the potential energy stored in the gross load lifted to the up-position and $W_{\mathrm{e,in}}$ is the input electric power to the system.

The following results of calculation do not include the efficiency of the motor and the converter. The analysis of the motor efficiency and the efficiencies of the converter and the hydraulic parts of the system will be done separately.

Fig. 2 shows the result of measurements for upwards movements for height from 1 meter to 5 meters with just tare, 250kg.

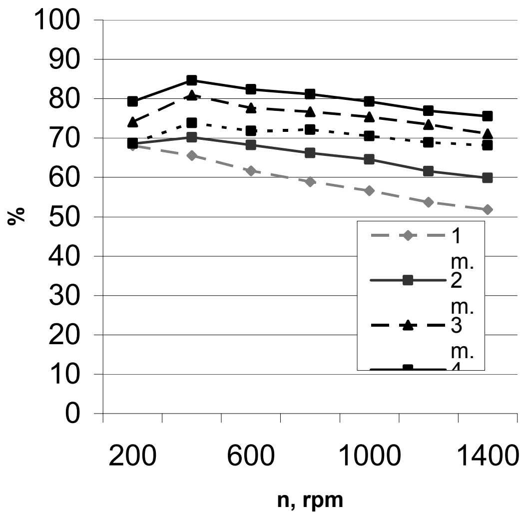

Fig. 2 - Efficiency for up movement η_{up} with tare 250 kg

Results show that with increasing speed of rotation more energy is needed for the upwards movement and the efficiency will be lower. The results indicate that the hydraulic losses become dominant as the speed and the flow increase.

The efficiency of the downwards movement is defined as

$$\eta_{\mathrm{down}} = \frac{W_{\mathrm{e,rec}}}{W_{\mathrm{pot,up}}}, \quad (4)$$

where $W_{\mathrm{e,rec}}$ describes the electrical energy recovered from the movement.

When comparing with Fig. 3 which presents the efficiency for the downwards movement with the same mass, it can be noticed that energy is clearly recovered. With the pump used, the efficiency is low for the original lifting height of 1 meter. The pump needs additional energy which can be achieved by increasing the mass. With increasing height and higher mass, the efficiency will also be higher.

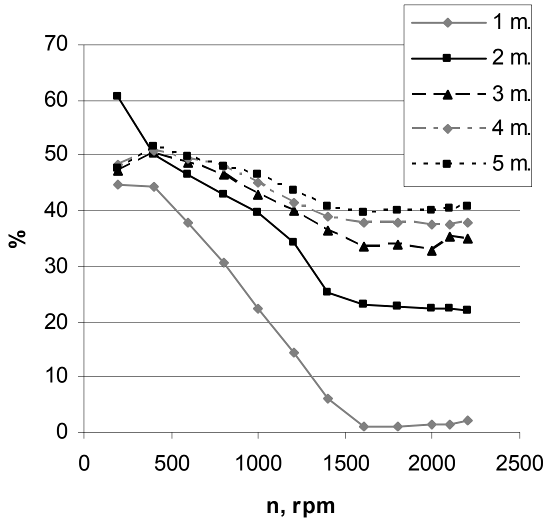

Fig.3 - Efficiency for down movement with only the 250 kg tare of the fork

Fig.4. shows the efficiency of downwards movement for a gross of 750 kg.

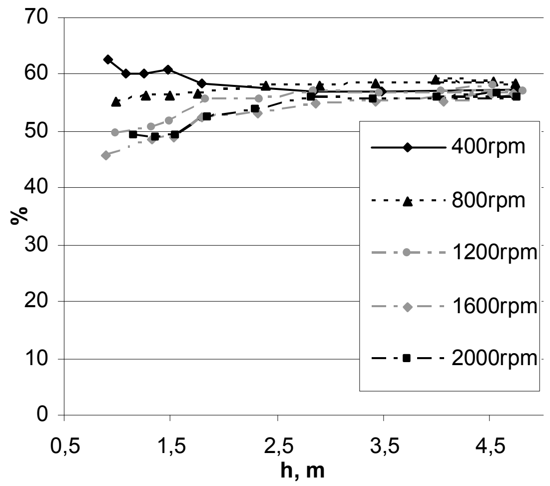

Fig.4 - Efficiency for down movement with gross 750 kg

According to Fig. 4 the worst case efficiency is 45% and in the best results the efficiency is 62%.

Fig.5 shows another interpretation of Fig. 4, efficiency depending on speed. With increasing speed in low heights, the efficiency is much lower than with heights of 4 and 4.5 meters.

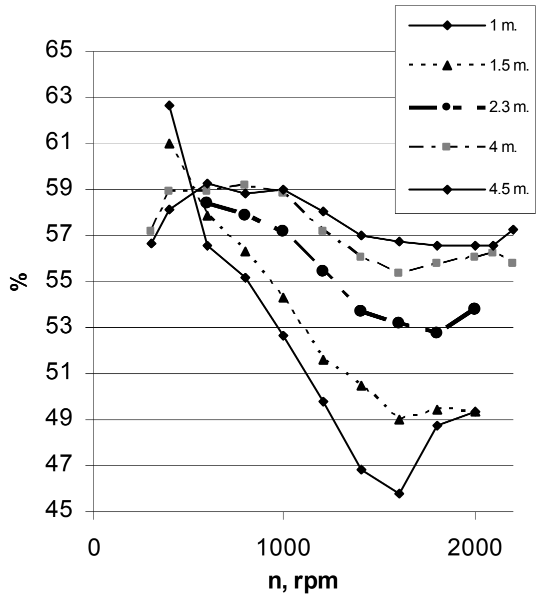

Fig.5 - Efficiency for down movements with gross 750 kg

Theoretically at the higher speed of operation, the pump is more efficient, but because of increasing of leakage in internal gear pump, efficiency of system in highest speeds decreased.

Fig. 6 shows upwards movement of gross 750 kg for different heights.

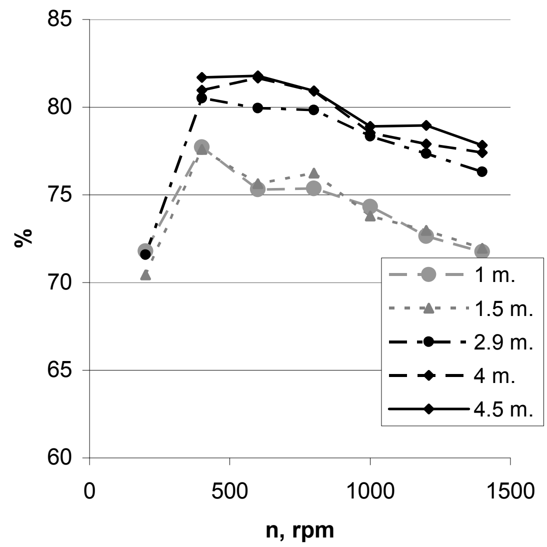

Fig. 6 - Efficiency for up movement with gross 750kg

When comparing Figs. 5 and Fig. 6, it can be seen that more energy is needed for lifting mass upwards than what can be recovered form the downwards movement. With the lowest speeds for up movements, the efficiency η_{up} is not so good. This is mainly the result of the pump "slip" that lets the oil leak.

Fig.7 shows comparison of downwards efficiencies with different masses and different speeds.

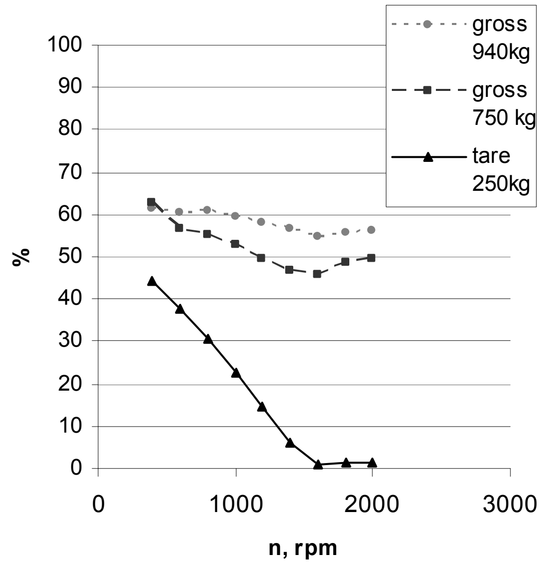

Fig.7 - Comparison of efficiency for down movement with different mass and height 1 meter

According results increasing the mass by 25% improved efficiency with 6% in average.

According to a separate analysis of efficiency: at the lower speed are 50% of losses in hydraulic, this can be explained by slip in pump, at higher speed losses of flow decrease efficiency of hydraulic part of system. Efficiency of hydraulic pump is similar to manufacturer's waveform. Comparing upwards and downwards movement there is near 20 % difference in efficiency. This difference can be explained by nonstandard usage of internal gear pump like a hydraulic motor. Efficiency of converter changes with increasing speed from 77 % to 97%, and efficiency of generator changes accordingly from 71% to 97%. According to these measurements biggest part of losses concentrate in hydraulic part, which contain pump, valves and pipes.

B. *Cycle calculation of efficiency*

There were 9 cases for cycle calculation of efficiency. Fig. 8 shows a working cycle when five masses of 500 kg are lifted from 0 m to 4.5 meters and the tare is lowered alone.

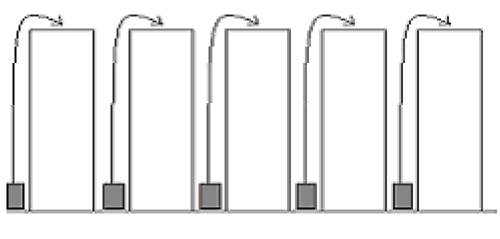

Fig. 8 - Case 1

Fig.9 shows the working cycle, when five masses of 500 kg are taken down from 4.5 meters to 0 meters repeating this 5 times. The 250 kg tare is lifted alone.

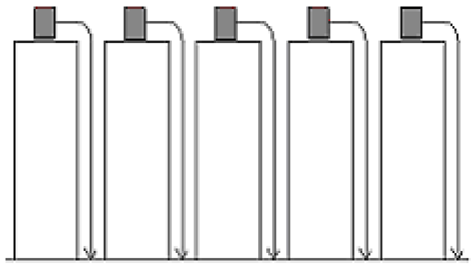

Fig. 9 - Case 2

In Fig. 10 the first picture shows a working cycle when five masses of 500 kg are lifted from 0 meters to 1 meter. The second picture shows a working cycle, where five masses of 500kg are taken down from 1 meter to 0.

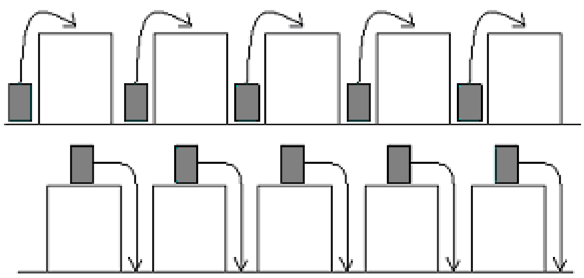

Fig. 10 - Case 3 and 4

In Fig. 11 the first picture represents the case number 5, where masses are lifted from floor level to 3 meter height 5 times and in case 6, mass is lifted 5 times down from 3 meters to floor.

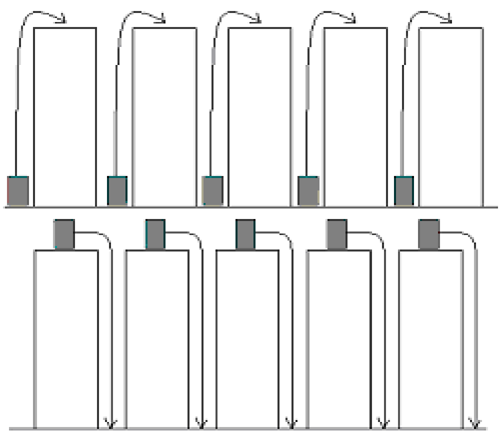

Fig. 11 - Case 5 and 6

In Fig. 12 is shown that presents a working cycle when a mass of 500 kg is taken down first from 5 m to 0 meters, then from 4 to 0 meters continuing with from 3 to 0 meters, from 2 to 0 meters and last from 1 to 0 meters.

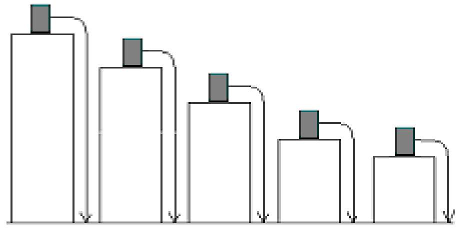

Fig. 12 - Case 7

Fig.13 shows the working cycle when a mass of 500kg is lifted up with the same cycle of heights like in case 7.

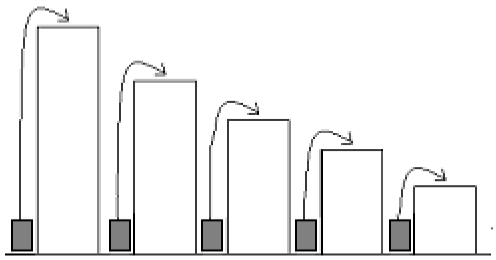

Fig. 13 - Case 8

Fig. 14 represents a case when lifting a mass of 500 kg from 1 meter to 4 meters, then lifting down a mass of 500 kg from 2 meters to 1 meter and then lifting a mass of 500 kg from 5 meters to 3 meters.

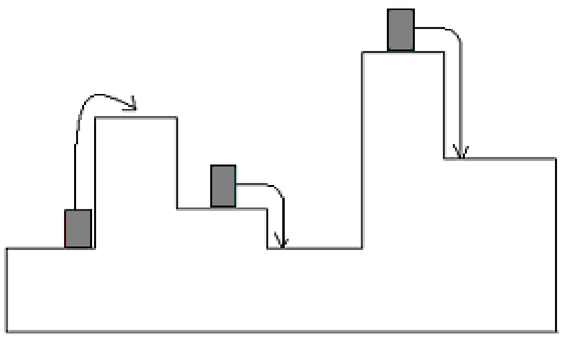

Fig.14 - Case 9

It was assumed that no adjustment of fork height when getting a load on forks was done, so that forklift user reached the needed height with the first attempt. Some calculated values were interpolated from the measured data.

Fig.15 shows two cases of energy usage from accumulator, system with and without energy recovery with speed 1400 rpm.

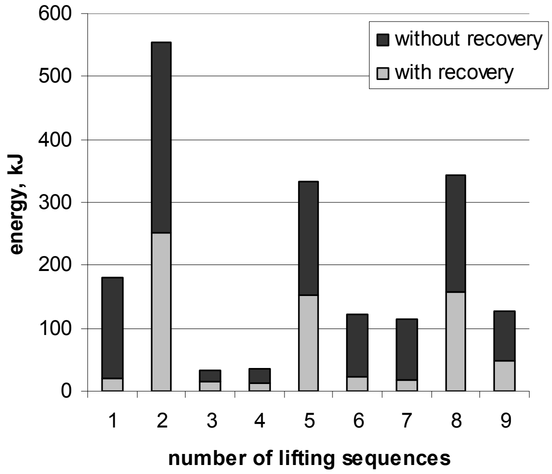

Fig.15 - Energy taken from accumulator and recovered from down movement with speed 1400 rpm

According to Fig. 15 in some cases the energy used from recovery is more than half of total energy used.

Fig. 16 shows ratio in per cent between recovered energy and energy taken from accumulator.

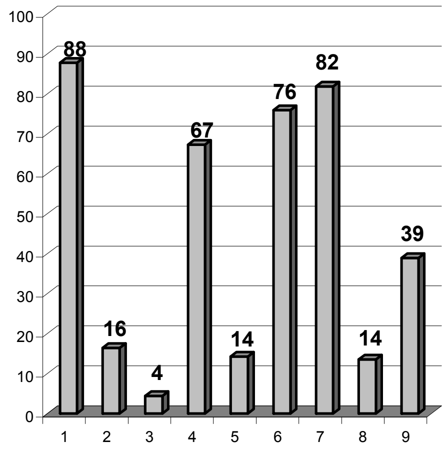

Fig.16 - Ratio between recovered energy and energy taken from accumulator for lifting sequences for motor speed of 1400 rpm.

Of course, it is impossible to calculate all possible working cycles, but it seems that if all recoverable energy could be stored and used again for upwards movement it would help to increase the working time and the life cycle of the accumulator remarkably.

Fig. 17 shows two cases of energy usage from accumulator, system with and without energy recovery with motor speed of 800 rpm.

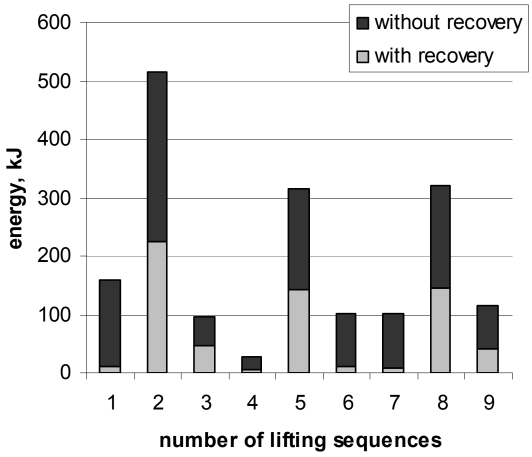

Fig.17 - Energy taken from accumulator and recovered from down movement with speed 800 rpm.

When comparing Fig. 17 with Fig. 15 it can be seen that both results are very efficient and the recovery of energy helps a lot. With the recovery of energy, the amount of work cycles for one complete discharge of the accumulator can be increased. For higher speeds bigger amounts of energy are needed for lifting mass up, but then it also gives more energy from the down movement, because drive does not need to force the speed to be so low and mass can go down more freely.

Fig.18 shows ratio of used and recovered energy for lifting sequences for speed 800 rpm.

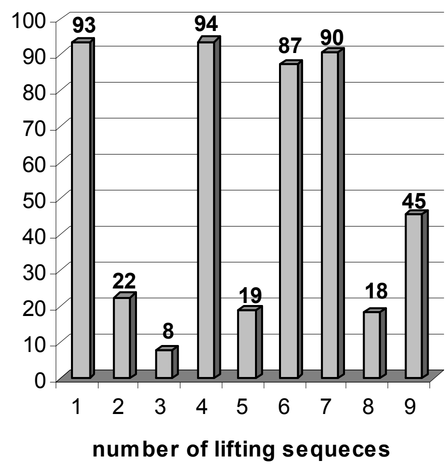

Fig.18 - Ratio between recovered energy and energy taken from accumulator for different lifting sequences for speed 800 rpm.

When comparing Fig. 16 and Fig. 18 there is bigger ratio between recovered energy and the energy taken from accumulator with lower speed.

It is assumed that the standard accumulator voltage/capacity in forklift is 48V/620Ah. The usable capacity, however, is very often only 80% of the rated capacity to ensure maximum accumulator life. Calculated average energy capacity in joules is equal to approximately 85.7 MJ. [8]

Table 1 shows the amount of work cycles with this accumulator, with and without recovery for different work cycles with a speed of 800 rpm.

Table 1.

Number of lifting frequences	Amount of work cycle for energy with recovery	Amount of work cycle for energy without recovery
1	8587	580
2	382	296
3	1838	1721
4	16143	4036
5	604	492
6	7325	942
7	9778	930
8	596	488
9	2125	1161

According to Table 1 the amount of work cycles depends greatly on the number and type of movements in that sequence and varying these can increase the life time of accumulator more than 50 %.

Table 2 shows the amount of work cycles according to energy usage and the types of cycles. The cycles are the same as before but now for speed of 1400 rpm.

Table 2.

Number of lifting frequences	Amount of work cycle for energy with recovery	Amount of work cycle for energy without recovery
1	4343	531
2	340	284
3	5261	5075
4	7398	3415
5	558	479
6	3630	873
7	4920	891
8	540	467
9	1777	1085

Comparison of Table 1 and Table 2 shows that with lower operational speeds there is a bigger amount of work cycles for one full discharge of the accumulator.

Fig.19 shows the difference of amount of work cycles with energy recovery, between speeds 800 rpm and 1400 rpm.

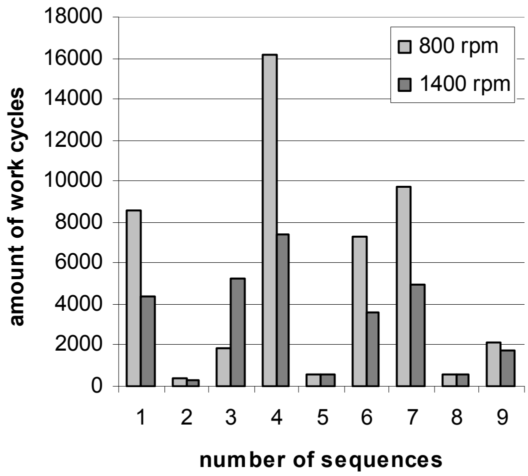

Fig.19-Amount of work cycles with energy recovery for speeds 1400 rpm and 800 rpm.

According to Fig. 19 there is a bigger amount of work cycles for speed 800 rpm. But results with 1400 rpm are still good when compared to the amount of work cycles without using energy recovery. In future more research must be done with higher speeds.

IV. CONCLUSION

The target of this study was to estimate the possibilities of recovering energy from hydraulic system movements by using an industrial electric drive and an electrical servo motor. The most important result was that it is possible to recover significant amounts of energy from the forklift system. Experiments were done with different speeds.

Experiments show that efficiency is extremely low during operation with only one cylinder height without load. With the lowest speeds for up and down movements, the efficiency is not so good. This is mainly the result of the pump "slip" that lets the oil leak. Efficiency of hydraulic pump is similar to manufacturer’s waveform. The 20 % difference in losses between upwards and downwards movement can be explained by nonstandard usage of internal gear pump like a hydraulic motor. Efficiency of converter changes with increasing speed from 77 % to 97%, and efficiency of generator changes accordingly from 71% to 97%. According to these measurements biggest part of losses concentrate in hydraulic part, which contain pump, valves and pipes.

The amount of work cycles for speed 800 rpm is bigger when compared with speed 1400 rpm. Choosing of work cycles was done randomly and some of the calculations were based on crude mathematical analysis, but still these will give us an idea of the energy efficiency.

Recovered energy from braking alone is not enough for upwards movement, but this energy can be used for reducing energy use from battery. This method will decrease lost time of forklift truck.

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