Technical and Economic Efficiency of Implementing a Frequency-Controlled Electric Drive for a Milling Installation

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**Abstract.** This paper presents an experimental approach to assessing the effect of drum rotation speed on the power consumption of a technological installation. Using the correlation method, the economic efficiency of applying a frequency converter to control the mill’s rotation speed is calculated based on experimental data showing variability in rotation speed from 9 to 12 revolutions per minute. Regression equations describing the dependence of power on each parameter are constructed, which allows for a quantitative assessment of the contribution of various factors to changes in energy consumption. The results demonstrate that energy savings can be achieved through rotation speed regulation and take into account the dependence on the hardness of the ore loaded into the drum, as well as the ratio of the liquid to solid phases of the ground ore. The economic assessment of implementing a frequency converter for MMS 70-23 mills indicates a payback period of 4.8 years, followed by profit generation.

**Keywords:** wet autogenous grinding mill, frequency converter, synchronous motor, regression equation, economic efficiency, rotation speed, ore hardness, ore density, liquid-to-solid phase ratio, energy consumption

# Introduction

In modern ore processing conditions, the efficiency of wet autogenous grinding mills (WAGM) plays a key role in production processes. To achieve maximum efficiency, it is necessary to optimize control algorithms with a focus on regulating the mill’s rotation speed based on the physical characteristics of the ore, such as hardness and density.

To identify the correlation between the main parameters of the technological process, it is necessary to conduct an active experiment over a wide range of changes in X (rotation speed) and Y (energy consumption). For this purpose, a study was carried out to examine changes in the power consumed by the mill during the loading and unloading phases.

In accordance with the stated objective, the following issues were addressed in the course of the study:

* statistical analysis of mill operation data was performed;
* a correlation analysis of WAGM power and performance was carried out;
* the specific energy consumption of the WAGM was determined.

# Matherials and Methods

As part of the present study, an active experiment was conducted to examine the effect of changes in drum rotation speed on the power consumption of the installation. The main objective of the experiment was to identify the relationship between technological parameters and energy consumption under different operating modes of the equipment.

## EXPERIMENTAL SECTION

The drum rotation speed was varied in the range of 9 to 12 rpm. To ensure data representativeness and enable statistical analysis, 30 experimental data points were collected, evenly distributed across the entire speed variation range. At each point, three parameters characterizing the process (denoted as tr, s, and m) were recorded, along with direct measurements of power consumption (P).

## DATA PROCESSING AND ANALYSIS

For each drum rotation speed value, average values of the parameters tr, s, m, and power consumption P were calculated. At the next stage, correlation and regression analyses were carried out to determine the degree of dependence of power consumption on the studied parameters.

Based on the experimental data, linear regression equations were constructed, expressing power consumption as a function of drum rotation speed (*m*), ore hardness (*tr*), and the ratio of liquid to solid phases in the ore (*s*).

The developed regression models make it possible to quantitatively assess the contribution of each parameter to changes in power consumption. The coefficients of the variables reflect the sensitivity of power consumption to the respective parameters, while the constant terms in the equations indicate the baseline power level at zero values of the influencing factors.

Thus, the applied methodology includes variation of one of the key operating parameters, systematic data collection, statistical processing, and regression modeling, providing a comprehensive approach to the analysis of energy consumption in the studied system.

# Results

During the grinding of ore of varying hardness in a semi-autogenous wet grinding mill (SAG mill), the drum contents are mixed with water, and the drum is driven by a synchronous motor (SM). In this process, ore hardness, the liquid-to-solid ratio, drum rotation speed, and energy consumption are interdependent parameters.

The SAG mill has a nominal hourly energy consumption of 2500 kW from the synchronous motor and operates 24 hours a day, on average 25 days per month.

Thus, the nominal daily energy consumption of the mill is:

24 hours × 2500 kW = **60,000 kWh**

and the monthly consumption is:

25 × 60,000 kWh = **1,500,000 kWh**

To reduce energy consumption, we consider the application of a variable-frequency drive (VFD) with a maximum power of 2500 kW.

Based on the ore grinding technology (wet autogenous grinding), to ensure efficient grinding, the required liquid-to-solid ratio, ore hardness, and drum rotation speed were identified, with energy consumption measured at drum speeds ranging from 9 to 12 RPM.

In the course of the experiment using a frequency converter, the following energy consumption values were obtained at drum speeds of 9 to 12 RPM under operating conditions (Table 1).

**TABLE I.** Experimental power consumption data depending on the above-mentioned factors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| № | **Drum Rotation Speed m (RPM)** | **Ore Hardness tr (Rockwell HRC)** | **Liquid-to-Solid Ratio s (%)** | **Power Consumption P (kW)** |
| 1 | 9 | 30 | 48 | 2100 |
| 2 | 10 | 25 | 50 | 2200 |
| 3 | 11 | 35 | 52 | 2250 |
| 4 | 12 | 40 | 54 | 2350 |
| 5 | 9 | 32 | 49 | 2130 |
| 6 | 10 | 27 | 51 | 2230 |
| 7 | 11 | 37 | 53 | 2280 |
| 8 | 12 | 42 | 55 | 2380 |
| 9 | 9 | 31 | 50 | 2160 |
| 10 | 10 | 26 | 52 | 2260 |
| 11 | 11 | 36 | 54 | 2310 |
| 12 | 12 | 41 | 56 | 2410 |
| 13 | 9 | 29 | 48 | 2120 |
| 14 | 10 | 28 | 50 | 2220 |
| 15 | 11 | 34 | 52 | 2270 |
| 16 | 12 | 39 | 54 | 2370 |
| 17 | 9 | 33 | 47 | 2080 |
| 18 | 10 | 27 | 49 | 2180 |
| 19 | 11 | 35 | 51 | 2230 |
| 20 | 12 | 40 | 53 | 2330 |
| 21 | 9 | 30 | 50 | 2150 |
| 22 | 10 | 26 | 52 | 2250 |
| 23 | 11 | 34 | 54 | 2300 |
| 24 | 12 | 39 | 56 | 2400 |
| 25 | 9 | 31 | 49 | 2140 |
| 26 | 10 | 29 | 51 | 2240 |
| 27 | 11 | 37 | 53 | 2340 |
| 28 | 12 | 42 | 55 | 2380 |
| 29 | 9 | 28 | 48 | 2160 |
| 30 | 10 | 33 | 50 | 2260 |

# Discussion

As shown in the table, the experiments were conducted based on continuous monitoring and recording of the energy consumption (P) required for grinding ore of a given hardness (tr), with the drum rotating at speeds of 9, 10, 11, and 12 revolutions per minute (m), while maintaining a specific liquid-to-solid ratio (s).

To facilitate the analysis of the obtained results, Table 1 can be simplified into the following format.

**TABLE 2**. Normalized experimental data on power consumption depending on the above-mentioned factors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| № | **Drum Rotation Speed m (RPM)** | **Ore Hardness tr (Rockwell HRC)** | **Liquid-to-Solid Ratio s (%)** | **Power Consumption P (kW)** |
| 1 | 9 | 30 | 48 | 2100 |
| 5 | 9 | 32 | 49 | 2130 |
| 9 | 9 | 31 | 50 | 2160 |
| 13 | 9 | 29 | 48 | 2120 |
| 17 | 9 | 33 | 47 | 2080 |
| 21 | 9 | 30 | 50 | 2150 |
| 25 | 9 | 31 | 49 | 2140 |
| 29 | 9 | 28 | 48 | 2160 |
| 2 | 10 | 25 | 50 | 2200 |
| 6 | 10 | 27 | 51 | 2230 |
| 10 | 10 | 26 | 52 | 2260 |
| 14 | 10 | 28 | 50 | 2220 |
| 18 | 10 | 27 | 49 | 2180 |
| 22 | 10 | 26 | 52 | 2250 |
| 26 | 10 | 29 | 51 | 2240 |
| 30 | 10 | 33 | 50 | 2260 |
| 3 | 11 | 35 | 52 | 2250 |
| 7 | 11 | 37 | 53 | 2280 |
| 11 | 11 | 36 | 54 | 2310 |
| 15 | 11 | 34 | 52 | 2270 |
| 19 | 11 | 35 | 51 | 2230 |
| 23 | 11 | 34 | 54 | 2300 |
| 27 | 11 | 37 | 53 | 2340 |
| 4 | 12 | 40 | 54 | 2350 |
| 8 | 12 | 42 | 55 | 2380 |
| 12 | 12 | 41 | 56 | 2410 |
| 16 | 12 | 39 | 54 | 2370 |
| 20 | 12 | 40 | 53 | 2330 |
| 24 | 12 | 39 | 56 | 2400 |
| 28 | 12 | 42 | 55 | 2380 |

Based on Table 2, we compiled the following Table 3, determining the average values of ore hardness (tr), the liquid-to-solid ratio (s), and power consumption (P), respectively, depending on the drum rotation speed (m) of the mill at 9, 10, 11, and 12 revolutions per minute.

**TABLE 3.** Average values of the obtained experimental data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***m*** – drum rotation speed (rpm) | 9 | 10 | 11 | 12 |
| ***tr***– ore hardness (Rockwell HRC) | 30,5 | 27,6 | 35,4 | 40,4 |
| ***s*** – liquid-to-solid phase ratio (%) | 48,6 | 50,6 | 52,7 | 54,7 |
| ***P*** – power consumption (kW) | 2130 | 2230 | 2283 | 2374 |

Based on Table 3, and in accordance with the laws of probability theory and statistical data analysis [6], a regression equation can be formulated as:

relating the average drum rotation speed to the power consumed by the electric drive,  
as well as the average ore hardness and the average liquid-to-solid ratio.  
Here, x (m, tr, s) and y (P) are the main parameters.

*and*

## REGRESSION EQUATION OF CONSUMED POWER CORRESPONDING TO DRUM ROTATION SPEED

We will compile a table for calculating the regression of the average energy consumption for ore grinding, corresponding to the drum rotation speed m:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| – drum rotation speed (*m* – rpm) | 9 | 10 | 11 | 12 |
| – average power consumption (*P* – kW) | 2130 | 2230 | 2283 | 2374 |

Now, let us derive the regression equation for the average power consumption corresponding to the average drum rotation speed:

*and*

To calculate the main parameters, we compile the following table:

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| 9 | 2130 | 81 | 19170 |
| 10 | 2230 | 100 | 22300 |
| 11 | 2283 | 121 | 25113 |
| 12 | 2374 | 144 | 28488 |
| =42 | =9017 | =446 | =95071 |
|  |  |  |  |
| 9 | 2130 | 81 | 19170 |
| 10 | 2230 | 100 | 22300 |
| 11 | 2283 | 121 | 25113 |
| 12 | 2374 | 144 | 28488 |
| =42 | =9017 | =446 | =95071 |

As is well known:

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Consequently, in the experimental test, the average drum rotation speed per minute corresponding to the energy consumption is described by the following regression equation:

*y = 78.5x + 1430 or P = 78.5m + 1430*   (1)

where: P – power consumption (kW), m – drum rotation speed (revolutions per minute).

## REGRESSION EQUATION OF POWER CONSUMPTION CORRESPONDING TO ORE HARDNESS

Let us compile a table for the regression calculation of the average power consumed for ore grinding depending on the average ore hardness:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *xᵢ – average ore hardness (tr)* | *30,5* | *27,6* | *35,4* | *40,4* |
|  | 2130 | 2230 | 2283 | 2374 |

We will determine the regression equation of the average power consumption with respect to the average ore hardness in the following form:

In this case, y is the average power consumption (P), and x is the average ore hardness (tr).

*and*

To calculate the main parameters, we will compile the following table.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| 30,5 | 2130 | 930,25 | 64965 |
| 27,6 | 2230 | 761,76 | 61548 |
| 35,4 | 2283 | 1253,2 | 80818,2 |
| 40,4 | 2374 | 1632,2 | 95909,6 |
| =133,9 | =9017 | =4577,3 | =303240,8 |

We then substitute the specified parameters into the following formulas:

*and*

As a result, we obtain the following:

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Therefore, the regression equation for the consumed power (P) corresponding to the average ore hardness (tr) is as follows:

*or* (2)

where: **P** is the consumed power, **tr** is the average ore hardness.

## REGRESSION EQUATION OF POWER CONSUMPTION IN RELATION TO THE ORE SLURRY RATIO (LIQUID-TO-SOLID PHASE)

Let us construct the regression table for calculating the average power consumed at the average liquid-to-solid phase ratio of the ore.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *xᵢ* – average ratio of the liquid to solid phase of the ore (s) | 48,6 | 50,6 | 52,7 | 54,7 |
| *yᵢ* – average power consumption (P) | 2130 | 2230 | 2283 | 2374 |

Now, we will consider the regression equation for the average consumed power depending on the average liquid-to-solid phase ratio of the ore in the following form:

In this case we take ***y*** is the average power consumption (P), and **x** is the average liquid-to-solid phase ratio of the ore (s). The coefficients are calculated using the following formulas:

*and*

To proceed with the main parameters’ calculations, we complete the following table:

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| 48,6 | 2130 | 2361,96 | 103518 |
| 50,6 | 2230 | 2560,36 | 112838 |
| 52,7 | 2283 | 2777,29 | 120314,1 |
| 54,7 | 2374 | 2992,09 | 129857,8 |
| =206,6 | =9017 | =10691,7 | =466527,9 |

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Regression equation of power consumption for the average ratio of liquid and solid fraction in ore:

*or* (3)

where P is the power consumption and s is the ratio of liquid to solid fraction in the ore.

As is known, the average consumed power when using a frequency converter, depending on the ore hardness and liquid-solid ratio, is 2249 kW (Table 1).

Now, given the average power consumption of 2250 kW, using regression formulas (1–3), we determine the corresponding average values:

* m: average drum rotation speed (rpm);
* tr: average ore hardness;
* s: average liquid-to-solid ratio.

That is, assuming , we find:

As seen, the values ; and match the corresponding indicators in Table 3.

Therefore, when using a frequency converter for the synchronous drive of the MMS 70-23 mill, the parameters should be maintained as follows: ; ; and kW.

The nominal power consumption of the semi-autogenous grinding mill is 2500 kW. Accordingly, under existing grinding technology, energy consumption per hour is about 2500 kWh.

Based on experimental data, when using a frequency converter, the mill rotates at varying speeds from 9 to 12 rpm. This enables energy savings by adjusting rotational speed based on ore hardness and liquid-solid content.

In this case, average hourly energy consumption can be calculated by the formula:

Average power consumption per hour at different stable speeds:

* At 9 rpm: kWh;
* At 10 rpm: kWh;
* At 11 rpm: kWh;
* At 12 rpm: kWh.

Thus, the average hourly power consumption of the mill:

*Wavg.h=(2136.5+2215+2293.5+2372)/4=2254.25 kWh*

Given the nominal (baseline) consumption of 2500 kW, the hourly energy savings from using a frequency converter:

*Wsaved.h=2500−2254.25=245.75 kWh*

Hence, the average daily consumption will be:

*Wavg.day = 24 х 2254,25=54 103,2 kWh*

And the average monthly consumption (assuming 25 working days):

*Wavg.month = 25 х 54103,2=1 352 580 kWh*

Considering the nominal energy consumption of 2500 kWh under the existing technology (without using a frequency converter), the total amount of energy consumed by the mill during a day would be:

*Pday. = 24 х 2500=60 000 kWh*

Thus, daily energy savings from using a frequency-controlled drive:

*Wsaved.day= Wday – Wavg.day = 60 000 – 54 103,2 = 5897 kWh*

According to the above calculations, the payback period for implementing the frequency converter in MMS 70-23 mills is:

*Wavg.day. = 24 х 2254,25=54 103,2 kWh*

Obviously, average electrical energy consumption during a month will be:

*Wavg.month = 25 х 54103,2=1 352 580 kWh*

Considering the nominal energy consumption of 2500 kWh under the existing technology (without using a frequency converter), the total amount of energy consumed by the mill during a day would be:

*Pday = 24 х 2500=60 000 kW*

Thus, daily energy savings from using a frequency-controlled drive:

*Wsaved day= Wday – Wavg.day = 60 000 – 54 103,2 = 5897 kWh*

According to the above calculations, the payback period for implementing the frequency converter in MMS 70-23 mills is:

*1772:365 = 4,8 years*

After this time the system will generate profit by reducing electricity costs.

# Conclusion

The experiment showed that changes in drum rotational speed significantly affect power consumption. The obtained regression relationships between power and the parameters tr, s, and m allow for evaluating and predicting energy consumption under various operating modes. According to the regression coefficients, the most influential parameter is m. The developed methodology can be used in the design and operation of similar systems to improve energy efficiency.

Based on experimental data, the average hourly energy consumption of the mill after installing a frequency converter is 2254.25 kWh, which is 245.75 kWh less than the nominal value (2500 kWh). This results in significant daily and monthly cost reductions. For comparison, under continuous nominal operation without a frequency converter, the mill would consume 60,000 kWh per day. Calculations show that the implementation of frequency-controlled electric drives leads to considerable energy savings. The payback period is about 4.8 years, after which operation will generate net profit by lowering energy expenses.

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