HPGR Grinding Technology in Mining and Cement

Decision making: Hydraulic vs. Electromechanical

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Technical white paper

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1 Abstract

High Pressure Grinding Rolls (HPGR) have increased in popularity primarily due to advantages in both operating and energy efficiency. Relative to the timeline of mining comminution evolution, HPGR can still be considered a young and evolving technology. While a significant amount of research has focused on the benefits of micro-fractures and advances in roller wear, far less analysis exists in the study of the reliability and selection of the prime moving system that rotates the rollers. While not necessarily intentional, a system standard has evolved that utilizes an electromechanical system for roller rotation and a hydraulic system for gap spacing control between the sliding and stationary roller.

This whitepaper provides the reader with a basic knowledge of alternative solutions for HPGR prime mover (motor/drive) systems, as well as potential preventative technology to decrease the impact of system shock.

2 Background

As the size of HPGR machines increased, so did the internal forces of shock and damping inherent in a dynamic system, causing the need for system components to be built that are larger, heavier and more robust. Consequently, an all-hydraulic solution should be considered as a fluid-based system which has traditionally been proven to better dissipate potentially destructive forces and has been widely used and accepted in high-shock mineral process systems such as apron feeders.

2.1 Mass/Spring/Damper (MSD) Model Review

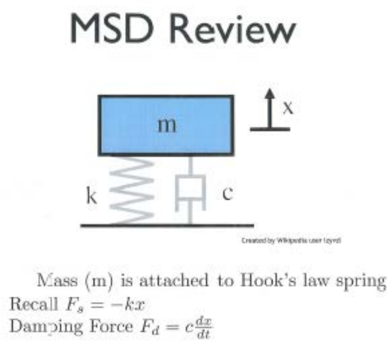

Figure 1: ESE112 Lecture 1, Fig 1

The HPGR system, during a shock event, behaves like a Mass Spring Damper (MSD) model. The mass of the HPGR system consists of the roller tyre and corresponding ore in contact with the tyre. The spring is the mechanical reactive force in response to the variation that the mass experiences, due to varying ore morphology or a non-standard operational event, such as reaction to metal detection. Without any dampening effect, the spring would oscillate towards infinity, but in actual practice, every physical component within the series of components of the HPGR prime mover provides resistance, and therefore a dampening effect. Damage to the HPGR system is more likely to occur if the system is under-damped or overdamped. Ideally, we desire the system to return very quickly to equilibrium if it is critically damped.

2.2 Deriving Equations of Motion and Applying it to a MSD

dividing by m

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x \tag{4}$$

if we let $\omega_0 = \sqrt{\frac{k}{m}}$, be the natural frequency of the system and $\zeta = \frac{c}{2\sqrt{km}}$, be the damping ratio, we get

$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0^2 x = 0 \tag{5}$$

http://en.wikipedia.org/wiki/Damping

Figure 2: EQUATION OF MOTION [1, p. 3]

We can classify the system into three distinct categories.
1.Under-damped: $\zeta < 1$. In this case the system oscillates with a frequency equal to $\omega_d = \omega_o \sqrt{1-\zeta^2}$
2.Over-damped: $\zeta > 1$. The system slowly returns to equilibrium
3.Critically Damped: $\zeta = 1$. The system returns to equilibrium

Figure 3: MSD CLASSIFICATION [1, p. 9]

Consider the scenario of a football linebacker running directly into a wall. Now, consider the same scenario with the linebacker running into a mattress leaning against the wall. In both scenarios, the linebacker is stopped, but in the first scenario, even though he is wearing collision protection, the linebacker is likely to be negatively impacted, and the wall starts to sustain damage. If this event is repeated many times, damage increases to both the linebacker and the wall.

The major difference between the two scenarios, is that the first has a negligible damping effect, while the second provides a means of both effective energy absorption and dissipation. Like the first scenario, bearings and gear teeth are designed with inherent strength but not intended to be shock absorbers. In comparison to the second scenario, a hydraulic system behaves as a shock absorber, effectively using the hydraulic fluid in the closed system, to absorb, dissipate and cushion against shock and vibration. This absorption occurs in concurrence with Pascal's Law: The pressure applied to part of a fluid in a closed container is transmitted uniformly to other parts of the fluid. Inherently, the system is critically damped and returns to equilibrium [1].

2.3 Mass/Spring/Damper (MSD) Model Review

The Effect of Shock on Gear Teeth

Studies of 44 records of Planetary gearbox damage used in various industrial operations have shown that 21 failures were related to Planetary gears and 23 failures were related to Planetary bearings [2]. Gearbox lubricant is the only material between the tyre shaft and gear teeth and has a poor damping effect due to an almost negligible thinness of lubricant film at the gear teeth. The hydraulic design does not have a gearbox, therefore gearbox damage is not possible.

The Effect of Shock on Shock Bearings

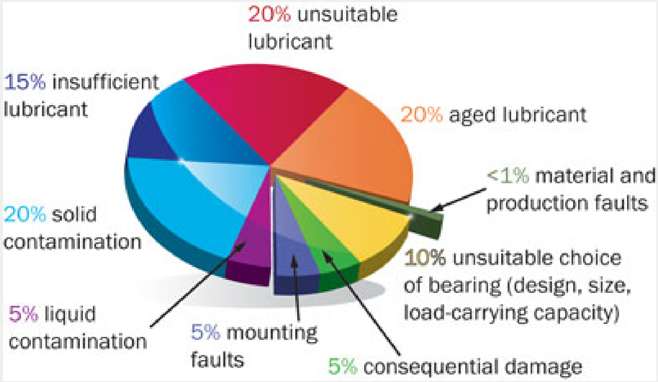

Figure 4: CAUSES OF BEARING FAILURE [3, para. 12]

Under standard operation, bearing failures are often caused by improper mounting, operational stress, environmental influence, their unsuitability for stress and shock, and bearing lubricant exceeding temperatures at which the lubricant is designed to function. In abnormal HPGR operation, shock can induce multiple forces that will result in bearing destruction.

Based on the image above [3], some identified causes of lubricant failure in rolling bearings are due to unsuitable lubricant (20%), aged lubricant (20%), and insufficient lubricant (15%). Other causes of a poor damping effect of gearbox lubricant include: distribution of oil over the wide surface area of the gearbox, degradation of viscosity due to temperature, and solids contamination. The advantage of hydraulic fluid as a damper is that liquid contained in a cylinder allows effective damping of shock through oil being forced through an orifice, which limits spring speed and reduces both oscillation and vibration [4], [5].

3 Facts About HRC Prime Mover

3.1 Basic HPGR System Configuration – Electromechanical

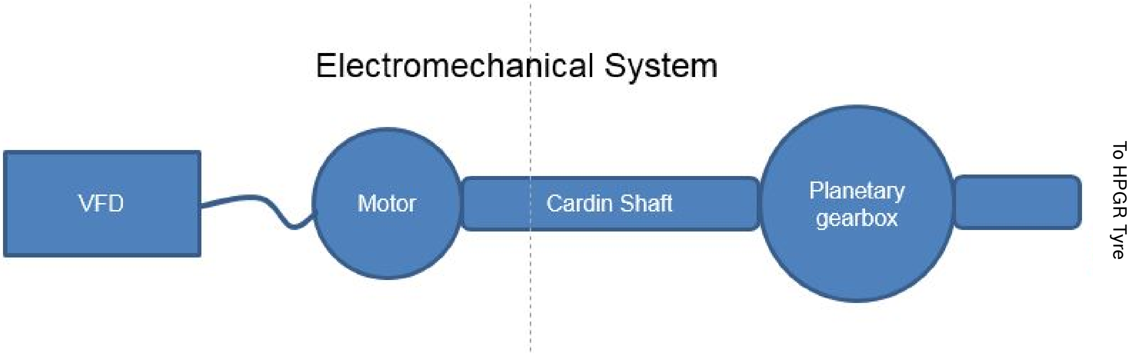

Figure 5: Electromechanical Configuration

Figure 2 (above), displays the standard configuration for a typical electromechanical HPGR machine. Electrical power is supplied to a Variable Frequency Drive (VFD), which provides power to a motor. The motor is then coupled to a Planetary gearbox via a cardin shaft. The Planetary gearbox is directly coupled to the HPGR tyres. It is important to note that each rotating machine in this system requires bearings, and for larger size applications, multiple bearing sets per machine may be specified [7].

The path of a shock event occurs in the reverse direction of the system just described, from the HPGR tyre then directly to the gear teeth of the gearbox. As [2] observes, for systems containing both Planetary gears and bearings, both the gears and bearings share an equal probability of failure. This suggests that the gear teeth are a predominantly weak link in the system. Even if failure of the gear teeth does not occur, [2] observes that excessive metallic wear or tooth chipping, can contaminate lubrication oil, leading to future bearing failure.

To date, there seems to be little evidence of motor bearing failure, suggesting that the gearbox inadvertently acts as a sacrificial circuit breaker, likely to be destroyed before any upstream damage would occur to the motor bearings. This does not suggest however, that the motor bearings are completely undamaged. It is suggested that bearings be monitored via vibration and/or temperature analysis to measure premature wear or secondary damage over time.

It is worthwhile to note that for at least the past decade, there has been ongoing discussion of a HPGR prime mover system that features an electrical motor directly coupled to the tyre, sans the gearbox. While this solution would certainly be advantageous, several significant barriers remain. First, the typical low speed motor has traditionally been manufactured by increasing the number of poles, which requires a corresponding increase in motor diameter. The motor becomes physically too large to bring the tyres together. Additionally, the centerline of the rotor is increased, corresponding to a HPGR machinery challenge in aligning the motor rotor with the tyre center.

The use of a permanent magnetic stator introduces a new potential problem. While this design would physically reduce the motor diameter, as in any directly coupled motor design, system shock would be transmitted directly to motor bearings. If the shock event is of sufficient magnitude to drive the rotor into contact with the permanent magnetic stator, the result is catastrophic, with no possibility of repair in the field.

3.2 HPGR Hydraulic System Configuration

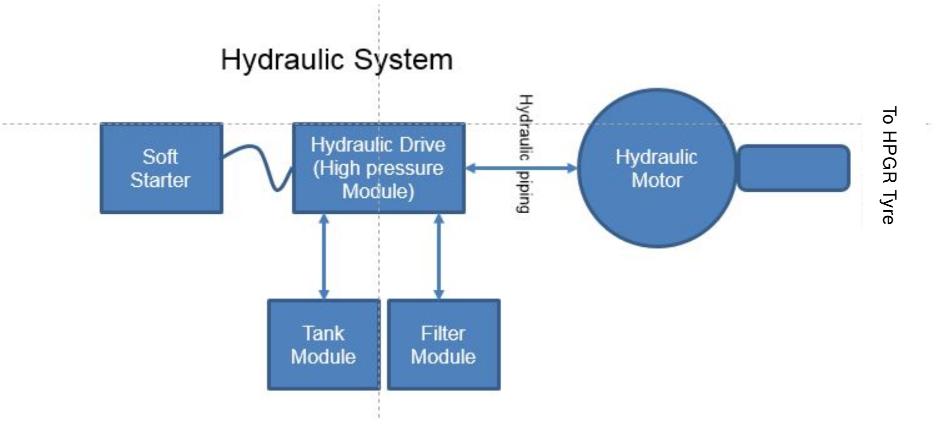

Figure 6: HPGR Configuration

The hydraulic HPGR prime mover system, as seen in Fig 5 (above), has a soft starter that is used to limit starting current to the hydraulic pump motors. The soft starter limits initial motor start up current and extends the life of the motor. Unlike a VFD, the soft starter cannot be used to vary motor speed.

Other than the functional requirement of providing torque and rotation at the delivery end, the hydraulic system appears to have very little in common with the electromechanical system. The hydraulic solution uses fluid pressure to turn the rotor, sequentially opening and closing pistons to produce motion. There are bearings in the hydraulic motor as well, typically both axial and cylindrical. The bearings, like the entire operation of the rest of the motor, are continuously functioning in a liquid bath of hydraulic fluid. This fluid is provided by hydraulic lines under pressure. If a shock to the system occurs and transmits first to the tyre and then to the hydraulic motor, the cavity of the motor and corresponding fluid-filled piping effectively behave as a hydraulic shock damper, dissipating damage energy in a uniform and controlled pattern.

4 Systems Comparison

4.1 Capital Cost (based on a 2300KWx2 system)

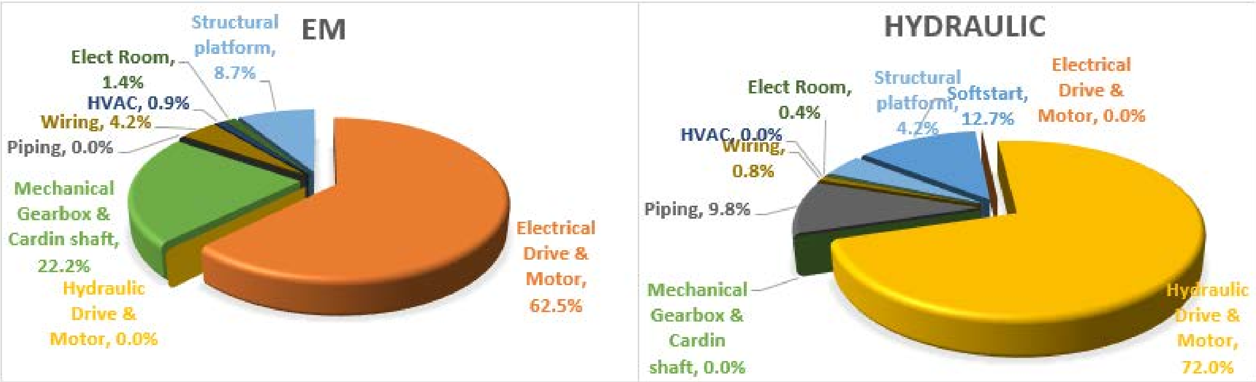

Figure 7: Comparison of Capital Cost

The capital cost factor for the electrical mechanical (EM) system is 1.0, compared to .82 (18% less) for the hydraulic system. This comparison is illustrated in the table below, listing percentage ratings for the infrastructure of both electrical mechanical and hydraulic systems, reflecting lower cost for the hydraulic system.

4.2 Equipment Costs – Electrical Mechanical vs. Hydraulic Capital Cost (based on a 2300KWx2 system)

EQUIPMENT	ELECTRICAL MECHANICAL	HYDRAULIC
Softstart	N/A	12.7%
Electrical Drive & Motor	62.5%	N/A
Hydraulic Drive & Motor	N/A	72%
Mechanical Gearbox & Cardin shaft	22.2%	N/A
Piping	0%	9.8%
Wiring	4.2%	.8%
HVAC	.9%	0%
Elect Room	1.4%	.4%
Structural Platform	8.7%	4.2%

4.3 Weight Comparisons – Electrical Mechanical vs. Hydraulic

The table below shows the approximate weights of both the electrical mechanical and hydraulic HPGR drive system options.

WEIGHTS FOR A TYPICAL 2000HP HPGR SYSTEM (AT THE HPGR MACHINE LEVEL)			
SYSTEM		FACTOR	
EM	71000KG	1	Includes Motor, Cardin Shaft, Gearbox, Torque Arm
Hydraulic	56700KG	0.8	Includes Motor, Torque Arm

4.4 Efficiency of the Hydraulic System

Energy efficiency plays a critical role in the selection of the HPGR drivetrain. At first glance, in the absence of a gearbox, the hydraulic system would have an advantage. However, it must be realized that while an electrical drive converts electrical power to electrical power, the hydraulic drive converts electrical power to hydraulic power- a process that is approximately 5 to 7% less energy efficient. Even so, the hydraulic motor exhibits a 1 to 1.5% improvement over its electrical counterpart. In addition, there are neither HVAC systems required nor separate lubrication systems required for the hydraulic system. Taking all of this into consideration and ignoring the typical “sales spin” that is generally practiced while stating system efficiencies and reducing complexity to a basic power output vs overall power input, The Hydraulic System can be expected to be 73% to 82% efficient, while the Electromechanical system 74% to 85% efficient.

4.5 Total Cost of Ownership (TCO) – Electrical Mechanical vs. Hydraulic

Plant and mine operators will typically decide on a grinding system based on the total cost of ownership. While the previously discussed capital cost and operating efficiency are major variables in this decision, numerous other variables should be taken into account for a proper TCO model. These variables include: cost and frequency of fluid changes, routine maintenance costs, spare parts costs, labor costs, training costs, remote monitoring cost, service cost, cost of impact due to down-time etc... There are many good software based TCO tools that can aid in this effort, and the scope of this study is too extensive for this paper. Also, more accurate results will occur given a higher level of specificity of system components. so a generalization based on a hypothetical system has very limited value.

5 Other Considerations – Shock Prevention

5.1 Metal Detection/Level Detection

Metal detectors are used to prevent metal material from entering the HPGR that may cause damage to the tyre roll face. The metal detectors either divert [7], [8] or pass through the metal debris. Either of the two corrective actions changes the state of normal operation and presents a potential for process interruption and/or increased shock and vibration of the system. It is beneficial then to design a system that detects potentially damaging metal as early as possible in the process and at a greater distance from the HPGR input hopper.

Traditional metal detectors, while effective at close-proximity detection, are highly distance-sensitive and ineffective at any rate of detection other than near field. Presently, progress is being made in video analytics-detection of metals through thermal imaging. This technology is becoming less expensive yet more capable. The advantage of this approach is the ability to adjust detection distance based on camera optics.

The thermal imaging camera can see a longer distance area, at a much wider angle than a metal detector. Thermal video analytics has also proven an effective means of providing a visible image of level and material morphology in a mining crusher [10]. Similarly, consideration can be given to the application of such technology as the HPGR hopper which has been observed to experience level detection issues due to the normality of dust in the hopper [9:17]. Level detection problems in the hopper will lead to reduced throughput of the HPGR machine.

5.2 Maintenance and Repair – Special Tools for Applications

Accommodations have to be made for the removal and replacements of the tyres (rolls) in the HPGR system, as a standard service requirement [6]. HPGR machine designers will typically work with the mining end-user, during the design and procurement stages, to develop a method and process for HPGR servicing. As each HPGR installation tends to be unique it is common that the service requires specialized tools, specifically designed for the application. Companies such as Bosch Technologies have aftermarket services that can design tooling specifically for these applications [10].

6 Summary

HPGRs are considered the present grinding technology of choice for both mining and cement applications, growing at a more rapid rate than alternative technologies. Initial problems with tyre surface life have been resolved, and the length of time HPGR equipment has been in use without catastrophic or major failure is typically 10 to 15 years.

While the process to deliver ore to the HPGR is controlled for size and geometry, ore variation typically causes HPGR reaction that results in operational fluctuation as opposed to operational consistency. Unusual events such as metal pass through or diversion require designed, preventative actions. These events can create shock and opposing forces on normal operation.

In the now “standard” HPGR system, reactive forces act initially on gear teeth and then on gear bearings, each of which are protected only by a thin layer of lubrication which provides a negligible damping effect.

As an alternative to an HPGR prime mover system, consisting of an electrical motor and mechanical gearbox, a hydraulic system should be considered. A hydraulic system, by the very nature of its physics, provides superior isolation from system abnormalities and dampening of unexpected shock events.

Relative to comparative system cost, efficiency and total operating cost, the hydraulic system represents significant capital cost savings, comparable energy efficiency and advantageous total cost of ownership due to the reduction in bearings, gears, separate lubrication systems and no need for special climate or dust control. As the overall weight of the hydraulic motors is also less than the electromechanical system, additional savings could be realized due to reduced structural support requirements.

The most intelligent investment in the HPGR system occurs prior to the input to the machine as preventative measures that protect against potential damage or reduced throughput. These preventative measures involve the early detection of metallic materials likely to result in tyre face damage. The earlier this material is detected, the better the reaction capability of either a diversion or pass-thru system can be executed, preferably in a smooth, controlled manner rather than in a fast, high-impact manner. In addition to traditional near-field metal detection, consideration should be given to new, video thermal imaging and video analytics.

Finally, no HPGR system is complete without consideration of how the machine can be maintained and repaired in an efficient manner that is both cost effective and most importantly, limits machine downtime. The design of a service system and associated special tools to facilitate maintenance is a critical part of overall operational efficiency.

7 Appendix A: About Bosch

The Bosch Group is a leading global supplier of technology and services. It employs roughly 390,000 associates worldwide (as of December 31, 2016,). The company generated sales of 73.1 billion euros ($80.9 billion) in 2016.

Operating across four business sectors – Mobility Solutions, Industrial Technology, Consumer Goods, and Energy and Building Technology – Bosch is uniquely positioned to offer customers a multitude of value-add, cross-sector solutions across diverse industry applications. It leverages its expertise in sensors, software, and services, as well as its own IoT cloud, to offer its customers these connected, cross-domain solutions from a single source. Bosch is a technology leader in the mining and concrete industries, providing a comprehensive range of products and solutions to assist mine owners, planners, contractors, material handlers and mining engineering companies worldwide. Whether the project requires state-of-the-art drive and control technology, cutting-edge security solutions, or proven-tough parts and tools, Bosch offers a choice of products that are commonplace across mining and concrete sites today.

Bosch Rexroth, a leader in industrial hydraulic and electrical drive technology, offers an extensive portfolio of drive and control technology, including for mineral processing and materials handling. Bosch also offers an expansive portfolio of components for mining vehicles as well as professional power tools that are optimized for reliability and long service life. Additionally, Bosch Security Systems offers a comprehensive suite of solutions to keep facilities safe and operating smoothly. The wide range of Bosch products and solutions for the mining industry deliver reliability, quality and durability.

The Bosch Group's strategic objective is to create solutions for a connected life and to improve quality of life worldwide with products and services that are innovative and spark enthusiasm. In short, Bosch creates technology that is "Invented for life."

Additional information is available online at cds.bosch.us/mining.

8 Appendix B: References

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