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A Predictive-Adaptive Hierarchical Control System of Bucket-Wheel Excavator: Theory and Experimental Results

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Abstract: Development of a new two-level hierarchical control system, which significantly increases excavating capacity, as well as availability, and reliability of the bucket wheel excavator, is presented in this paper. On the first – basic level functions of local regulators and sensors are executed and the second – higher level is performing adaptation based on prediction of cutting resistance of materials to be excavated. Development of basic control system consists of design and tuning of local regulators, as well as design of highly precise and reliable sensors of basic movements. The predictive–adaptive higher-level control system is a neuro-fuzzy controller. By predicting cutting resistance of materials to be excavated reference of slewing speed and controller parameters are adapted. The structure of the new control system is based on expert knowledge, gained through numerous simulations of developed non-linear model in state space, where the disturbances are precisely modelled, and numerous experiments.

Keywords: Bucket wheel excavator, predictive-adaptive control, neuro-fuzzy controller.

1 Introduction

Bucket wheel excavators (BWE) (Fig. 1-a) are used in surface mining for excavating overburden, as well as digging coal. Those are extremely complex electromechanical systems, of great mass, dimensions and power, which are executing translator and slewing movement [1]. To secure efficient use of this system, following

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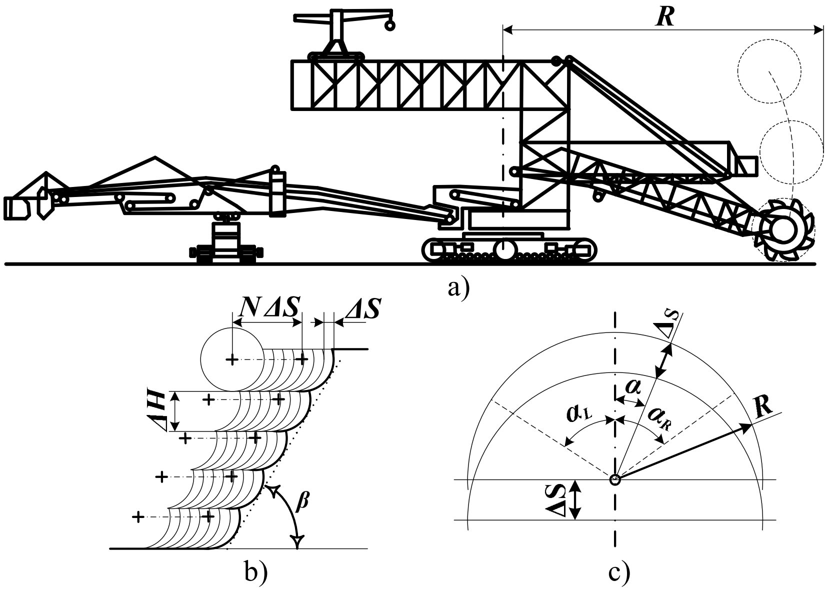
contradictory demands have to be met: maximal capacity of excavating with minimal loading of mechanical construction, as well as electromechanical equipment.



a)

b)

c)

Fig. 1. (a) BWE, (b) terrace cut and (c) crescent shape

To control BWE two strategies are proposed. The first one is: S1) constant capacity of excavating (Q) by synchronizing slewing speed (V_k) with geometry of cut. Second one is: S2) to secure constant load of cutting elements that only under strictly restricted conditions can present constant capacity of excavating. At present, method of terrace cut is used for realisation of these solutions (Fig. 1-b). Operating regimes of BWE in terrace cut are: advance, excavating by slewing movement, repeated advancing, excavating by slewing movement in opposite direction and repeat this operations N times, actually working in cut to the depth of $S = N \cdot \Delta S$. After exiting the cut, lowering the bucket wheel (BW) to the next level of excavating the height of the new cut is defined (ΔH). The same operations are being repeated with new parameters (α_L, α_R and N as shown in Fig. 1-b and 1-c).

Control strategy in this technology is to compensate for crescent loss [2] securing that capacity of the machine is used equally. By machine movement and cutting in circular formation the crescent shape is created in the ground. An actual depth of cut Δs is the function of slewing angle α. Its maximum is achieved in direction of moving axis, and it is equal to size of advance (ΔS). Crescent shape is shown on Fig. 1-c), where sizes ΔS and R are not realistically shown (practical ΔS:R=1:50).

Basic disadvantage of this technology, especially in excavating non-homogeneous materials, lies in overloading electromechanical equipment or decreasing of excavating capacity. Operator, using frequent changes of references, must solve the problem. Therefore, the efficiency of BWE depends on operator's experience, fatigue etc. The experience shows that the interrupts are relatively frequent and expensive. This solution does not secure maximal productivity, economical exploitation and reliability.

Hierarchical two-level control system is proposed as an efficient way to avoid previously mentioned problems and contradictory demands, by introducing new technologies to implement a combined strategy which takes into account good properties of both strategies S1 and S2.

2 Hierarchical Control System Design

Hierarchical control system designed as two-level control system of BWE is presented in Fig. 2. Functions of local regulators, sensors and interfaces are executed in the first - basic level. In fact, this level realise the reference $V_k^{ref}[\alpha(t),t]$ of slewing speed and partly fulfil condition of minimum loading of mechanical construction and electromechanical equipment. Basic movements are: slewing – α', translator – s' and vertical – h'. To satisfy demands of the new control system new very precise sensors for slewing and translator movement are developed and implemented, taking into account extreme working conditions on BWE. Two groups of interfaces developed, implemented and adjusted are: converters of electrical (I_{bw}', I_m') and non-electrical (V_k) values to adequate analogue signals and group of A/D and D/A converters in between two controlling levels $(\alpha$, V_k, s, h, I_{bw}, $V_k(\alpha,t)$, $V_t(s,t)$ and $V_h(h,t))$. In Fig. 2 measurements are denoted with apostrophe and adequate electrical signals are denoted without apostrophe.

References and commands for basic level, adaptation to the existing blocking, safety and signalization system of BWE and communication with operator are realised in second level. Interfaces have 24 digital inputs, 16 digital outputs, 16 10-bits A/D converters, 4 10-bits D/A converters, 4 DC/DC converters and 2 AC/DC converters, including 8 LED displays and keyboard with 16 keys. Control system is realised as industrial computer system based on 8-bit microprocessor Zilog Z80.

References are generated by memorizing cutting resistance of the material to be excavated ("picture" of cutting resistance is created). Based on created picture from the previous cuts, higher level control system enables to predict the desired references for speed of BWE movements, $V_k(\alpha)$ and $V_t(s)$, and advance ΔS. Due to space limitation in the next section only adaptation of slewing movement is presented in detail.

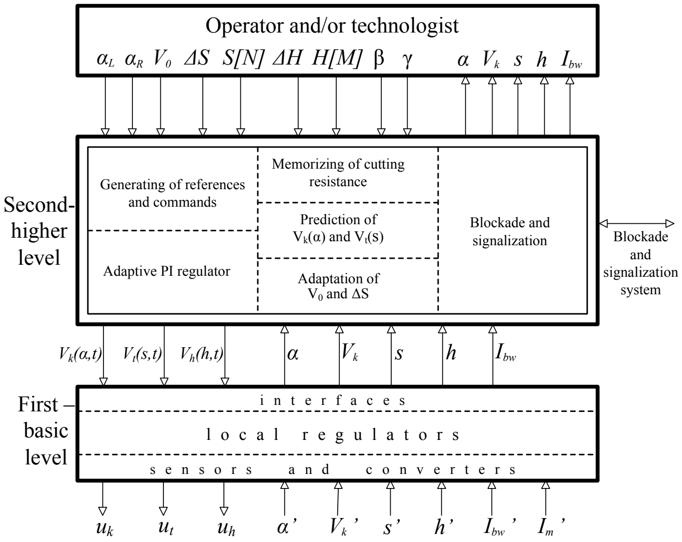


Fig. 2. Hierarchical structure of control system

3 Design and Tuning of the Basic Control System

The most used technology in surface mining is terrace cut. BWE SRs 1200, constructively as well as by control concept, is designed for this type of operation. If advance of BWE is constant, technology of terrace cut is realised so that speed of slewing moment V_k follows the reference $V_k^{ref}(\alpha)$, where

$$V_k^{ref}(\alpha) = \begin{cases} \dfrac{V_0}{\cos(\alpha)}, & \alpha \in (-60^\circ, 60^\circ) \\ 2V_0 = const, & |\alpha| \geq 60^\circ \end{cases}$$

However, in Fig. 3, presenting the new basic control system, the reference $V_k^{ref}(\alpha)$ is denoted by $V_k^{ref}[\alpha(t),t]$, as generated by higher hierarchical level (HHL). To ensure reference tracking and disturbances rejection in both operating regimes of BWE (old or new control system), basic control level is realised as shown in Fig. 3.

By generating signals $\boldsymbol{r}$ and $\boldsymbol{y}$, converters K_r and K_y perform normalisation and galvanic insulation of reference V_k^{ref} and controlled value V_k, Fig. 3. Control signal $\boldsymbol{m}$, acts as input to the current converter G_{sp}. To protect overload of transistors in output of current converter and to avoid over excitation of Ward-Leonhard group (I_p^{max}) and damping machine (I_{dm}^{max}) [3, Fig. 2] a limiter has been introduced to ensure that current I_i is always less than I_i^{max}, i.e. $I_i \leq I_i^{\max}, I_i^{\max} = I_p^{\max} + I_{dm}^{\max}$.

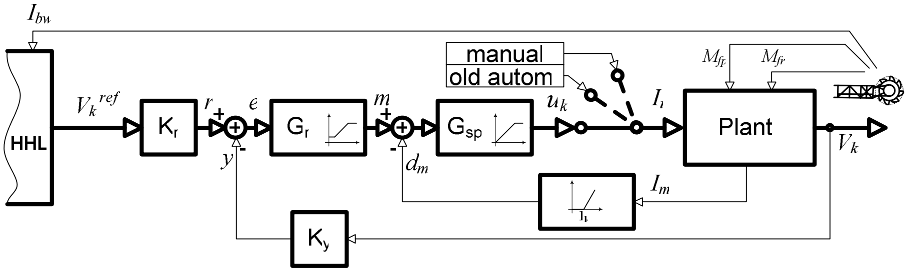


Fig. 3. Block diagram of the basic control system

PI regulator is defined by transfer function $G_r(s)$, i.e. $m(t) = K_p \cdot [e(t) + 1/T_i \int e(t)dt]$. K_p and T_i parameters, determined by simulation on developed nonlinear model have values K_p=100 and T_i=12.5[s]. The final values of these parameters, determined by fine readjustment on the plant, are K_p=128, T_i=12.48[s]. This result confirms validity of developed nonlinear model.

To obtain better characteristics of control system even in irregular cut, nonlinear internal feedback is introduced as shown in Fig. 3, where

$$d_m(t) = \begin{cases} 0, & I_m(t) \le I_k \\ K_i(I_m(t) - I_k), & I_m(t) > I_k \end{cases}$$

When current overload occurs ($I_m > I_k$), control signal $m(t)$ is reduced because $d_m \neq 0$. This implicates electro-dynamical slowing down of superstructure that momentarily reduces mechanical stress of construction and equipment [2]. Parameters of this feedback, determined by simulation [3] are I_k=67[A] and K_i=0.16[V/A]. The final values of these parameters obtained by fine readjustment on the plant are I_k=72.5[A] and K_i=0.184[V/A].

4 Design and tuning of the higher level control system

In process of excavating cutting resistance of material stochastically changes. Significantly different cutting resistance may appear in neighbouring slewing angles. This is the main cause of frequent interruptions, overload of cutting equipment and overburdening of transport system. In general, this variation of cutting resistance is responsible for decreasing capacity of excavating, and availability or even reliability of BWE. From stereo metric viewpoint, the layers or borders of different cutting resistance are continuously passing through the cuts. On the basis of this fact and knowing the picture of cutting resistance from the previous cuts, it is possible to predict cutting resistances in the next cut. This concept offer a possibility to adapt reference V^{ref}_k=$V^{ref}_k[\alpha(t),t]$ in the new cut. This is carried out in accordance with the predicted cutting resistance for different slewing angle $\alpha(t)$ and momentarily loading measured through $I_{bw}(t)$. Cutting resistance characteristics in only one cut can vary by ratio over 1:6 [4]! They can be determined on the basis of BW motor's current I_{bw}, as an indicator of integral dynamical cutting properties. For the purpose of measurements and prediction of cutting resistance, loading $L(\alpha)$ is defined as a function of V_k and I_{bw}, approximated by discrete fuzzy rules as shown in Table 1, for each discrete measured value of slewing angle α.

Table 1. Fuzzy rule defining loading $L(\alpha)$ as function of V_k and I_{bw} (UL-under load; NL-normal load; OL-overload; SL-super load; Index: 0-load less and n-nominal value)

V_k I_{bw}	$V_k < 0.86V_{kn}$	$0.86V_{kn} \leq V_k \leq 1.14V_{kn}$	$V_k > 1.14V_{kn}$
$I_{bw0} \leq I_{bw} \leq 0.8I_{bwn}$	0(NL)	−1(UL)	−1(UL)
$0.8I_{bwn} < I_{bw} \leq I_{bwn}$	+1(OL)	0(NL)	−1(UL)
$I_{bwn} < I_{bw} \leq 1.2I_{bwn}$	+2(SL)	0(NL)	0(NL)
$1.2I_{bwn} < I_{bw} \leq I_{bwmax}$	+2(SL)	+1(OL)	0(NL)
$I_{bw} > I_{bwmax}$	+2(SL)	+2(SL)	+1(OL)

Prediction $P(\alpha)$ of loading $L_i(\alpha)$ is obtained by interpolation of loading in two previous cuts $L_{i-1}(\alpha)$ and $L_{i-2}(\alpha)$, as shown in Fig. 4. Because of the constant advance ΔS and discrete measurement of angle α prediction of α_i is given by $\alpha_i = (2\alpha_{i-1} - \alpha_{i-2})/2$. Thus, $P(\alpha_i) = [2L^j_{i-1}(\alpha_{i-1}) - L^j_{i-2}(\alpha_{i-2})]/2$, as presented in Fig. 4. Discrete set of load prediction values is memorised as array $P(i{\cdot}\Delta\alpha)$ and

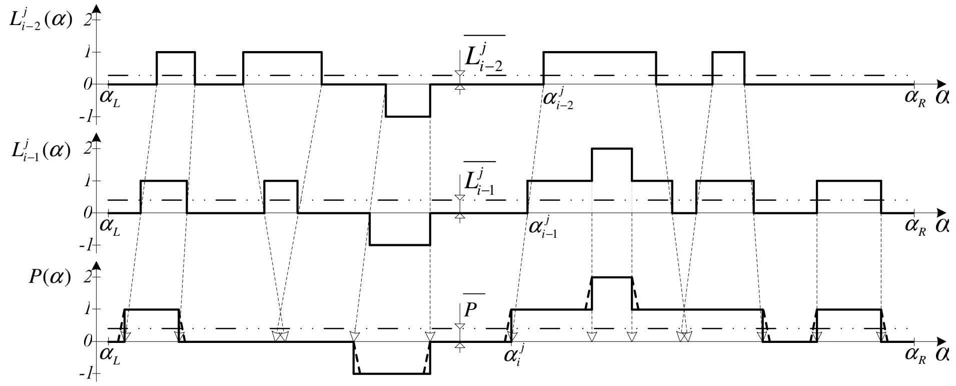


Fig. 4. Prediction $P(\alpha)$ of loading $L^j_i(\alpha)$ in i-th cut of the j-th level $j \cdot \Delta H$, based on loading in two previous cuts $L^j_{i-1}(\alpha)$ and $L^j_{i-2}(\alpha)$

used for generating reference $V^{ref}_k[\alpha(t),t]$, as shown in Fig. 5. Mean value of this array ($\overline{P}$) is used to adapt basic slewing speed V_0 as $V_b = V_0 \cdot (1 - k_b \cdot \overline{P})$. Parameter

k_b is adjusted on the plant and his value is k_b=0.1. Then a neural network is used to define an effective prediction of loading $P_w[\alpha(t)]$ (dashed line in graphic $P(\alpha)$ shown in Fig. 4) obtained as maximum

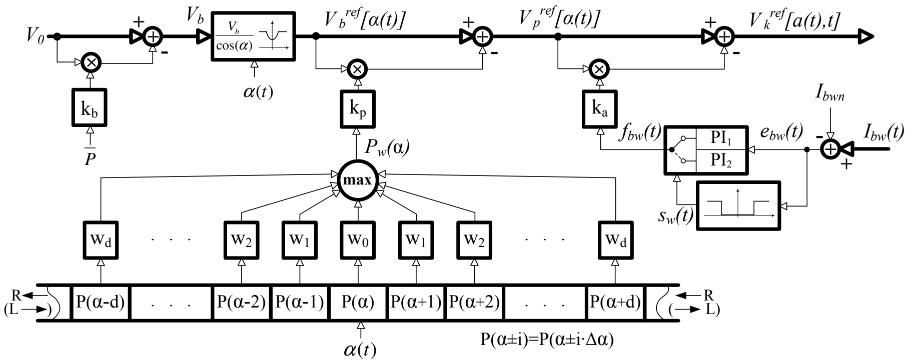


Fig. 5. Block diagram of the higher-level control system.

$$P_w(\alpha) = \max[P(\alpha-d)w_d, \ldots, P(\alpha-1)w_1, P(\alpha)w_0, P(\alpha+1)w_1, \ldots, P(\alpha+d)w_d]$$

and adaptation is defined with

$$V_p^{ref}[\alpha(t)] = V_b^{ref}[\alpha(t)] \cdot \{1 - k_p \cdot P_w[\alpha(t)]\}.$$

Great inertia of superstructure requires slowing down the slewing speed before positioning of BW in the layer with the higher cutting resistance. Many experiments are carried out in the different cutting conditions and regimes, in order to obtain very precise angle when to start with mentioned correction of speed V_k (this angle was called angle of preventive activity δ). On the basis of those experiments large nonlinearity was noticed in between angle δ and dynamic of loading in cut. To optimize complex demands and simplified realization, neural network within adaptive regulator was introduced, as shown in Fig. 5. Learning rule of neural network is defined by following procedure:

First, mean angle width is determined as $\overline{d_\alpha} = (\alpha_R - \alpha_L)/(N_d + 1)$. In previous equation α_L and α_R are left and right cut angles and N_d is a number of loading prediction $P(\alpha)$ discontinuity.

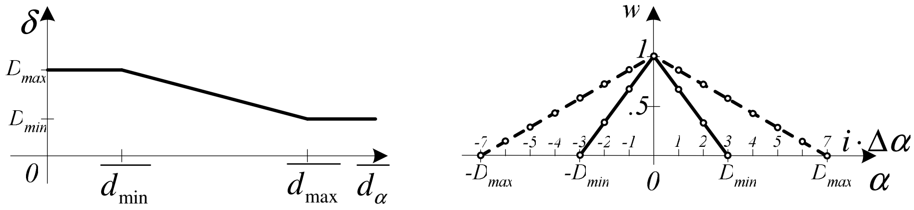
Then angle of preventive activity δ is determined by

$$\delta = \begin{cases} D_{\max}, & \overline{d_\alpha} \le \overline{d_{\min}} \\ \dfrac{D_{\min}(\overline{d_\alpha} - \overline{d_{\min}}) + D_{\max}(\overline{d_{\max}} - \overline{d_\alpha})}{\overline{d_{\max}} - \overline{d_{\min}}}, & \overline{d_{\min}} < \overline{d_\alpha} < \overline{d_{\max}} \\ D_{\min}, & \overline{d_\alpha} \ge \overline{d_{\max}} \end{cases}$$

Finally, weighting values of preventive activity $\boldsymbol{w}$ are determined by

$$w = \begin{cases} \dfrac{\delta+\alpha}{\delta}, & -\delta \leq \alpha < 0 \\ \dfrac{\delta-\alpha}{\delta}, & 0 \leq \alpha \leq \delta \end{cases}$$

By experimental analysis, parameters of this part of regulator are established, and they are: $\overline{d_{\min}} = 3°$, $\overline{d_{\max}} = 7°$, $D_{\min} = 1.5°$, $D_{\max} = 3.5°$ and k_p=0.15. Instead of continuous, equivalent discrete functions were used due to realization of high control level in microprocessor technology, as shown in Fig. 6, were $\Delta\alpha = 0.5°$.



(a) (b)

Fig. 6. Functions for (a) adaptation of preventive activity angle δ and (b) determining weighting values of preventive activity w, realised as discrete values w_i, $i = 1, 2, \ldots 7$, $w_0 = 1$.

To avoid negative effect of slewing angle discrete measuring, as well as to improve digging in neural network learning faze, new adaptive PI regulator is implemented. This regulator is performing fine adaptation of reference by BW current, so that this reference is finally defined for the lower hierarchical level (Fig. 5) as $V_k^{ref}[\alpha(t),t] = V_p^{ref}[\alpha(t)][1 - k_a f_{bw}(t)]$ were $f_{bw}(t)$ is given by $f_{bw}(t) = K_{bw}[e_{bw}(t) + 1/T_{bw} \int e_{bw}(t)dt]$. Parameters of this regulator are obtained using simulations and experiments. The final values of these parameters are: k$_a$=0.1, K_{bw}=65, T_{bw}=14.2[s] for $|I_{bw}(t) - I_{bw_{nom}}| \leq 0.181 I_{bw_{nom}}$ or k_a=0.1, K_{bw}=75, T_{bw}=7[s] for $|I_{bw}(t) - I_{bw_{nom}}| > 0.181 I_{bw_{nom}}$.

5 Experimental results

Development of basic level of control system requires comprehensive theoretical analysis, modelling, identification and simulation of plant. By this analysis, control objectives, operating regimes, dominant disturbances and finally structure and parameters of BWE slewing regulator are defined. Regulator is realised in analogue technique. All necessary adjustments were carried out, according to working conditions on surface mine, electromechanical characteristics and equipment on BWE.

The new control system was implemented and tested while BWE was in full operating capacity. Because of limited space, only two experiments will be shown, indicating the most significant characteristics of the new control system. In Fig. 7 is shown layout of the cut where the measurements are carried out. From this figure we can see inconvenient configuration of soil: large variety in cutting height (ΔH) and poor disposition of soil strength in the cut (by using Protodjakonow classification method for the strength of the material [4]). Geometry and mining-technological parameters of this cut are: $\alpha_L = -35°$, $\alpha_R = +63°$, $\Delta S = 55$[cm] and V_0=14.55[m/min].

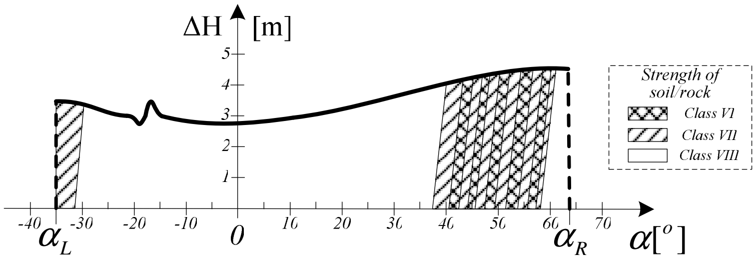
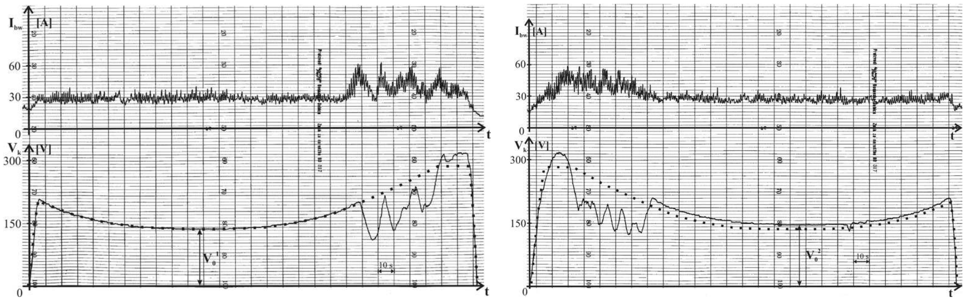


Fig. 7. Layout of the first cut - ground level.

In Fig. 8 are shown measurements from the first two cuts. From the measurements in the first cut (Fig. 8-a) we can see significant deviation of slewing speed V_k from the reference, which is effect of adaptive PI regulator action. In this way reaction of system safety and blockade is avoided, as well as continuity in production is enabled with negligible lowering in excavating capacity. Very inconvenient disposition of layers, with large cutting resistance, and inertia of BWE results into BW current (I_{bw}) oscillations.



(a) (b)

Fig. 8. Current of BW motor (I_{bw}) and voltage of slewing motors (V_k) in first cut (a) and second cut (b). Technological reference is marked by dotted curve.

The effect of learning at the higher control level is shown in the next cut (Fig 8-b). Because of adaptation and prediction, BWE calmly and safely enters the zones with larger soil strength (less oscillation in BW current). Simultaneously, increase of the basic speed V_0 (about 5%) compensate decrease of excavating capacity in loading zone.

It is important to emphasize that new control system increases efficiency and digging capacity and, at the same time, significantly lowers time for repair and maintenance. The new control system has a possibility to memorise loading image, even in manual working mode of BWE. This is very useful capability, because it lowers the learning time in automatic working mode. BWE is excavating smoothly, with full capacity, already in the first cut.

Previously described concept for control of slewing movement, is used for control of translator movements as well. This system enables positioning of BWE in the block in all allowable inclination, with high precision.

6 Conclusion

The purpose of development and realization of the new two-level hierarchical control system was to avoid essential disadvantages of existing control system BWE SRs 1200, by keeping existing actuators as well as the existing system of blockade and safety. However, since new control system requires high precision measurements of circular and translator movements, new sensors have been developed and implemented.

In absence of financial support, higher level of control system was developed and realized with microprocessor of modest possibilities. Due to that: low precision (only 16-bits arithmetic), low speed and low memory capacity, only the limited number of loading pictures and only 2-bits fuzzy rules are used for determining loading $L(\alpha)$ and prediction $P(\alpha)$ functions. Nevertheless, the exploitation confirms that the new control system is very efficient: excavating capacity is increased and reliability of BWE improved. Furthermore, the new control system has lowered need for every day maintenance and periodical servicing. Finally, realised system indirectly helps mining authorities in defining optimal excavating parameters and in maintenance planning. For example, if significant decrease of slewing speed is noticed, due to adaptive-predictive properties of the new control system, it means that technological parameters are wrongly set or likely abrasion has arisen in one of the vital cutting parts.

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