



Research Article

Improving the Electrical Energy Efficiency of a Cone Crusher in the Ore Crushing Process Through Adaptive Adjustment of Supply Frequency

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Abstract

Cone crushers in the mining and metallurgical industries operate under conditions where ore properties and throughput constantly fluctuate, yet many industrial electric drives are still controlled at a fixed nominal frequency. This study developed an adaptive frequency control system that treats the supply frequency (f) of a variable frequency drive (VFD) as the control variable, while accounting for external factors such as ore hardness (H) and mass flow rate (Q) measured via a belt scale. The objective of the research is to minimize the crusher's specific electrical energy consumption ($SEC = P/Q$) while adhering to constraints regarding frequency, electric motor power, throughput, and product size. The study integrates the speed-frequency relationship of the induction motor, the crusher's electrical energy consumption, hardness and load factors, and a function representing the deviation from the optimal operating point for current conditions. Thirty planned experimental trials—covering ranges of $H = 7\text{--}15$, $Q = 1900\text{--}2300$ t/h, and $f = 45\text{--}60$ Hz—were compared against a standard 50 Hz operating mode. Adaptive modeling reduced the SEC by an average of 5.57% while maintaining throughput. The proposed approach aligns with existing preliminary scientific findings indicating that adjusting eccentric speed and utilizing mass flow feedback can enhance cone crusher efficiency; furthermore, the 30 experimental modeling results presented were validated against production-scale metrics and criteria prior to industrial implementation. Our research paper details the governing equations, the practical control architecture, and the experimental protocol dataset.

Keywords

Cone Crusher, Ore Hardness, Mass Flow, Frequency Converter, Specific Energy Consumption, Eccentric Speed, Energy Efficiency, Adaptive Control

1. Introduction

Crushing and grinding processes are among the primary consumers of electrical energy in mineral processing. Cone crushers are widely used in secondary and tertiary crushing stages due to their high productivity and the reliability of their

compression-based crushing mechanism. However, the operational efficiency of these crushers is intrinsically linked to a number of factors, such as the properties of the feed material, the closed-side setting (CSS), the filling level of the crushing

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chamber, the eccentric speed, and the time-varying strength of the ore. Recent research on modeling and implementing optimal control systems for cone crushers indicates that while PID and expert control systems have predominantly been used in industrial settings, the demands of Industry 4.0, sustainability, and economic efficiency are now accelerating the implementation of optimization and data-driven control systems [1].

Electrical energy consumption in crushers is not determined solely by the variation in operating frequency. Factors such as ore strength, particle size distribution, throughput, compression pressure, residence time in the crushing chamber, and others influence power consumption. Experimental and modeling studies have shown that cone crusher energy consumption depends on operating speed and crushing chamber geometry [5], while rock strength characteristics correlate with crusher power and product size [6]. Consequently, operating a cone crusher at a fixed frequency is not energetically optimal when processing ore streams with varying physico-mechanical properties. This is because fluctuations in ore competence and mass flow rates lead to changes in the crushing chamber's load level, the required crushing work, drive torque, and electrical power consumption. Therefore, the optimal supply frequency—which determines the rotational speed of the eccentric mechanism—should be established as a function of the input process parameters.

The scientific problem addressed in this study is the development of a simple control system that precisely defines the

crusher's VFD frequency as a function of two measurable variables—ore hardness and mass flow—and formulates the control objective based on the criterion of specific electrical energy consumption. The proposed method is validated through the results of 30 planned scientific experiments conducted during industrial trials.

2. Materials and Methods

Parameters such as the Bond Work Index, drop-weight parameters, uniaxial compressive strength, and the Protodyakonov strength index can be used to characterize ore undergoing comminution in industrial plants. In this study, since the hardness signal corresponds to operating conditions where the ore hardness level falls within the $H=7-15$ range, H is interpreted as an online hardness/competence index; it requires calibration against Bond W_i , SMC/JK drop-weight metrics, UCS , or a site-specific validated hardness estimator. The relationships between rock properties measured under operating conditions, Protodyakonov strength, and the Bond Work Index provide the basis for such a calibration strategy [7].

For the new control system, the mathematical model must be identifiable and computationally simple. We use the following expression:

$$\hat{P}(H, Q, f) = P_0 + a_H h + a_Q q + a_{HQ} hq + a_f [f - f^*(H, Q)]^2 + a_v (f - 50)^2 \quad (1)$$

Where: $\hat{P}$ — calculated electric power, kW; P_0 — base power; h — normalized ore hardness; q — normalized mass flow rate; a_H — coefficient representing the effect of hardness on power; a_Q — coefficient representing the effect of mass flow rate; a_{HQ} — combined effect of hardness and flow rate; f — current frequency, Hz; $f^*(H, Q)$ — optimal frequency for the specific ore condition; a_f — effect of deviation from the optimal frequency; a_v — coefficient representing the effect of deviation from the 50 Hz nominal operating mode; $h = (H - H_{min}) / (H_{max} - H_{min})$ and $q = (Q - Q_{min}) / (Q_{max} - Q_{min})$ represent the normalized levels of hardness and mass flow rate, respectively. The first four terms represent the increase in load due to harder ore and higher throughput; the quadratic term

represents the loss in energy and comminution efficiency occurring when the eccentric speed deviates from the optimal point under current conditions; and the final term represents minor additional losses in the drive/mechanical system. The dependence of specific energy consumption on the rotational speed of the eccentric mechanism may exhibit a minimum. Consequently, both an excessive decrease and an increase in rotational speed lead to a reduction in energy efficiency. The optimal speed varies depending on ore hardness, mass flow, and the loading conditions of the crushing chamber [3-5].

The frequency setting, determined by operating conditions, is inextricably linked to the VFD's operating range:

$$f^*(H, Q) = \text{sat}_{[45, 60]} \{45 + k_H h + k_Q q\}, k_H > 0, k_Q > 0 \quad (2)$$

Where: sat is the saturation operator, $f^*(H, Q)$ is the optimal frequency Hz, h is the normalized ore hardness, q is the normalized mass flow rate, and k_H and k_Q are the coefficients representing their influence on frequency. In the numerical study, values of $k_H = 8$ Hz and $k_Q = 7$ Hz were adopted; consequently,

the target frequency increases as hardness or mass flow rate rises. These coefficients are not universal constants but rather calibration parameters that must be determined through production tests [11-15].

$$\min J = \widehat{SEC}(H, Q, f) + \lambda_P (\hat{P} - P_{max}) + \lambda_D (f - f_{prev})^2 + \lambda_S (\widehat{P}_{80} - P_{80, target})^2 \quad (3)$$

Where: J — the overall criterion to be minimized; $\widehat{SEC}(H, Q, f)$ — calculated specific energy consumption per tonne

of product; P_{max} — maximum permissible power kW; f_{prev} — the previous frequency value Hz; $\widehat{P}_{80}$ — calculated product

size mm; $P_{80,target}$ — required product size mm; $\lambda_p, \lambda_D, \lambda_S$ — corresponding penalty coefficients.

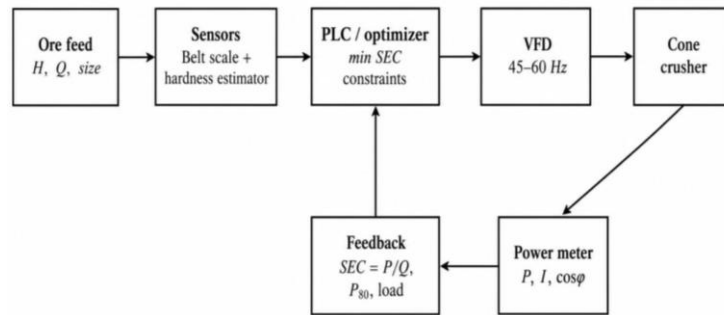


Figure 1. Closed-loop diagram of the proposed control system.

In the control system, all sensor signals are synchronized in time, random spikes are filtered out, and time-averaged values are used to account for the material lag effect within the crusher. If the hardness sensor does not directly measure the

Mohs scale, its output signal is treated not as Mohs hardness, but as a calibrated competence index characterizing ore grindability.

Table 1. Set of measurements required for industrial implementation and model validation.

Variable	Sensor / source	Typical update rate	Function
Mass flow Q	Conveyor belt scale / weigh roller	1–5 s	Primary throughput feedback
Hardness H	Online proxy based on power/force/acoustic signal; calibrated via laboratory rock tests	1–10 s	External input / ore competence
Electrical power	Three-phase power meter at VFD input	0.1–1 s	Energy KPI
VFD frequency	Drive register / PLC	0.1–1 s	Controlled variable
CSS	Hydraulic position sensor	1–5 s	Constraint / secondary variable
Crusher load	Motor current, hydraulic pressure, vibration	0.1–1 s	Protection / overload detection
Product size	Online camera/laser or belt sample	10 s – minutes	Quality validation

The study examined 30 operating scenarios covering ore hardness values of $H = 7–15$ and mass flow rates of $Q = 1900–2300$ t/h. For each scenario, the crusher's constant 50 Hz mode was compared with an adaptive mode featuring automatic adjustment within the 45–60 Hz range. The computational model was adapted for an industrial electric drive with a power rating

of 300–500 kW, accounting for the increase in electrical load associated with rising ore hardness and flow rates. The results obtained represent a deterministic simulation based on a mathematical model, intended for the preliminary assessment of the proposed control method and its subsequent calibration using actual production data.

Table 2. Planned experiments. P_{50} , SEC_{50} — 50 Hz constant mode; P^* , SEC^* — adaptive frequency control mode results.

Experiment	H	Q (t/h)	f^* (Hz)	P_{50} (kW)	P^* (kW)	SEC_{50}	SEC^*	Result (%)
1	14.45	1900	52.45	369.8	361.1	0.1946	0.1901	2.35
2	11.14	1969	50.34	347.8	347.7	0.1767	0.1766	0.05
3	13.34	2176	56.17	470.1	414.9	0.2161	0.1907	11.75

Experiment	H	Q (t/h)	f^* (Hz)	P_{50} (kW)	P^* (kW)	SEC_{50}	SEC^*	Result (%)
4	11.69	2259	55.97	467.3	415.7	0.2069	0.1840	11.04
5	9.21	2079	50.34	352.6	352.4	0.1696	0.1695	0.05
6	9.48	1997	49.17	340.0	339.0	0.1703	0.1698	0.29
7	14.72	2190	57.79	521.6	433.6	0.2382	0.1980	16.88
8	13.62	2038	54.03	409.0	385.4	0.2007	0.1891	5.77
9	10.31	2066	51.21	362.0	359.9	0.1753	0.1743	0.58
10	7.00	2300	52.00	378.2	372.4	0.1644	0.1619	1.53
11	8.10	2231	51.90	376.2	371.0	0.1686	0.1663	1.39
12	11.41	2203	54.72	432.6	400.2	0.1963	0.1816	7.48
13	8.38	2121	50.24	352.7	352.6	0.1663	0.1663	0.02
14	10.59	1941	49.31	338.2	337.5	0.1742	0.1738	0.20
15	10.03	1914	48.28	332.0	327.7	0.1735	0.1712	1.30
16	13.07	2134	55.17	441.0	402.2	0.2066	0.1884	8.80
17	7.28	2010	47.21	334.4	323.1	0.1663	0.1607	3.38
18	7.55	1983	47.00	333.6	320.5	0.1682	0.1617	3.91
19	13.90	2217	57.45	511.4	431.0	0.2307	0.1944	15.73
20	7.83	1955	46.79	332.9	317.9	0.1702	0.1626	4.48
21	12.79	1928	51.28	355.5	353.1	0.1844	0.1832	0.66
22	14.17	2162	56.76	486.8	420.6	0.2252	0.1945	13.61
23	11.97	2052	52.62	382.5	372.6	0.1864	0.1816	2.60
24	15.00	2148	57.34	504.5	426.3	0.2348	0.1984	15.51
25	12.52	2245	56.55	484.1	421.9	0.2157	0.1879	12.86
26	8.93	2093	50.31	352.7	352.6	0.1685	0.1684	0.04
27	9.76	2107	51.38	365.8	363.1	0.1736	0.1723	0.75
28	10.86	2286	55.62	458.3	412.4	0.2004	0.1804	10.00
29	12.24	2272	56.76	491.4	425.2	0.2162	0.1871	13.48
30	8.66	2024	48.83	339.1	337.1	0.1675	0.1665	0.59

The results indicate that a single constant frequency cannot be considered energetically optimal for a cone crusher across all operational conditions. Variations in ore hardness and mass flow rate lead to changes in electric drive load and specific energy consumption. Consequently, adaptively adjusting the frequency to suit operating conditions yields significant energy savings in certain modes. Modeling results showed a peak efficiency of 16.88% and an average efficiency of 5.57% across all 30 operating points. These findings demonstrate the advisability of implementing a control algorithm that adjusts frequency based on ore properties and load.

3. Results

Modeling results demonstrated that adaptive frequency control improves the energy performance of the cone crusher. Across 30 tested operating conditions, the average specific energy consumption decreased from 0.1902 kWh/t to 0.1784 kWh/t, achieving an average energy saving of 5.57%. Concurrently, the average power consumption dropped from 400.8 kW to 375.0 kW. The energy efficiency gains were particularly significant in cases where the constant 50 Hz frequency deviated substantially from the optimal operating point for the given ore hardness and mass flow rate.

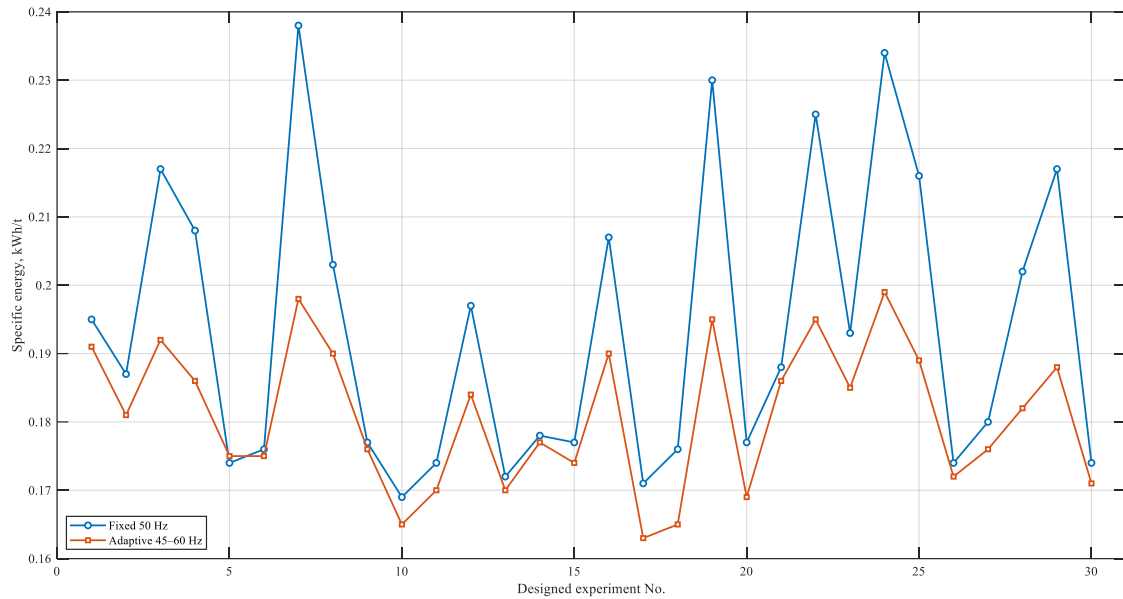


Figure 2. Comparative electrical energy consumption for the existing and new control systems.

Under conditions of low ore hardness and low mass flow rates, the optimal operating frequency may fall below 50 Hz. However, as hardness and flow rate increase, the optimal frequency shifts toward higher values. This aligns with the technological hypothesis that increasing the eccentric mechanism's speed is necessary to maintain crushing productivity

under conditions of high load and hard ore. Nevertheless, in actual crushers, the relationship between speed and efficiency may be non-monotonic at certain operating points. Therefore, the proposed model should be applied only within the experimentally verified range and calibrated based on production data.

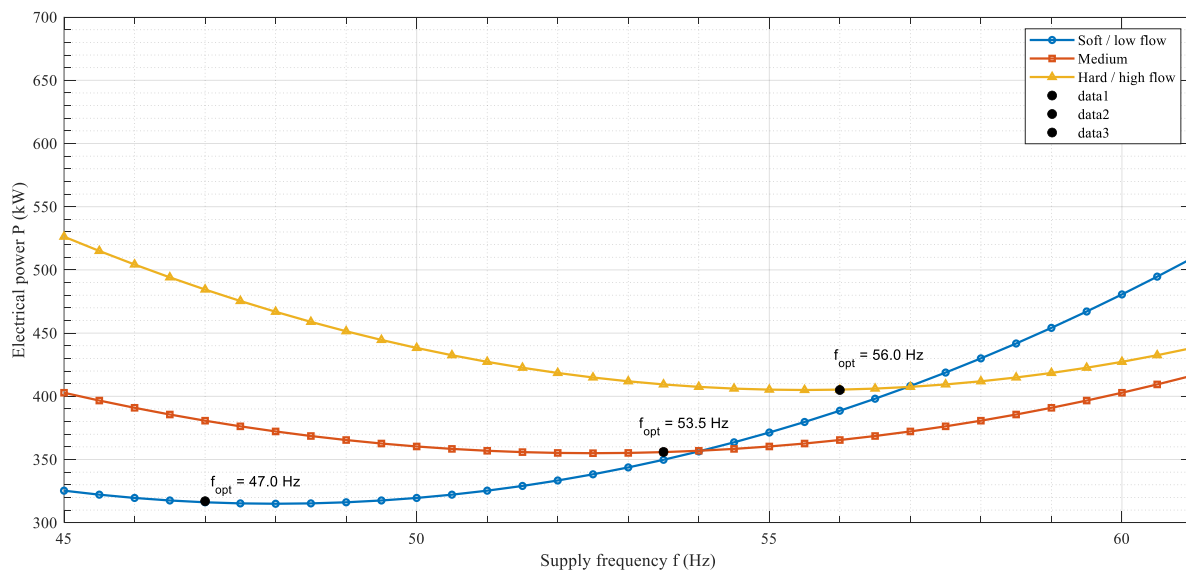


Figure 3. Representative curves showing the variation of the optimal frequency value as a function of power for each ore condition.

The rotational speed of a cone crusher directly affects the frequency of ore compression within the crushing chamber and the movement patterns of the particles. Changes in speed

alter both the crusher's throughput and the particle size distribution of the crushed product [3]. Existing research indicates that rotational speed, the eccentricity angle, and the CSS value significantly influence the crusher's energy consumption [5].

Consequently, the frequency that ensures the lowest specific energy consumption for a specific ore condition may not be optimal under different circumstances. For instance, if the ore hardness increases or the conveyor load rises, the optimal frequency value for the crusher changes accordingly.

$$SEC_i = \beta_0 + \beta_1 H_i + \beta_2 Q_i + \beta_3 f_i + \beta_4 f_i^2 + \beta_5 H_i f_i + \beta_6 Q_i f_i + b_{block} + \varepsilon_i \quad (4)$$

Where: SEC_i — specific electrical energy consumption in the i -th experiment, typically in kWh/t ; H_i — ore hardness in the i -th experiment; Q_i — mass flow rate, t/h ; f_i — VFD frequency, Hz ; f_i^2 — quadratic effect of frequency, helping to represent the existence of an optimal frequency; β_0 — initial or baseline coefficient of the model and b_{block} is a random factor accounting for variations specific to a particular ore batch or work shift. ε_i represents random errors not accounted for in the model.

The optimal frequency for each ore condition can be determined from the model:

$$f_{opt}(H, Q) = -\frac{\beta_3 + \beta_3 H + \beta_6 Q}{2\beta_4}, \beta_4 > 0 \quad (5)$$

This expression demonstrates how the optimal frequency shifts in response to changes in ore hardness and feed rate. In

When analyzing the experimental results, it is important to evaluate the individual effects of ore hardness, conveyor load, and frequency on energy consumption. The following regression model can be used for this purpose:

other words, as ore hardness increases or the volume of material fed into the crusher rises, the frequency value that ensures minimum specific energy consumption may also change.

The advantage of such a model is that it allows not only for the determination of the optimal frequency but also for an assessment of the result's reliability. Scientific articles typically present model coefficients, their standard errors, statistical significance, confidence intervals, model validation errors, and residual error analyses. Furthermore, the uncertainty associated with the energy-saving results must be evaluated. While 30 experiments may suffice for a preliminary or pilot study, drawing reliable conclusions at an industrial scale requires repeating the experiments multiple times across different ore batches, shifts, and operating conditions.

The table below provides a clear and concise comparison of the proposed method with previous studies focused on cone crusher control and energy consumption reduction.

Table 3. Comparison of the proposed method with previous studies on cone crusher control and energy efficiency.

Study	Key parameters investigated	Type of study	Main result
Hulthén & Evertsson [2, 3]	Crusher eccentric speed and material flow	Dynamic, real-time control	Demonstrated potential to improve efficiency by approximately 5–20% in the tested crusher
Hulthén et al. [4]	Frequency converter, SCADA system, and mass flow sensors	Iron ore industrial-scale tests	Determined that operating the crusher at variable speed, rather than a constant nominal speed, can be more efficient in certain cases
Liu et al. [5]	Speed, eccentricity angle, and CSS	Energy model and experimental verification	Confirmed that crusher speed significantly affects energy consumption
Atta et al. [8]	Control-oriented energy model of a cone crusher	Laboratory and industrial-scale verification	Developed a model accounting for energy consumption and verified it using practical data
This study	Selection of frequency (f) based on ore hardness (H) and mass flow (Q)	Preliminary numerical analysis based on 30 experiments	Proposed a control law aimed at reducing energy consumption and a procedure for its verification in an industrial setting

The primary distinction of our research is that, while previous studies typically examined parameters such as crusher speed, CSS, eccentricity, or material flow either in isolation or in pairs, this study considers ore hardness and mass flow simultaneously to determine the optimal operating frequency. Consequently, the control system is capable of adapting to varying ore conditions.

The automatic control system for the cone crusher's operating frequency is implemented via a *PLC*, which transmits control signals to a Variable Frequency Drive (*VFD*). Avoiding abrupt frequency changes is crucial, as mechanical wear, fluctuations in ore flow, and errors in hardness detection could adversely affect system performance.

The core principle of this algorithm is that the system monitors changes in ore hardness and material flow, selects the

optimal frequency for the crusher based on this data, and controls it via a VFD. Simultaneously, protective parameters such as power, vibration, and hydraulic pressure are continuously monitored. As a result, the crusher can be operated not only in an energy-efficient manner but also safely and stably.

$$f_{cmd}(k) = clip\{f_{cmd}(k-1) + clip[f^*(k) - f_{cmd}(k-1) + r_f T_s], 45, 60\} \quad (6)$$

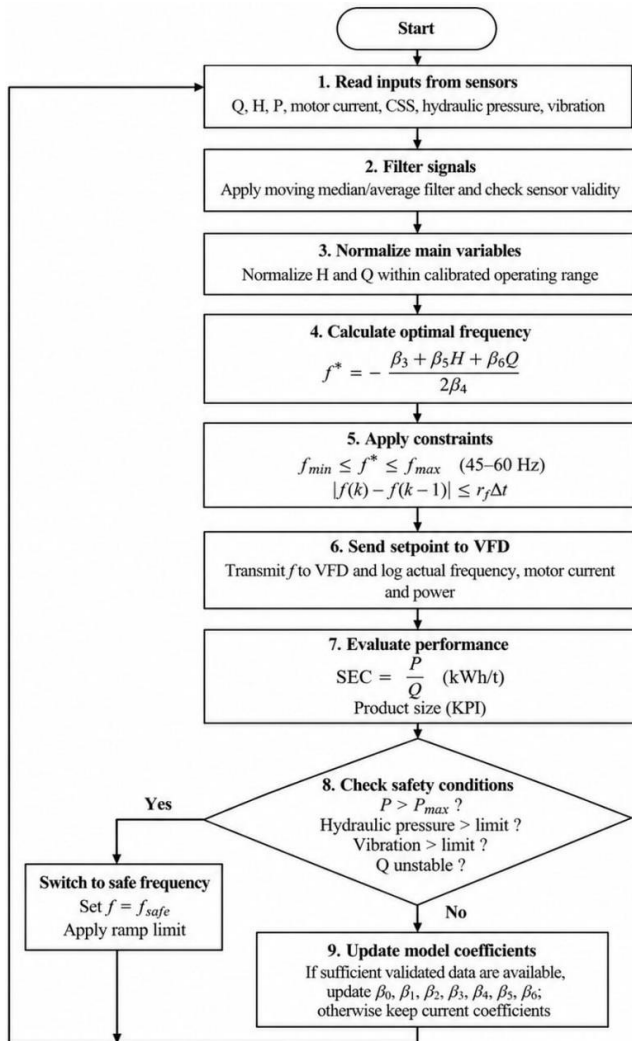


Figure 4. Practical algorithm for adaptive frequency control of a cone crusher.

It is not recommended to make sudden, drastic changes to the crusher frequency using the proposed system. Therefore, the control system must transition gradually to the newly calculated frequency. This can be achieved using the following expression:

Where: $f_{cmd}(k)$ — the new frequency command currently sent to the VFD, Hz; $f_{cmd}(k-1)$ — the frequency at the previous time step; $f^*(k)$ — the optimal frequency calculated by the model; T_s — the control system's computation or update interval, s; r_f — the permissible rate of frequency change, Hz/s; $clip$ — an operation that constrains the value within specified limits; 45 and 60 — the minimum and maximum permissible frequencies, Hz. As a result, the calculated frequency is maintained within the 45–60 Hz range, and no excessively abrupt commands are sent to the VFD.

In this context, the objective of reducing energy consumption must not take precedence over the equipment's safe operating requirements. Constraints specified by the manufacturer regarding motor torque, rotational speed, lubrication systems, bearings, mechanical resonance, and minimum permissible speed always take priority.

During the crushing process, it is difficult to continuously and directly measure the actual hardness of the ore while the crusher is in operation. Therefore, in practical systems, hardness is estimated by jointly analyzing data from multiple measurements rather than relying on a single sensor. Data such as material flow on the conveyor, feed ore size, crusher hydraulic pressure, motor power, vibration, and acoustic signals can be utilized for this purpose. Based on these signals, a proxy index representing the ore's hardness or resistance to crushing is calculated. Meanwhile, strength parameters measured periodically in the laboratory—such as UCS, Bond, or SMC—serve as benchmarks for calibrating and validating this online estimation system. Previous studies have demonstrated that the Bond Work Index can be correlated with measurable properties such as compressive strength and the Protodyakonov strength coefficient [7]. The stiffness assessment model can be written in a simplified form as follows:

$$\hat{H} = \omega_0 + \omega_1 UCS_{norm} + \omega_2 P_{norm} + \omega_3 F_{hyd,norm} + \omega_4 A_{vib,norm} \quad (7)$$

Where: $\hat{H}$ — the calculated ore hardness or competency index; ω_0 — the initial coefficient; $\omega_1, \omega_2, \omega_3, \omega_4$ — coefficients indicating the degree of influence of each parameter; UCS_{norm} — the normalized value of compressive strength; P_{norm} — the normalized value of crusher electric power; $F_{hyd,norm}$ — the normalized value of hydraulic pressure or hydraulic force; $A_{vib,norm}$ — the normalized value of the vibration

signal.

To ensure the model's reliability, it must be validated not only against the original training data but also against independent experimental data. This determines how accurately the ore hardness assessment system performs under actual industrial conditions.

4. Discussion

The proposed method is scientifically sound for three main reasons. First, the control strategy considers not merely the crusher's electrical power consumption, but the specific energy expended to crush a ton of product; reducing power by lowering the crusher speed is not always advantageous. Second, ore hardness and mass flow are accounted for separately, as crushing efficiency depends not only on frequency but also on ore properties and the load level within the crushing chamber. Third, the VFD frequency is selected as the primary control variable; this is a parameter readily available in industrial settings that can be constrained within necessary safety limits.

The proposed approach also aligns with classical theories of comminution energy. For instance, Bond's equation relates the specific energy required for crushing to the ore's work index and the reduction ratio, while Morrell's model extends energy consumption estimation to both conventional crushers and HPGR systems [9, 10]. However, these models do not directly provide an optimal VFD frequency value on a real-time (second-by-second) basis. Consequently, they serve as a theoretical foundation and a validation benchmark, while the practical optimal frequency is determined based on actual process data. If sufficient information regarding ore characteristics and the crushing process is available, it may be more appropriate to use a Morrell-type model for the cone crusher or a model based on an energy balance measured at the plant [10].

5. Conclusion

This article proposes a control method for a cone crusher that automatically adjusts the VFD frequency based on ore hardness and material flow. The study aims to reduce the specific energy consumption (*SEC*) per ton of ore while adhering to constraints regarding crusher power, frequency, and product quality. In 30 simulated experiments conducted within the ranges of $H=7-15$ and $Q=1900-2300$ t/h, the adaptive control method demonstrated an average *SEC* reduction of 5.57% compared to a constant 50 Hz operating mode. However, the primary achievement is not merely this percentage reduction, but the development of a control system architecture that can be validated through real-world testing. This system measures ore hardness and flow, determines the optimal frequency for the given conditions, constrains the frequency to the 45–60 Hz range, and evaluates efficiency in terms of *SEC*.

The proposed method aligns with findings from previous studies indicating that controlling eccentric speed and utilizing material flow feedback can enhance cone crusher efficiency.

Author Contributions

Olimov Jasurjon Sadridin Ugli: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Research Field

Olimov Jasurjon Sadriddin Ugli: Electrical Power Engineering, Electric Drive Systems, Induction Motors, Energy Efficiency, Predictive Control Systems, Industrial Automation