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USE OF THE POTENTIAL ENERGY OF LOAD

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Introduction

When lifting a load of *G* gravity to *H* height, its potential energy will increase in increments of $\Delta E=G.H.$ To raise the load, the energy has to be supplied. When lowering the load, the same energy may be obtained and properly used. The article describes a hydraulic circuit of fork lift truck lifting mechanism with an electric drive. The source of the electrical energy is accu-battery. When lifting the load, energy is drawn from the battery. When lowering the load, a part of the energy may be obtained and used to recharge the battery. A diagram of arrangement of power transmission system and flow of energy in lifting the load is on Figure 1.

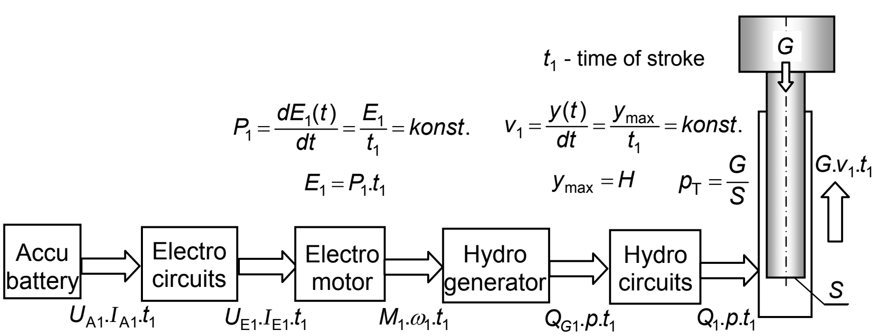


Fig.1. Output Transfer System and Flow of Energy in Lifting a Load.

With one stroke of the load, energy E_{A1} is consumed from the batteries and potential energy of the load will increase by $\Delta E=G.y_{max}=G.H=E_{A1}-\Sigma\Delta E_{Z1}$. Here, $\Sigma\Delta E_{Z1}$ is the sum of energy losses on the path from the accu-battery to the lifting cylinder and $y_{max} = H$ is a constant stroke of the cylinder.

The energy balance is performed for the steady state at the end of the transition process when all the performance variables are constant.

The flow of energy in lowering the load is shown in Figure 2.

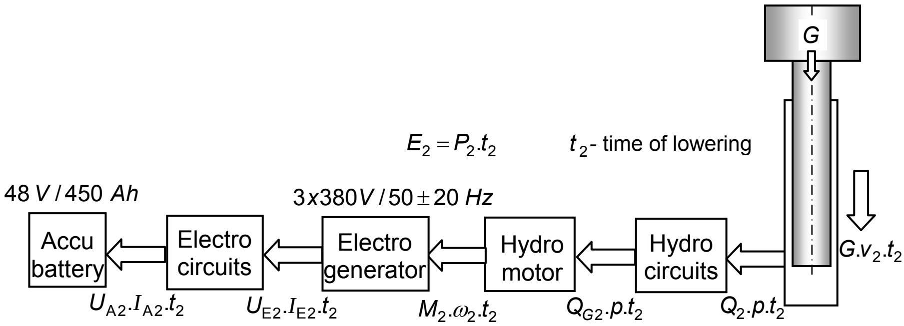


Fig.2. The Flow of Energy in Lowering the Load.

When lowering, the G gravity of the load is an external driving force. The output and energy are transferred from the hydraulic cylinder to the accumulator battery. Used for charging batteries, energy $E_{A2} = G.H - \Sigma \Delta E_{Z2}$ returns to the batteries. It is a condition for the successful recuperation of energy that there are no passive energy outputs, with power vented outside the closed transmission system, in the hydraulic and electrical circuits of the transmission system. Properties of all the transmission elements must be adapted to the energy recuperation. As an illustrative example, adjustment is given of the hydraulic circuits of a fork lift truck. The lifting mechanism of the forklift is shown in Fig.3.

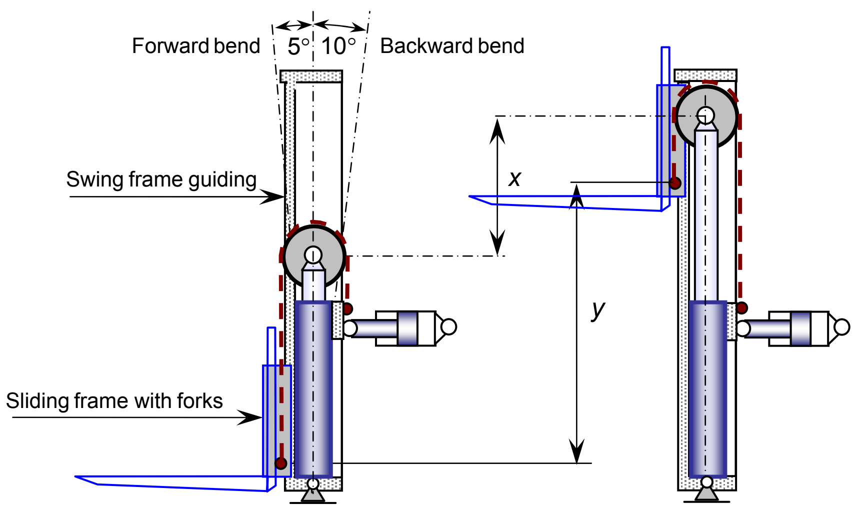


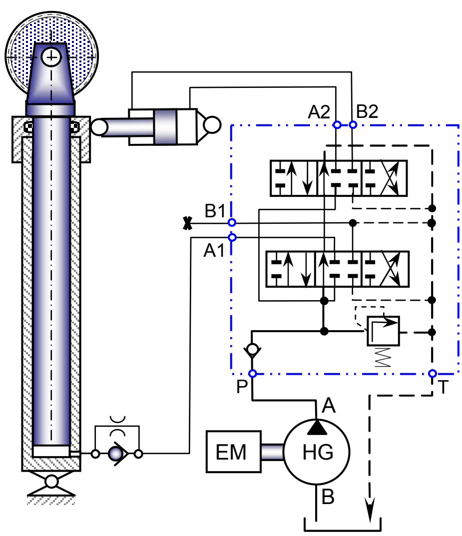
Fig.3 Layout of the Lifting Mechanism of Forklift Truck.

Forks are attached to a sliding frame, which moves vertically in the line of the swing frame. In Figure 3, the swing frame bents forward 5° and backward 10 °.

The lifting cylinder piston rod is topped with a pulley, through which a Gall chain is belted for transferring forces. One end of the chain is attached to the swing frame, the other to the shifting frame. A forked sliding frame stroke *y* is twofold in comparison to the cylinder stroke *x*. ($y = 2.x$). Also the speed of lifting the load is twice as large as the speed of the piston stroke. $\dot{y}(t) = 2.\dot{x}(t)$. The hydraulic circuit with energy recuperation requires that in lowering the load a hydrostatic transmitter work in the motor mode and power the electric motor operating in the generator mode.

1. Hydraulic Circuit Layout

The hydraulic circuit with a single-acting cylinder for lifting is simple. The problem of energy recuperation lies only in an appropriate choice of the switchboard and its wiring. Figure 4 shows a classic arrangement of a hydraulic circuit of a fork lift truck.



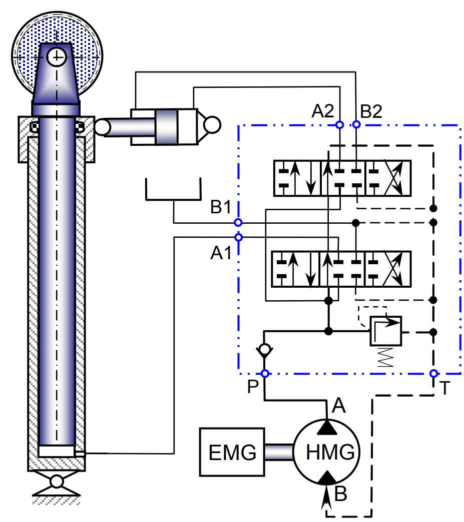


Fig. 4 Hydraulic Circuit with No Recuperation. *Fig.5 Connection for Recuperation*

Figure 4 and Figure 5 marks:

EM - Asynchronous electric motor with squirrel cage.

HG - Hydro-generator.

EMG - Electric motor - generator

HMG - Hydro-motor - generator

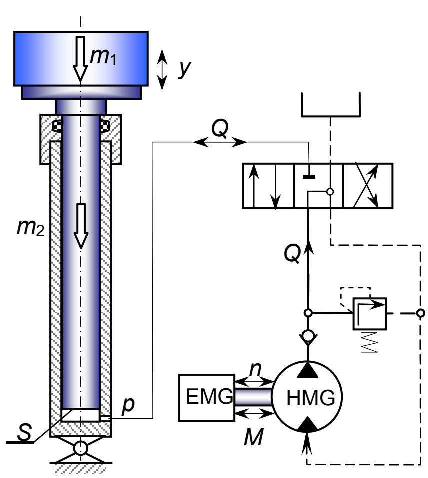
Figure 4 shows a type section switchboard with an open centre. The upper section controls the position of the small cylinder, for bending forward and backward as shown in Figure 3. The lower section is used to control the lifting cylinder. The single-acting lifting cylinder is connected to the switchboard output A1. The output B1 is blinded.

When lowering the lifting cylinder (with and without the load), the A1 line is connected through the switchboard to a pressure-free lead into the tank T. The A1 line incorporates a built-in damping resistance R with a bypass via one-way valve. The damping resistor is used to reduce the speed of lowering the load. When lowering the load, the piston is under pressure $p = R.Q^2$ and the whole output $P_R = p.Q$ turns into heat. Behind the resistance (or from the resistance to the tank), there is pressure $p_T = 0$ in the A1 line. Without the damping resistance, when lowering there is theoretically zero pressure in the space below the piston. The energy of the lowered load can not be used. When lifting and lowering, HMG works in the generator mode.

Figure 5 shows the layout of the hydraulic circuit with energy recuperation at lowering. Exactly the same section switchboard is used as one in Figure 4, just connected in a bit different way. Connection of the upper section of the switchboard for bending forward and backward does not change. Output B1 blinded in Figure 4 is separately connected to the storage tank in Figure 5. The common lead of the T switchboard is connected to the input suction channel B of the hydro-generator. This creates a closed hydraulic circuit. That is all. Minor adjustments made of the connection will radically change properties of the circuit. In lowering the lifting cylinder (with and without the load), there is a pressure proportional to the load in the piston of the cylinder. The same pressure is in the A1 line and at the input of the B hydro-generator. HMG works in the motor mode and drives EMG operating in the regenerative mode. The energy acquired is used to charge the battery. This is how recuperation of energy is realized in lowering.

2 Substitutive Mechanism and Theoretical Equations

With the arrangement according to Figure 3, one should consider the impact of the transfer through the pulley. The energy balance will be carried out in dimensionless variables. Then, the constant ratios have no influence on the outcome. The substitutive lifting mechanism will be according to Figure 6, without a pulley gearing and without a small roller for forward bend and backward bend.



In Figure 6 is marked:

- m_1 - load weight, (load bearing capacity)
- m_2 - weight of the piston and the sliding frame,
- y - stroke of the load and the piston
- S - piston area
- p - pressure under the piston
- Q - flow rate
- n - revolutions
- M - transmitted torque

When lifting EMG in the motor mode.
HMG in the generator mode

Fig.6 Substitutive Mechanism. When running EMG in the generator mode HMG in the motor mode

Quantities at different operating modes are distinguished by indices as follows. When lifting the load index 1, when lifting without the load index 10. When lowering the load index 2, when lowering without the load index 20.

External loading force on the piston in lifting and lowering the load

$$F_{Z1} = F_{Z2} = (m_1 + m_2).g = G_1 + G_2 \quad (1)$$

when lifting and lowering without load

$$F_{Z10} = F_{Z20} = m_2.g = G_2 \quad (2)$$

Theoretical driving force for lifting the load:

$$F_{H1} = F_{Z1} = S.p_1 \quad (3)$$

When lowering the load, the external loading force is driving force acting in the direction of the motion while the hydraulic force from the pressure under the piston acts against the motion.

At a constant speed, lowering the load is:

$$F_{Z2} = F_{H2} = S.p_2 \quad (4)$$

Driving force in lifting without the load:

$$F_{H10} = F_{Z10} = S.p_{10} \quad (5)$$

When lowering without the load.

$$F_{Z20} = F_{H20} = S.p_{20} \quad (6)$$

4 different theoretical pressures can be identified of these equations.

Theoretical flow rates in the described operating modes:

$$Q_1 = \mathrm{V_g}.n_1, \quad Q_{10} = \mathrm{V_g}.n_{10}, \quad Q_2 = \mathrm{V_g}.n_2, \quad Q_{20} = \mathrm{V_g}.n_{20} \quad (7)$$

Actual flow rates are smaller than the HMG loss of flow.

Theoretical moments transmitted between EMG and HMG

$$M_1 = +\frac{\mathrm{V_g}}{2\pi}\cdot p_1, \quad M_{10} = +\frac{\mathrm{V_g}}{2\pi}\cdot p_{10}, \quad M_2 = -\frac{\mathrm{V_g}}{2\pi}\cdot p_2, \quad M_{20} = -\frac{\mathrm{V_g}}{2\pi}\cdot p_{20} \quad (8)$$

Actual moments are bigger by passive moments of HMG and EMG.

Each amount of torque transmitted is assigned a value of revolutions, in the static characteristics of the EMG.

3. Static Characteristics of Electric Motor.

Each DC motor can operate in the generator mode, as a dynamo. Each asynchronous engine under zero load torque has theoretically synchronous revolutions. In the motor mode, under the load with a positive moment M_Z, revolutions are smaller than synchronous. In the generator mode, driven by a negative torque, revolutions are greater than synchronous.

Catalogue sheets of Siemens three-phase asynchronous electric squirrel cage electric motors contain a table of nominal parameters, synchronous revolutions and moment of inertia. Electric engines are divided into several classes of torque, which are given dimensionless values of selected moments and courses of dimensionless characteristics.

The driving torque course of the electric motor depending on the revs (torque characteristics course), is described by a general approximation function in the form:

M=M0*exp(-K0*n)+a1*n^K1-a2*n^K2 (9)

As a model, the course was chosen of dimensionless torque characteristics of electric motors of the KL 16 moment class.

By the regression analysis, numeral values were found to this course of constant coefficients of the dimensionless approximative function (9), as given in the following table.

M0	K0	a1	K1	a2	K2
2,8	1,548	3,28	1,23	3,875	10,64

The result of the calculation is the dimensionless moment characteristics in Figure 7.

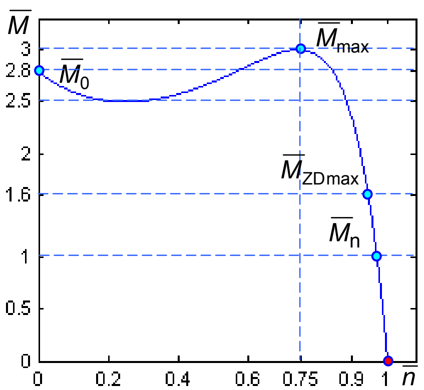


Fig.7 Torque Characteristics of EM.

In the dimensionless characteristics, the dimensionless moments values are:

$\overline{M}_{n} = 1$ Nominal moment.

$\overline{M}_{ZDmax} = 1{,}6$ The maximum allowable load moment.

$\overline{M}_{max} = 3$ Maximum driving torque EM.

$\overline{M}_{0} = 2{,}8$ Starting torque.

and the dimensionless revs: $\overline{n} = \frac{n}{n_S}$,

where n_S are synchronous revolutions adjusted by the frequency converter.

It applies to the nominal values of the theoretical quantities:

$$M_n = \frac{V_g}{2\pi} \cdot p_n, \qquad p_n = \frac{F_{Zn}}{S} \tag{10}$$

It applies to the maximum values of the load theoretical values:

$$M_{Zmax} = \frac{V_g}{2\pi} \cdot p_{Zmax}, \qquad p_{Zmax} = \frac{F_{Zmax}}{S} = \frac{G_1 + G_2}{S} \tag{11}$$

According to the manufacturer's catalogue and Figure 7, is the maximum permissible dimensionless value of the loading torque of the electric motor $\overline{M}_{ZDmax} = 1{,}6$. The values of load quantities according to (10) are theoretical. The actual values will be greater. The maximum values of the dimensionless load theoretical parameters should be chosen.

$$\overline{M}_{Zmax} = \frac{M_{Zmax}}{M_n} = \frac{p_{Zmax}}{p_n} = \frac{F_{Zmax}}{F_{Zn}} = \overline{p}_{Zmax} = \overline{F}_{Zmax} = 1{,}5 \tag{12}$$

It applies to the minimum values of the load theoretical quantities:

$$M_{Z\min}=\frac{V_g}{2\pi}\cdot p_{Z\min},\qquad p_{Z\min}=\frac{F_{Zmim}}{S}=\frac{G_2}{S} \tag{13}$$

Whence:
$$\frac{M_{Z\min}}{M_{Z\max}}=\frac{p_{Z\min}}{p_{Zm\max}}=\frac{F_{Z\min}}{F_{Z\max}}=\frac{G_2}{G_1+G_2}=\frac{m_2}{m_1+m_2} \tag{14}$$

For a forklift truck with the capacity m_1 = 1000 *kg,* the sliding frame weight with the piston cylinder may be around m_2=177 *kg*. In this case:

$$\frac{F_{Z\min}}{F_{Z\max}}=\frac{m_2}{m_1+m_2}=\frac{117}{1117}=0{,}15 \tag{15}$$

In the dimensionless form:

$$\overline{M}_{Z\min}=\overline{p}_{Z\min}=\overline{F}_{Z\min}=0{,}15.\overline{F}_{Z\max}=0{,}15.1{,}5=0{,}225 \tag{16}$$

The approximating function (9) applies only to the course of the EMG driving torque in the motor mode. In the generator mode, the approximating function (9) does not apply. In order to perform the necessary calculations even in the generator mode, then an alternative solution is adopted. The nonlinear course of the torque characteristics of the course near the synchronous point shall be replaced with a straight line. (Figure 8). The linear replacement is symmetric around the synchronous point, and applies to the motor mode as well as to the generator mode.

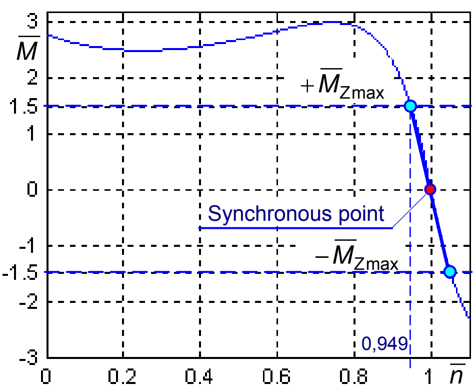


Fig.8 Torque Characteristics of EMG

According to equation (9), the value $\overline{M}_{Z\max}=1{,}5$ corresponds to the revolutions $\overline{n}=0{,}949$. Thereof, it applies to the equation of the substitute line:

$$\overline{M}=29{,}411.(1-\overline{n}) \tag{17}$$

Steepness of the substitute line determines the size of the dimensionless proportional gain of the EMG image transmission load in the motor and generator mode.

The value of the proportional gain is the ratio of deviations in the new steady state:

$$\overline{r}_0=\lim_{t\to\infty}\frac{\Delta\overline{n}(t)}{\Delta\overline{M}(t)}=\frac{\Delta\overline{n}}{\Delta\overline{M}}=\frac{1-0{,}949}{1{,}5}=0{,}34 \tag{18}$$

The validity of the linear replacement is limited to the interval of revolutions $\overline{n}\in\langle 0{,}949\,;\,1{,}051\rangle$.

4 Dynamic Characteristics of the Electric Motor and System

The basic dimensionless motion equation for the rotational motion, (when neglecting the resistance against deformation of the short shaft between EMG and HMG), has the general shape:

$$\overline{M}_H(t)=\overline{M}_Z(t)+\Sigma\,\Delta\overline{M}(t)=\overline{M}_Z(t)+T_0.\dot{\overline{n}}(t)+\overline{B}.\overline{n}(t) \tag{19}$$

where: $\overline{M}_H(\overline{n}(t))$ - linear course of the driving torque according to the replacement line

$\overline{M}_Z(t)$ - the course of the external load moment.

$T_0.\dot{\overline{n}}(t)$ - dimensionless passive moment of resistances against acceleration.

$T_0 = \frac{(J_E + J_G).\omega_{max}}{M_n}$ (s) - start time constant with HMG connected.

$\overline{B}.\overline{n}(t)$ - dimensionless passive moment of resistances against the EMG movement

$\overline{B}$ - dimensionless coefficient of viscous friction.

(Note: Derivation of dimensionless revolutions has the dimension $\dot{\overline{n}}(t) = d\overline{n}/dt$ (s^{-1}). Then, the product $T_0.\dot{\overline{n}}(t)$ is dimensionless).

On the linear replacement, through the application of Laplace transformation, the partial image transmission load is detected:

$$\frac{\Delta\overline{n}(s)}{\Delta\overline{M}_Z(s)} = -\frac{1}{T_0.s + \overline{B}} = -\frac{\bar{r}_0}{T_1.s + 1} \qquad (20)$$

where: $T_1 = T_0 / \overline{B}$ - the first-order time constant of the image transmission

$\bar{r}_0 = 1/\overline{B}$ - dimensionless proportional gain of the image transmission

Dimensionless proportional gain value according to (18) is. In the publication [3], start time constant was determined $T_0 = 0{,}155\ s$, which may be used for all electric motors of the KL 16 torque class. The time constant of the first order in transmission (20) then will have a value.

So far, EMG has been loaded with constant moments. Between EMG and the load, there is a hydraulic system containing HMG and the lifting cylinder. The constant load torques are theoretical, in the steady state identical with the constant load forces. The actual load moments will be greater by the internal resistance moments of the system. The output quantity of the system is the lifting and lowering speed. The speed will be smaller by the losses. Equations:

HMG output flow $\quad Q(t) = Q_T(t) - \Sigma\ \Delta Q_Z(t) = V_g.n(t) - C_1.\dot{p}(t) - G_1.p(t) \qquad (21)$

Roller output speed $\quad v(t) = v_T(t) - \Sigma\ \Delta v_Z(t) = Q(t)/S - C_2.\dot{p}_T(t) - G_2.p_T(t) \qquad (22)$

In the dimensionless form

$\overline{Q}_T = \overline{n} \qquad \overline{Q}(t) = \overline{n}(t) - T_{D1}.\dot{\overline{p}}(t) - \overline{G}_1.\overline{p}(t) \qquad (23)$

$\overline{p}_T = \overline{F}, \quad \overline{v}_T = \overline{Q} \qquad \overline{v}(t) = \overline{Q}(t) - T_{D2}.\dot{\overline{p}}_T(t) - \overline{G}_2.\overline{p}_T(t) \qquad (24)$

The driving force in lifting $\quad F_H(t) = S.p = F_Z + m.\dot{v}(t) + b.v(t) \qquad (25)$

in lowering $\quad -F_H(t) = -F_Z + m.\dot{v}(t) + b.v(t) \qquad (26)$

In the dimensionless form

$$\pm \bar{F}_H(t) = \pm \bar{F}_Z + T_{D3}.\dot{\bar{v}}(t) + \bar{b}.\bar{v}(t) \qquad (27)$$

$\bar{p}_T = \bar{F}_Z$
$$\bar{p}(t) = \bar{F}_Z + T_{D3}.\dot{\bar{v}}(t) + \bar{b}.\bar{v}(t) \qquad (28)$$

where: C - hydraulic capacity,
G - leakage permeability,
T_D - derivative time constant. ($T_D = r_1$ (s) is the derivative gain)

Simulation model of the entire system compiled According to last equations is in Figure 9.

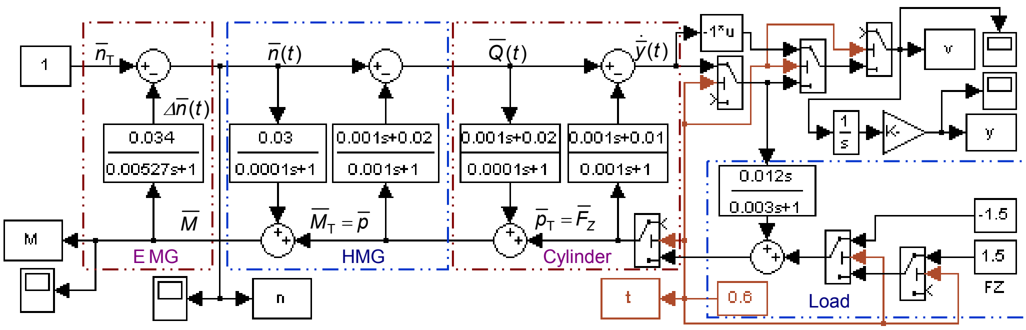


Fig.9 Simulation Model of Power Transmission of a Forklift Truck.

The simulation results at maximum load with a burden $\bar{F}_Z = 1{,}5$ are in Figure 10 ÷ 12.

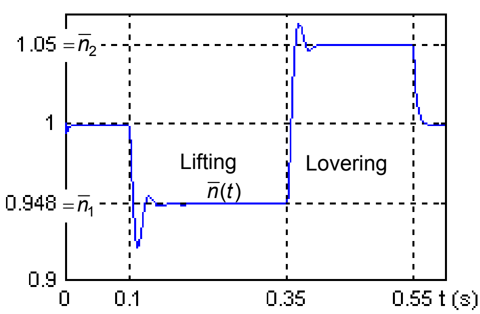


Fig.10 Time Course of Revolutions

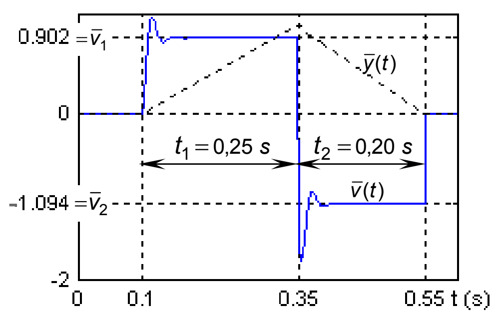
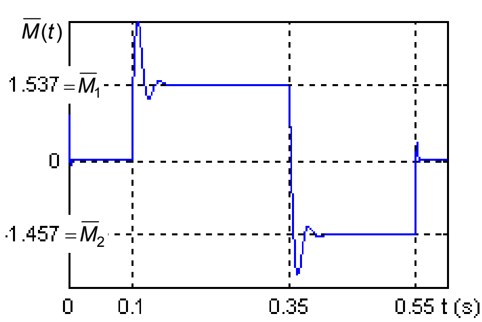


Fig.11 Speed and Lift Path Course.



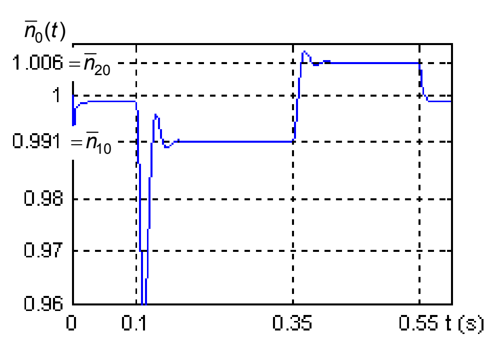


Fig.12 Moment with a load. *Fig.13 Revolutions without a load*

The course of revolutions during lifting and lowering without the burden is in Fig.13.

EMG revolutions during lifting and lowering without a load differ from synchronous by less than 1%.

5 Energy Balance

Energy balance will be made provided that the steady values of the output quantities as calculated by the simulation model are constant throughout the lifting and lowering of the load. When lifting the load, EMG works in the engine system with parameters:

Performance when lifting $\overline{P}_1 = \overline{M}_1 . \overline{n}_1 = 1{,}537 . 0{,}948 = 1{,}457$

Stroke time: $t_1 = 0{,}25\ s$

Specific energy consumed per stroke

$$\tilde{E}_1 = \overline{P}_1 . t_1 = 0{,}364 \quad (29)$$

When lowering the load, EMG operates in the generator mode and supplies power. The performance in lowering is greater because everything moves faster.

Performance in loading $\overline{P}_2 = \overline{M}_2 . \overline{n}_2 = 1{,}457 . 1{,}05 = 1{,}5298$

Lowering time $t_2 = 0{,}20\ s$

Specific energy gained when lowering for one stroke

$$\tilde{E}_2 = \overline{P}_2 . t_2 = 0{,}3059 \quad (30)$$

Recuperation efficiency $\eta_E = \dfrac{\tilde{E}_2}{\tilde{E}_1} = \dfrac{0{,}3059}{0{,}364} = 0{,}84$ (31)

This applies with the mentioned simplifying assumptions and correctness of the choice of dynamic parameters, in the system model in Figure 8.

Conclusion

It is shown in the article that by a simple adjustment of the connection of the hydraulic circuit switchboards we can achieve energy recuperation with forklifts, using the potential energy of the load lifted. By lowering the same load, we gain about 84% of energy from the energy expended for one lift of the load. But this is only a recuperation of the hydraulic circuit and EMG. The energy gained at the EMG output is in the form of electrical current with 3x380V voltage, with a frequency of 50±20 Hz, an adjusted frequency converter. Between EMG and the battery there has to be a 380V/48V transformer, a rectifier to change AC to DC and other electronic equipment to adjust the charging current amount. The issues of adjustment of electrical circuits for forklift energy recuperation are solved by an electrical engineering department dissertationist. This article deals only with energy recuperation by a hydraulic circuit, with an optimistic result (31). The continuing electrical part is addressed in this article.

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Resumé

VYUŽITÍ POTENCIÁLNÍ ENERGIE BŘEMENE

Gabriela KOREISOVÁ, Josef KOREIS

V článku je popsáno uspořádáni hydraulického obvodu zvedacího mechanismu vysokozdvižného vozíku. Vysokozdvižný vozík, má elektrický pohon pojezdu a také hydraulického mechanismu. Zdrojem elektrické energie je akubaterie. Při zvedání břemene hydrostatický převodník poháněný elektromotorem pracuje v generátorovém režimu a spotřebovává část energie akumulované v baterii. Při spouštění břemene je možné část potenciální energie zvednutého břemene využít pro dobíjení baterie. Hydraulický obvod s rekuperaci energie vyžaduje, aby při spouštění břemene hydrostatický převodník pracoval v motorovém režimu a poháněl elektromotor pracující v generátorového režimu. Článek je věnován tomuto problému.

Summary

USE OF THE POTENTIAL ENERGY OF LOAD

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The article describes a hydraulic circuit arrangement of a forklift lifting mechanism. The forklift's travel and hydraulic mechanism is electrically driven. The source of electrical energy is an accu-battery. When lifting the load, the hydrostatic transducer driven by an electric motor works in the generator mode and consumes a part of the energy accumulated in the battery. When lowering the load, a part of the potential energy of the load lifted may be used for recharging the battery. The hydraulic circuit with energy recuperation requires that in lowering the load the converter works in the engine mode and drives the electric motor operating in the generator mode. The article is devoted to this issue.

Zusammenfassung

VERWENDUNG VON DER POTENTIELLE ENERGIE LADEN

Gabriela KOREISOVÁ, Josef KOREIS

Der Artikel beschreibt eine Hydraulikkreis.-Anordnung der ein Gabelstapler Hubwerk. Des Gabelstaplers Reisen und hydraulische Mechanismus wird elektrisch angetrieben. Die Quelle von elektrischer Energie ist eine Akku-Batterie. Wenn Sie die Last zu ziehen, wird der hydrostatischen Wandler durch einen elektrischen Motor angetrieben arbeitet in den Generator-Modus und verbraucht einen Teil der Energie in der Batterie angesammelt. Wenn die Last zu senken, kann ein Teil der Energie Potenzial der Last aufgehoben verwendet werden, für den Akku aufladen. Die hydraulische Schaltung mit Energie Erholung erfordert, bei der Senkung der Last, die der Konverter arbeitet in den Engine-Modus und Laufwerke von der Elektromotor im Generator-Modus.