OBTAINING THE MINIMUM ELECTRICAL ENERGY CONSUMPTION CONDITION FOR BUCKET WHEEL EXCAVATORS (BWE) FROM LIGNITE OPEN PITS

by
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Abstract: The Bucket Wheel Excavator (BWE) is an huge complex electromechanical machine used to excavation the lignite from lignite open pits. This machine is the main element into a technological line and for it`s normal operation depend the implements function from downstream. Through the applying of some mathematical methods it is possible to reduce the electrical energy consumption of these machine.
Keywords: Bucket Wheel Excavator (BWE), splinter, sliding angle, extremal, condition

1. Introduction

The BWE is used for exploitation of lignite open pits in Romania. Here, is applied the technology in continous flux and the most important machine is bucket wheel excavator. The installed power on (BWE) is in the range from 500 kW to 4000 kW and there are about one hundred of BWEs for four types: BWE-470, BWE-1300, BWE-1400, BWE-2000.

A technological line is made by BWE, the Belt Conveyor (BC) and a dumping machine (DM). The BWE is the leader element and it`s well working at the high parameters depends the function of the other machines from downstream (which have the installed power between 2000-3000 kw).

Due to the high electrical energy consumpuion to these machines from lignite open pits, the lignite exploitation has became an energointensive process and subduing to restructure and retechnologizing.

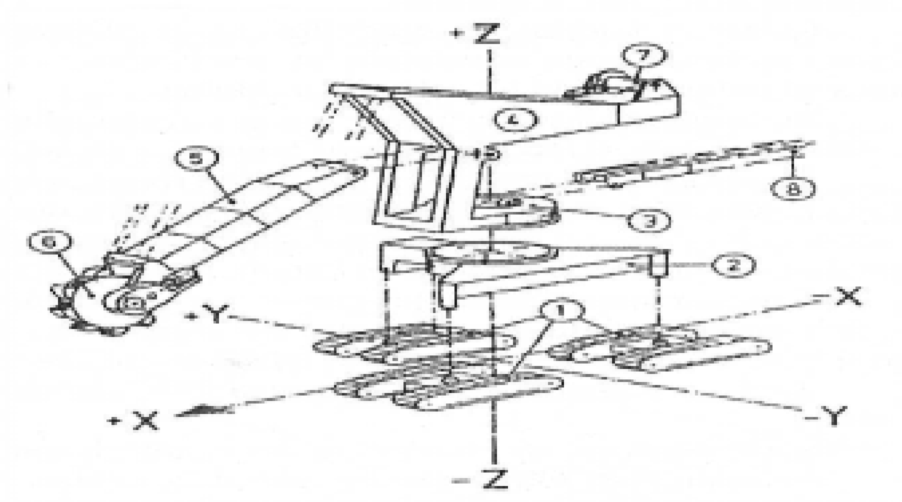
2. The analysis of the excavation process. The determination of the some specifical parameters

The figure 1 shows that the BWE has a continous working and it is compound by the following mechanismes:

1. the removal mechanisme;
2. understructure;
3. sliding mechanisme;
4. abovestructure;

5. bucket wheel arm;
6. bucket wheel;
7. rising/down winch of bucket wheel arm;
8. overfall arm.

The BWE is a complex electromechanical machine and the figure 1 emphasis the main moves of the subanssemblies:



$(\omega_r, \dot{\beta})$- the rotation speed of BWE;

Fig.1 BWE`s mechanismes

$(\omega_s, \dot{\varphi})$- the sliding speed of arm in the horizontal plane face the lead direction ;

(v_{rid}, v_{cob})- rising/down speed of BW arm with α angle face the horizontal;

(v_{retrag}, v_{avans})- indention/lead speed of BW;

φ- the slide angle is the main parameter and it is realised by the BW`s arm face to the lead axis.

The technical characteristics to the BWE are; D- the wheel diameter; q- the bucket capacity;

z- the number of bucket; Q- productivity; H- hight of excavated block; H_1- the excavation deep;

h- the deep of excavated splinter; v_{s0}- the initial slide speed; k_1, k_S- the specifical cutting force;

L_b -the arm`s length; L_a - dimension between the sliding axis to the anchorage axis; s_0 - the maximum of excavated splinter thick; α - the maximum angle of rising/down of BW arm.

The BWE excavation process is more complicated due to the wheel has a rotation move in vertical plane $\omega_r, \dot{\beta}$, v_r and an elicoidal move in horizontal plane, the shape of propeller is modifying when the slide speed $\omega_s, \dot{\varphi}, v_s$ is adjustabled in dependence with φ.

As the excavation process to be able in good conditions (without mechanical shocks to the bucket wheel or abovestructure) it is necessary that (b_e) the proppeler step to be less or equal with the bucket width (b), so between $\dot{\varphi}$ and $\dot{\beta}$ have to exist an established reportwhich depends by excavation conditions:

$$b_e \le b; \ \frac{\dot{\varphi}}{\dot{\beta}} = k \qquad (1)$$

The splinter width depends of β (the angle realised by the bucket in contact with the block) value:

$$S_\beta = S_0 \sin\beta \qquad (2)$$

For a some position of bucket, the width has the expression:

$$b = \frac{2\pi}{z} \cdot \frac{\omega_s}{\omega r} \ (L_0 + R\sin\beta); \quad \text{with } L_0 = L_a + L_b\cos\alpha \qquad (3)$$

If we take into account that $\beta \in (0; \beta_h)$ we obtain the average width of splinter in vertical plane:

$$b_{med} = \frac{2\pi}{z} \cdot \frac{\omega_s}{\omega r} \frac{1}{\beta_h} [L_0 \beta_h + R(1 - \cos\beta_h)] \qquad (4)$$

The splinter cross section for some hight is $S_0 = S_\beta \cdot b$ and based on rel. (3) and (2), the average value for that splinter cross section becomes:

$$S = \frac{S_\varphi \beta_h}{\beta_h^2} \cdot \frac{\omega_s}{\omega r} (1 - \cos\beta_h) \ [L_0 \beta_h + R(1 - \cos\beta_h)]$$

(5)

The splinter width is modified in dependence by sliding angle and it takes the maximum value when BWE arm is right on the BWE lead axis and $\beta_h = \pi/2$, results that $S\varphi$ has a similar expression to (1):

$$S_{\varphi} \cong S_0 \cos\varphi \text{ ; } S_{\varphi} \cong S_0 \sin\varphi \qquad (6)$$

In the site, for to define the cutting force it is used the following parameters:

a) the specifical excavation force on 1 cm length of cutting at the cutting bucket edge is:

$$K_l = \frac{F_t}{L_{sm}} \qquad (7)$$

with Lsm represents the global length of bucket`s cutting edges simultanous in contact with the block.

b) the specifical excavation force on 1 cm^2 cross section of excavated splinter:

$$K_S = \frac{F_t}{S_m} \qquad (8)$$

with Sm represents the global cross sections of excavated splinters by the simultanous splinters existing in contact with the rock block.

There appear a diference of the values between the parameters for same deposit block.

It is able to consider that the cutting edge length (L_{β}) for a bucket is the sum between S_{β} and b, and the average length value for a some splinter hight when $\beta = \beta_h$, is:

$$L_m = \frac{1}{\beta_h}\int_0^{\beta_h} L_\beta d\beta = \frac{1}{\beta_h}\left[S_0 \sin\varphi(1-\cos\beta_h) + b\beta_h\right] = \frac{1}{\beta_z}\left[k_m \cdot \frac{hS_0 \sin\varphi}{R} + b\beta_h\right] \qquad (9)$$

where k_m=1,5-2 is a coefficient in depending by the wear of bucket knives.

In the site K_l, takes different values in function of the rock block nature:

- (300-800) N/cm the forifying sands;
- (200-300) N/cm for sands- gravels;
- (250-700) N/cm for clay;
- (300-1000) N/cm for granit.

If we take into account the number of bucket in contact with the rock $n_z = \frac{\beta_h}{\beta_z}$ and the excavated splinter average section, there results the global cross section which corresponds to the number of buckets in simultanous contact:

$$S_m = n_z s = \frac{S_0 \sin\varphi}{\beta_h} \cdot \frac{\omega_s}{\omega_r} (1 - \cos\beta_h)\ [L_0 \beta_h + R(1 - \cos\beta_h)] \quad (10)$$

So, the escavation force (7) is: $F_t = K_l L_{sm}$ and based on (1), (6), (9) we obtain:

$$F_t = \frac{k_1}{\beta_z} K_m S_0 \sin\varphi (1 - \cos\beta_h) + K_l [L_0 \beta_h + R(1 - \cos\beta_h)] \cdot \frac{\omega_s}{\omega_r} \quad (11)$$

In the case that bucket wheel speed is constant (the real case in reality) we obtain:

$$F_t = A \sin\varphi + B_1 \dot{\varphi} \quad (12)$$

where: $A = \frac{k_1}{\beta_z} K_m S_0 (1 - \cos\beta_h)$; $B = K_l [L_0 \beta_h + R(1 - \cos\beta_h)] \frac{1}{\dot{\beta}}$,

and based on rel.(10), and (8) we obtain:

$$F_t = M \dot{\varphi} \sin\varphi \quad (13)$$

where: $M = K_s S_0 \frac{1 - \cos\beta_h}{\beta_h} [L_0 b_h + R(1 - \cos\beta_h)] \frac{1}{\dot{\beta}}$

So, in the reality to the Oltenia Lignite Basin, the $\beta_h \geq \pi/2$and the filling up/emptiness preocess can be consider like a continous process, the rising force is equal with the sum of rock`s weight from z/2 wheel`s buckets.

For $\beta < \beta_h$ the weight from each bucket increases and for $\beta > \beta_h$ that will decrease on the same law:

$$G = \sum_{i=1}^{n} G_i \ ; \quad F_g = \gamma \frac{\beta_z}{\beta_h} \cdot \frac{\omega_s}{\omega_r} R (L_0 \beta_h + h) S_0 \sin\varphi \sum\theta \quad (14)$$

γ is the specifical weight for excavated rock.

For some excavation hight and for (α = constant), expression (14) takes the form;

$$F_g = C_1 \sin\varphi \cdot \frac{\dot{\varphi}}{\dot{\beta}} \text{ , if } \dot{\beta}=\text{ct., } F_g = C\dot{\varphi}\sin\varphi \quad (15)$$

where : $C=\frac{C_1}{\dot{\beta}} = \gamma \frac{\beta_z}{\beta_h} S_0 R [L_0 \beta_h + R(1 - \cos\beta_h)] \frac{\sum\theta}{\omega_r}$.

Depending how the excavation force is on K_l or K_s relantionshipas (7) and (8), and based on rel. (15) result the expression for static force:

$$F = A\sin\varphi + B_1 \frac{\dot{\varphi}}{\dot{\beta}} + C_1 \frac{\dot{\varphi}}{\dot{\beta}} \sin\varphi \quad (16)$$

And if $\dot{\beta}$=ct. $F = A\sin\varphi + B\dot{\varphi} + C\dot{\varphi}\sin\varphi$; $B=\frac{B_1}{\dot{\beta}}$ and $C=\frac{C_1}{\dot{\beta}}$,

$$F = M_1 \frac{\dot{\varphi}}{\dot{\beta}}\sin\varphi + C_1 \frac{\dot{\varphi}}{\dot{\beta}}\sin\varphi \quad (17)$$

if $\dot{\beta}$=ct , $F = M\dot{\varphi}\sin\varphi + C\dot{\varphi}\sin\varphi = D\dot{\varphi}\sin\varphi$.

Using the rel. (16) it can determ the static power expression of the bucket wheel:

$$P = FR\dot{\beta} = (A\sin\varphi + B_1\frac{\dot{\varphi}}{\dot{\beta}} + C_1\frac{\dot{\varphi}}{\dot{\beta}}\sin\varphi)R\dot{\beta} \quad (18)$$

if $\dot{\beta}$=ct, $P = a\sin\varphi + b\dot{\varphi} + c\dot{\varphi}\sin\varphi$.

Taking into account the motor winding power losses proportional with static force F and no-losd losses (k4), the absorbed power will become $P_1 = k_3F + k_4$, and based on rel.(18) it takes the form:

$$P_1 = a_1\sin\varphi + b_1\dot{\varphi} + c_1\dot{\varphi}\sin\varphi + k_4 \quad (19)$$

where:

$$a_1 = a + k_3A; \quad b_1 = b + k_3B; \quad c_1 = c + k_3C.$$

The productivity for the BWE can be exprimated in dependence by the technological and gauge parameters. If consider that at the each rotation of BW, a number of z buckets are empting, we obtain:

$$Q_h = V \cdot n_r \cdot z \cdot 60 \cdot f \quad \left[m^3/h\right] \qquad (20)$$

where : V- the bucket volum ; n_r - BW revolution ; z- number of buckets ; f- soil factor ; f = 1,1 – 1,25. The volum excavated by a bucket during one rotation is:

$$V = S_\varphi \cdot b \cdot R \cdot (1 - \cos\beta_h) \qquad (21)$$

where: S_φ - the cross section of splinter ; b – the average width of splinter ; β_h - the angle coressponding with the splinter hight, h= (0,4-0,7)D, and $\beta_h \cong \frac{\pi}{2} - \frac{2\pi}{3}$.

Based on (3), (6), (21) the rel. (20) takes the form:

$$Q_h = \sin\varphi \cdot R \cdot (1-\cos\beta_h)\frac{\beta_z \omega_s}{\beta_h \omega_r} R\left[L_0\beta_h + R(1-\cos\beta_h)\right]S_0 \cdot n_r \cdot z \cdot 60 \cdot f \qquad (22)$$

in which the BW revolution is::

$$n_r = \frac{60\omega_r}{2\pi} = \frac{60\dot{\beta}}{2\pi} \qquad (23)$$

If takes in consideration that $\dot{\beta}$ =ct, rel. (22) becomes:

$$Q = (1-\cos\beta_h)\frac{\beta_z}{\beta_h \omega_r} R\left[L_0\beta_h + R(1-\cos\beta_h)\right]S_0 \cdot \dot{\varphi} \cdot \sin\varphi \cdot 3600$$

(24)

or Q=q$\dot{\varphi}\sin\varphi$; where

$$q = (1-\cos\beta_h)R\left[L_0 + R/\beta_h \cdot (1-\cos\beta_h)\right]S_0 \cdot f \cdot 3600$$

The conclusion is that the theoretical productivity and the absorbed power to the ERC depend by gauge and technological parameters and these can modify in function of excavation process.

3. Obtaining the adjustable rotation speed law for abovestructure using variational calculus when the performance indicator is the specifical electrical energy consumtion

The minimum specifical consumption of electrical energy is an important technical-economical indicator for BWE, because BWE is the leader element into a technological line from a lignite open pit (BWE-BC-DM).

The performance indicator takes the form:

$$I = \int_{t_0}^{t_1} F[\varphi, \dot{\varphi}(t)]dt \text{; or } I = \int_{t_0}^{t_1} \psi(t)dt \qquad (25)$$

The problem which appear consists in to extrem rel. (25), as to fiind an optimal law for slide speed $\dot{\varphi} = \dot{\varphi}(t)$ or $\varphi = \varphi(t)$ forthe functional I have to take the extremum value (minimal).

Because the final time is free, we propose to change the variable which are going to limit the domain. The sliding angle will be consider like an argue and an independent value not like a time function and time becomes a functionwhich depends by slide angle t = h(φ).

Based on rel.(26) the sliding speed will be:

$$\dot{\varphi} = \frac{d\varphi}{dt} = \frac{1}{\frac{dt}{d\varphi}} = \frac{1}{h'(\varphi)} = \frac{1}{t'}$$

and the acceleration is:

$$\ddot{\varphi} = \frac{d\dot{\varphi}}{dt} = -\frac{h''(\varphi)}{h'^3(\varphi)} = -\frac{t''}{t'^3} \qquad (27)$$

and the functional (25) takes the form:

$$I = \int_0^{\pi} F(\varphi, t^{`})d\varphi \qquad (28)$$

It must be fiind the curve t = t(φ) ehich will extrem rel. (28) as to take the minimum value. If that curve will realise the functional extrem in accordance with Euler-Poisson condition, we obtain:

$$\frac{\partial F}{\partial t} - \frac{d}{dt}\left(\frac{\partial F}{\partial t'}\right) = 0 \qquad (29)$$

For the extrem to be minimum it have to fulfil the legendre condition:

$$F^{``}_{t't'} \geq 0 \qquad (30)$$

It is possible to touch a sliding speed higher than it`s maximum value established to work, that been require by the BW speed and also by the bucket width. In thid situation the law $\dot{\varphi} = \dot{\varphi}(t)$ is keeping till the asserted limit $\dot{\varphi} \leq \dot{\varphi}_{max}$.

In the site, when $\dot{\beta}$=ct., the analitic expression of useful power is givenby rel.(18) and productivity is given by rel. (24).

The specifical electrical energy consumption is given by:

$$I = \int_{t_0}^{t_1} \left(\frac{a}{q} \frac{1}{\dot{\varphi}} + \frac{b}{q \sin \varphi} + \frac{c}{q} \right) dt \qquad (31)$$

where a,b,c are coefficients determ by rel. (16, 18, 24).

If we based on substitution (26), the functional (31) takes the form:

$$I = \int_{t_0}^{t_1} \left(\frac{a}{q} t'^2 + \frac{b}{q \sin \varphi} t' + \frac{c}{q} t' \right) d\varphi \qquad (32)$$

The problem is to find an optimal law $\dot{\varphi} = \dot{\varphi}(t)$ or $\varphi = \varphi(t)$ or t = t(φ), as the functional (32) to take minimal value. It have to carry out the Lgendre condition:

$$F''_{t't'} = 2 \frac{a}{q} \geq 0 \qquad (33)$$

Because the coefficients a, b are always positive so the rel.(33) is verified. The law $\varphi = \varphi(t)$ or t = t(φ) will verify the above condition so:

$$2a \sin^2 \varphi t'' - b \cos \varphi = 0 \qquad (34)$$

Equation (34) after a first integration becomes:

$$t' = -\frac{b}{2a} \frac{1}{\sin \varphi} + k_5 \qquad (35)$$

Taking into account rel.(27) and (35) we obtain:

$$\frac{1}{\dot{\varphi}} = -\frac{b}{2a} \frac{1}{\sin \varphi} + k_5 \qquad (36)$$

Constant of integration k_5 is determed from the condition that the extremal curve $\varphi = \varphi(t)$ to cross through the point of ($\varphi_0, \frac{\pi}{2}$), obtaining:

$$k_5 = \frac{1}{\dot{\varphi}_0} + \frac{b}{2a} \qquad (37)$$

Through application of variational calculus it is obtained the optimal law of command $\dot{\varphi} = \dot{\varphi}(\varphi)$ for (31) takes the maximum value:

$$\dot{\varphi} = \frac{\dot{\varphi}_0}{1 + \frac{b}{2a}\left(1 - \frac{1}{\sin\varphi}\right)\dot{\varphi}_0} \qquad (38)$$

In the right of lead axis of BWE (when $\varphi = \frac{\pi}{2}$) the sliding speed is equal with $\dot{\varphi}_0$ the based speed and it increases from lead axis to boarders in the same time with the variable the sliding angle.

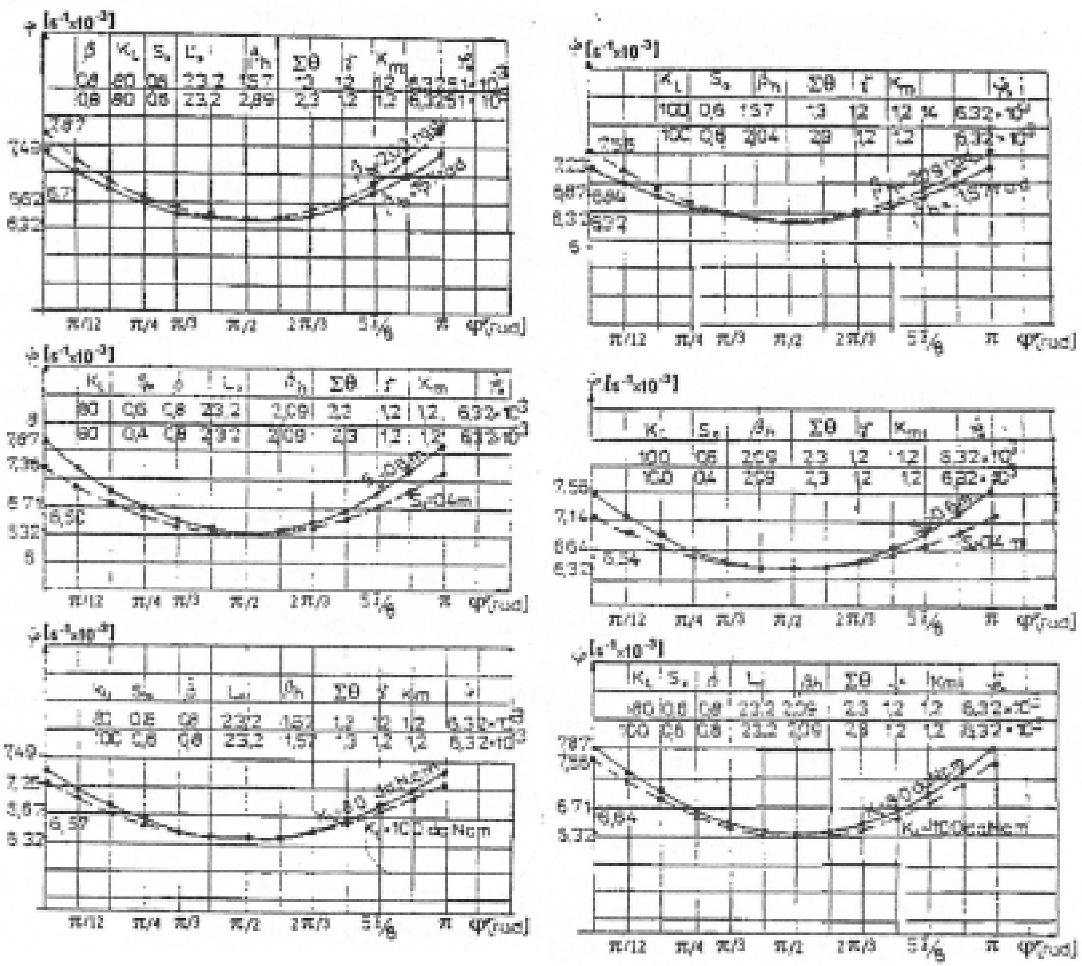


Fig.2

4. Conclusions

It can observe from rel (38) that in the optimal law appear technological and gauge BWE`s parameters through the a, b constants. Because the final expression is complex, using a computer it was possible to obtain the optimal law for BWE-1400 (fig.2). In the case of the performance indicator is the specifical electrical energy consumtion, the variation curve of speed are different as the command law applied in the present to BWE-1400 when the sliding speed must be modify into a large range.

When the splinter hight is increased the spliding speed have to decrease and the other parameters will keep to a constant values. When the weatness of knives is increasing for a same hight and width splinter, the sliding speed have to decrease as the electrical energy consumption to stay at the required value.

When the splinter width is decreasing and the other parameters stay to a constant value the sliding speed have to rise for a minimum electrical energy consumption.

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