Anti-hanging system of the hoisting equipment in the shaft

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Abstract. In this paper, the structure and mathematical description are proposed, as well as simulation of the protection system operation against hanging of the hoisting equipment in the shaft between the unloading curves and the dispenser is carried out.

1. Introduction
When the skip breaks or falls, not only emergencies are possible, leading to equipment breakdowns and downtime for a long time, but also to accidents. On the hoisting rig of “Glavnyyi” shaft at OOO “Abazinsky Rudnik”, an emergency with hanging of the skip occurred, in which the downward skip jammed, While the unloaded skip was descending and the rope being lifted from the side of the jammed skip, the rope was pulled out of the attachment in the thimble and the bearing of the pulley wheel was crushed, at the same time the skip hung and remained in the shaft.

As a result of this accident, even in the absence of injured workers, serious damage to the shaft and the hoisting equipment, the downtime of the hoisting machine was more than a month. When analyzing the emergency that led to the accident, it turned out that currently there is no reliable protection against hanging of the skip, which provides protection throughout the depth of the shaft.

The calculation of the static modes of the hoisting unit allows the required torque and power of the engine to be determined in order to carry out the process of load lifting, and the calculation of the balance of forces of the counterweight and the weight of the lifted load allows not only the required power of the drive motor to be determined, but also the condition of the accident in the event of an empty skip hanging in the shaft.

2. Analysis of the emergency
The oscillograms of the analyzed emergency are shown in figure 1. After the dispatch, the loaded Southern skip moves upwards, while the empty Northern skip goes down. Release and acceleration in the lifting cycle of the Southern Skip are carried out in the normal mode (section 1). At a distance of 280 meters from the North Skip exact stop sensor, the North Skip going down hangs, which can be seen from the anchor current graph (red graph – Ia), which sharply increases due to the fact that the counterweight disappears in the form of an empty skip mass (section 2, 344 s. Time 12:55:44 in figure 1), while the speed control system correctly fulfills the increase in torque, maintaining the speed (blue graph – Utg) practically unchanged.

Since the rope under its own weight is exhausted into the trunk, the mass of the loaded skip is partially compensated by the exhausted rope, which can be seen from the slope of the armature current (section 3).
Figure 1. Oscillograms of the emergency development.

The lack of operation of the cable protection, regulated by the Safety Rules [1, 2], against string slacking and rope overlap, is caused by the fact that such protection is adjusted to operate when leaving the curves and reliably operates when the hoisting equipment hangs at a depth of 30-60 m, since the greatest the probability of “hanging” and, as a consequence, string slacking and rope overlap occur in the upper end position of the unloading hoisting skips.

In this case, the operation of protection at a greater depth largely depends on the mass of the rope (the greater the mass, the less the probability of operation with increasing depth) and the length of the rope branch from the hoisting drum to the pulley wheel [2].

Then the loaded Southern skip decelerates and enters the unloading curves, while due to the absence of a counterweight in the form of a second skip, the current at the entrance to the curves (section 4) is 2800 A (7 divisions) instead of the usual 800-1000 A.

After sending the Southern skip down, in 14.1 seconds after the end of the previous cycle, release occurs (section 5) and the southern skip goes down in recuperative mode (the current is in the positive area, but should be in the negative area), after passing 278 meters (while being opposite the frozen Northern skip), the load arises and a drop in speed occurs (section 6, 470 s, Time: 12:57:50). This is due to the fact that the machine accelerates and moves at a full speed of 9.0 m/s, which leads to the rope catching on the hanging skip with a strong jerk and breaking the rope.

Based on the results of the accident investigation, the task was set to develop a system of protection against skip hanging, which would make it possible to track hanging along the entire depth of the shaft. Technological protection should be implemented on the basis of the PAZK-SU system operated since 2011 on a skip lift [4, 5] by adding a software protection module.

3. Algorithm of device functioning
The technological process “Lifting” is carried out and controlled on the basis of measuring the process parameters by sensors located in the shaft, on the hoisting machine and the hoisting motor. Therefore, the value of the moving masses and the position of the hoisting units are calculated based on the measurement of the parameters of the lifting motor and the angle of rotation of the drum of the hoisting machine. Thus, it is obvious that all the components used to calculate the protection must be
expressed in terms of actually measured parameters, such as current, position (angle of rotation), speed [6].

Below, the methodology for the development and implementation of the anti-hanging protection module is proposed, based on the analysis of the kinematic diagram of the skip hoisting installation and taking into account the modularity principle [7, 8].

It is known that the basic equation of an electric drive motion (1) is determined by the ratio between the moments of the moving forces:

\[ M_d - M_{st} = J \frac{d\omega}{dt}, \]  

(1)

where \( M_d \) is the engine torque;
\( M_{st} \) – static moment.

Obviously, this equation should underlie the determination of the conditions for the hanging of the hoisting equipment or difficulties in its passage, since full skip jamming or hanging cannot occur immediately.

The static moment \( M_{st} \) can be determined from the kinematic diagram in figure 2.

\[ M_{st} = [(m_g + (m_{so} - m_{se}) + (m_{kg} - m_{kp})]g \cdot r_b, \]

(2)

where \( m_g \) – weight of load;
\( m_{so} \) – weight of the skip on the loaded branch, kg
\( m_{se} \) – weight of the skip on an empty branch, kg;
\( m_{kg} \) – weight of the rope on a loaded branch, kg;
\( m_{kp} \) – weight of the rope on an empty branch, kg;
\( g \) – free fall acceleration, 9.81 (m/s²);
\( r_b \) – radius of the hoisting drum, m.

The motor torque, and therefore its measured total current, can be found from the expression:

\[ M_d = M_{st} \pm J \frac{d\omega}{dt}, \]  

(3)

where the “+” sign is taken during acceleration;
the “-” sign is taken when braking.

The condition for determining whether a skip hangs or “gets stuck” in the conductors can be formulated as a violation of the balance of the loaded counterweight branch – the mass of the skip and rope in the “counterweight” chain \( m_{so} + m_{se} \) – the mass of the rope in the counterweight chain plus the mass of the empty skip. As a result, it is possible to propose the following algorithm for detecting hanging or violation of the passage of an empty skip.

1. The weight of the load is measured at the beginning of the movement cycle after exiting the curves of the empty skip. In this case, the main relationship is determined by measuring the current value of the motor current based on the equation:

\[ I_d = I_{st} \pm I_{din}, \]  

(4)

the dynamic moment is defined as:

\[ M_{din} = J \frac{d\omega}{dt}. \]  

(5)

The weight of the load \( m_g \) can be obtained from the equation (2):

**Figure 2.** Balance of the equipment weights
\[ m_g = \frac{M_{st}}{g \cdot r_b} - (m_{SG} + m_{KG}) + (m_{KP} + m_{SP}). \]  \( \text{(6)} \)

Since the weights of the skips on the branches are the same \( m_{SG} = m_{SP} \), then

\[ m_g = \frac{M_{st}}{g \cdot r_b} - m_{KG} + m_{KP}, \]  \( \text{(7)} \)

the uncompensated rope weight can be calculated as

\[ m_k = (m_{KP} - m_{KG}) \rho \cdot h_s \]  \( \text{(8)} \)

where \( h_s \) is the distance from the lower receiving platform to the hoisted skip, m;
\( \rho \) – the weight of the running rope meter, kg/m;
\( m_k \) – uncompensated rope weight, kg;

Then expressing the uncompensated mass of the rope through the depth of the trunk (\( H_{max} \)) and the position of the skip being hoisted (\( h_c \)):

\[ m_k = \frac{(H_{max} - 2h_s)}{\rho} \]  \( \text{(9)} \)

The value of the skip weight is specified according to the algorithm for measuring the weight of the lifted load and is fixed at the beginning of the cycle, since in the process of measuring the mass, the total motor current \( I_d \) is measured:

\[ I_d = \frac{M_d}{k \Phi} \]  \( \text{(11)} \)

then the static torque of the motor:

\[ M_{st} = I_{st} k \Phi, \]  \( \text{(12)} \)

considering that

\[ M_{st} = M_d - M_{din}, \]  \( \text{(13)} \)

then the static rated current \( I_{st,r} \):

\[ I_{st,r} = I_a - j \cdot \frac{d\omega}{dt}. \]  \( \text{(14)} \)

2. The measured value of the current \( I_{mg,e} \) corresponding to the weight of the load at the beginning of the cycle is fixed and is a reference. When the loaded skip is lifted, the static current value changes by an amount corresponding to the change in the rope weight, which is monitored by the protection system. When the skip gets stuck or hangs, the current value of \( I_{m} \) will change to the value of the empty skip \( m_{SP} \). Thus, the \( m_{SP} \) value is the reference for the protection operation. Then:

\[ I_{mg,e} = \left( I_a - j \cdot \frac{d\omega}{dt} \right) - I_{st,e}, \]  \( \text{(15)} \)

\[ I_{mg,r} = \left( I_a - j \cdot \frac{d\omega}{dt} \right) - I_{st,t}, \]  \( \text{(16)} \)

then

\[ \Delta I_{st,t} = I_{mg,r} - I_{mg,e}. \]  \( \text{(17)} \)

Thus, during the entire lifting cycle, the difference \( \Delta I_{st,t} \) currents values \( I_{mg,r} \) and \( I_{mg,e} \) should be equal to zero, but this is possible only in the ideal case, since in reality, due to the irregularities of the
guiding curves, friction in the rollers in the process of hoisting, the emergence of a small difference in currents $\Delta I_{s,z}$ is inevitable, both positive and negative. Thus, in order to avoid false alarms, the actuation current $\Delta I_{sr.z}$ must be determined by several hoisting cycles of empty and loaded skips. The threshold value of the protection operation $\Delta I_{sr.z}$ can be set in the range from a quarter to half of the empty skip weight:

$$\Delta I_{sr.z} = \left( \frac{m_{sp} + m_{sp}}{4} \right) \frac{g r_b}{k \Phi}. \quad (18)$$

Then the alarm triggering condition:

$$y_a = \begin{cases} 0, & \text{if } \Delta I_{st.t} \leq I_{sr.z} \\ 1, & \text{if } \Delta I_{st.t} > I_{sr.z} \end{cases} \quad (19)$$

Thus, the problem of skip hoisting control can be solved through the calculation and control of the static motor current $I_{st}$, and the operation of the protection from hanging when it changes in relation to the calculated value.

On the basis of the above equations, the structure of the skip protection from hanging is drawn up and is shown in figure 3.

Figure 3 shows: $U_a$ – armature voltage, $h_s$ – skip position, $h_{kr}$ – depths of the exit from the curves, $I_a$ – total armature current of the motor, $I_{st}$ – static current, $I_{din}$ – dynamic current, $I_{din.r}$ – calculated dynamic current, $I_{st.r}$ – static rated current (actual), $I_{st.t}$ – current static current, taking into account the rope weight, $I_{mg,e}$ – static current generated by the load, reference, $I_{mg,r}$ – static current generated by the load, calculated in a cycle, $\Delta I_{st.t}$ – difference in static currents, $I_{sr.z}$ – current of the protection actuation, $y_a$ – signal of protection actuation (emergency).

Based on the structure shown in figure 3, a model was built and the protection actuation was simulated. The results are shown in figure 4.
Figure 4 indicates: \( U_a \) – armature voltage, \( I_a \) – total armature current of the motor, \( I_{st.r} \) – static calculated (actual) current, \( y_a \) – alarm signal.

![Simulation of protection actuation.](image)

### 4. Conclusion

In this work, a structure and a mathematical description are proposed, as well as a simulation of the operation of the protection system against hanging of the hoisting equipment in the shaft is carried out.

By simulation it was established that the proposed algorithm makes it possible to implement protection against skip hanging along the entire length of the shaft, which will prevent severe accidents and ensure the safety of the hoisting machine. The proposed technological protection was implemented on the basis of PAZK-SU system, which has been in operation since 2011 and up to the present time, by adding a software protection module, without taking the installation out of operation.

For hoisting machines in operation, this protection system can be implemented as a separate device or together with a microprocessor-based speed limiter [9], which will fully ensure their safe operation.

### References

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