THE ENGINEERING AND PROCESS EFFECTS OF CHOOSING A MOTOR DESIGN SPEED

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ABSTRACT

Many grinding mill owners choose a variable speed drive for their mill to cope with variations in ore hardness, plant throughput and other process considerations. Two important engineering decisions that owners must make before purchasing a variable speed drive system are the selection of the motor nominal design speed and the motor maximum speed.

An inherent design characteristic is that motors operating below their nominal design speed are capable of operating with constant torque, but at a reduced power output. Motors operating above their nominal design speed are capable of constant power, but at an ever reducing torque. This transition speed (called the knee point) is important because according to the characteristic of any turning machine (Power = Torque × Speed × 2π), the power varies in the constant torque speed range and the torque varies in the speed range with constant power. The operator must keep the process demand for power and torque below these constraints (eg. by adjusting mill speed or charge level) while still operating in an efficient manner.

The owner's choice of the knee point (motor rated speed) coupled with the owner's choice of the motor rated power define the rated torque of a motor. The electrical designers of motors use this rated torque to fix the size of the motor components. The price of a motor depends on the rated torque of the motor (more-so than the motor rated power and diameter), so for large mills a slight increase of the motor rated speed can result in substantial price savings. Operating at higher mill speeds can reduce operating costs by permitting operation at lower ball charges for a given mill power draw.

KEYWORDS

Motor design, motor speed, mill speed, rated speed

INTRODUCTION

The purpose of this paper is to provide guidance to Owners and EPCM engineers in the specification of the "design" and "maximum" speed of grinding mill motors. Purchasing a fixed-speed or variable-speed mill drive requires the specification of several important engineering values: the motor rated output power, motor rated speed and the motor maximum speed. The motor rated output torque is calculated using these specified values as shown in Equation 1. This applies whether purchasing a large Gearless Mill Drive (GMD) or a conventional gear drive.

$$T = P \times (2\pi \times \omega)^{-1} \qquad\qquad\qquad (\, 1 \,)$$

where,

T is motor output torque measured at the output shaft (pinion) or mill shell (GMD), N·m;
P is motor output power measured at the output shaft (pinion) or mill shell (GMD), W;
ω is the motor speed, revolutions per second or Hz.

The motor output torque is a major cost driver in the construction of a motor as the torque determines the loading that the motor structure must accommodate (ergo, affecting the stiffness of the motor and mill structures). Increasing the motor speed, ω, holding the power, P, constant results in a reduced torque, T. Thus, a purchaser who specifies a higher rated speed of the mill will get a lower torque design, usually resulting in a lower motor cost.

The paper specifically describes SAG mills, but the equations and principles apply equally to any conventional tumbling mill, such as AG, ball or rod mills.

MOTOR ELECTRO-MECHANICAL CHARACTERISTICS

The cost of a motor of a Gearless Mill Drive depends mainly on two parameters:
- Diameter of the motor,
- Rated Torque of the motor,

The diameter of a GMD motor is defined by the diameter of the mill, as the motor is wrapped around the mill. The torque of the motor is what makes the mill turn and torque output is a function of the geometry of the mill it is turning and operator setpoints (the "process"). The rated torque of the motor is calculated from its rated power and its rated speed (at the knee-point) according to Equation 1. The faster the knee-point (rated speed), the lower the torque required to turn the mill. The Rated Torque is the main characteristic of interest in the mechanical and structural design of a motor; therefore, the faster the knee point, the lower the capital cost of the motor.

The "constant torque" speed range, where the motor rated (maximum) torque value is available to the operator, goes from the lowest operating speed up to the knee-point speed. Torque is created by the magnetic field and the electric current of the motor. As the torque of this motor is constant over the speed range up to the knee point, the magnetic field and current are also constant over this speed range. The requirement for "constant torque" causes the current to have the same value at low speed operation as at the knee-point. The current remains the constant above the knee-point, but weakening of the magnetic field causes a reduction in available torque (but at constant power) above the knee-point as shown in Figure 1.

The electric current of the motor is the main creator of power losses flowing through the conductors of the equipment. It has direct impact on:

- conductor design,
- amount of copper in the motor,
- heat dissipation equipment,
- design of the converter, which provides variable speed.

The amount of power a motor can deliver is a function of the rated power and the knee-point (rated speed) nominated by the Owner. Below the rated speed, the amount of power is linearly related to the speed, as shown in Figure 2 for the same example mill.

The operator can operate a variable speed drive and mill in the complete red or blue area. Moreover, the red and blue areas coincide! Each point in the blue area corresponds to a point in the red area given by the relation in Equation 1. Therefore the complete red area is available for operation (power draw), as well as the complete blue area (torque demand).

In daily practise, the operator can operate a mill with a variable speed drive at any speed the grinding process may require, as long as:

1. The motor temperatures keep below the maximum values defined by the supplier, and
2. The current of the motor does not exceed its rated current value specified by the supplier.
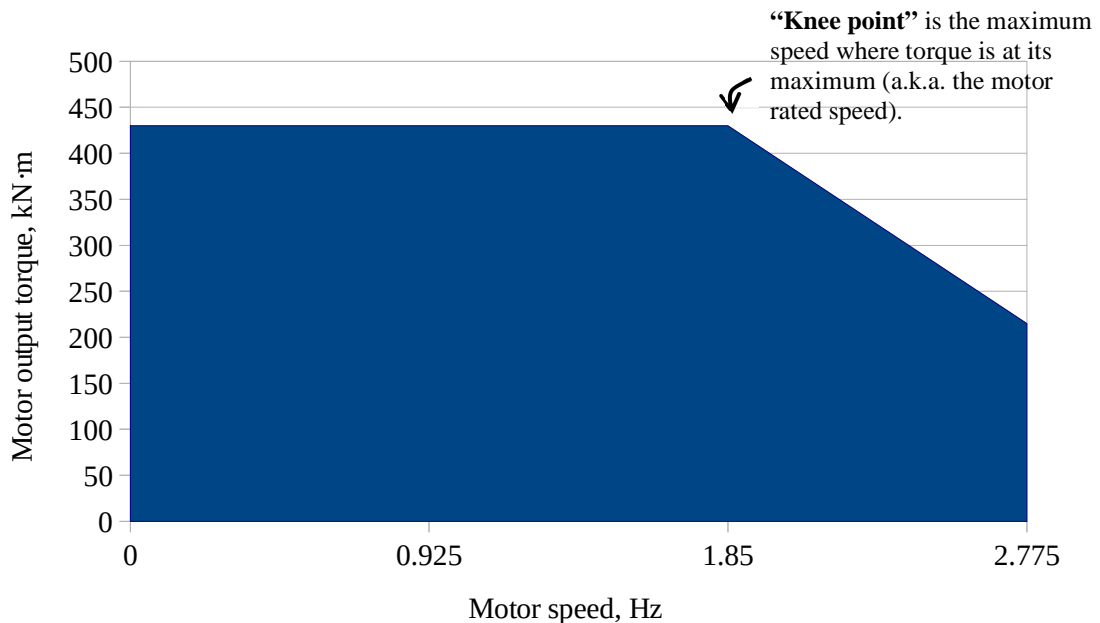
"Knee point" is the maximum speed where torque is at its maximum (a.k.a. the motor rated speed).

Figure 1 – Example motor torque available as a function of motor speed
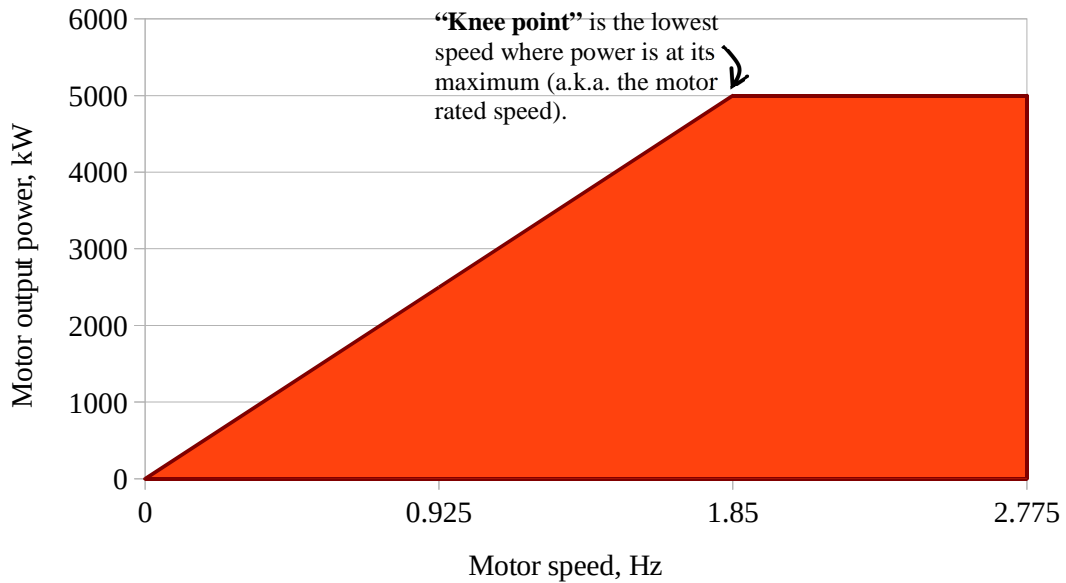
Figure 2 – Example motor power available as a function of motor speed

GRINDING MILL PROCESS CHARACTERISTICS

The geometry of the grinding mill and the charge it contains determines the actual amount of power used to drive the mill. This geometry describes the normal operating and design parameters that engineers use to describe grinding mills: the mill diameter, effective grinding length, charge filling, and so on. The operating power draw of the mill and, consequently, the motor torque consumed will vary during mill operation as the operating parameters vary.

The SAG mill power draw model of Austin (using the calibration by Doll, 2013) is used to predict the process power draw at the mill shell, P_{shell}, and the efficiency losses for the drive's mechanical components based on Doll (2012) are used to determine the motor output power, P. The effect of varying the mill speed as a fraction of the critical speed, ϕ_C, can be observed by plotting the process power and torque draw superimposed on the relevant motor capability curve. Such plots for an example mill, the SAG mill at Cadia (described by Dunne et al., 2001) is shown in Figure 3.
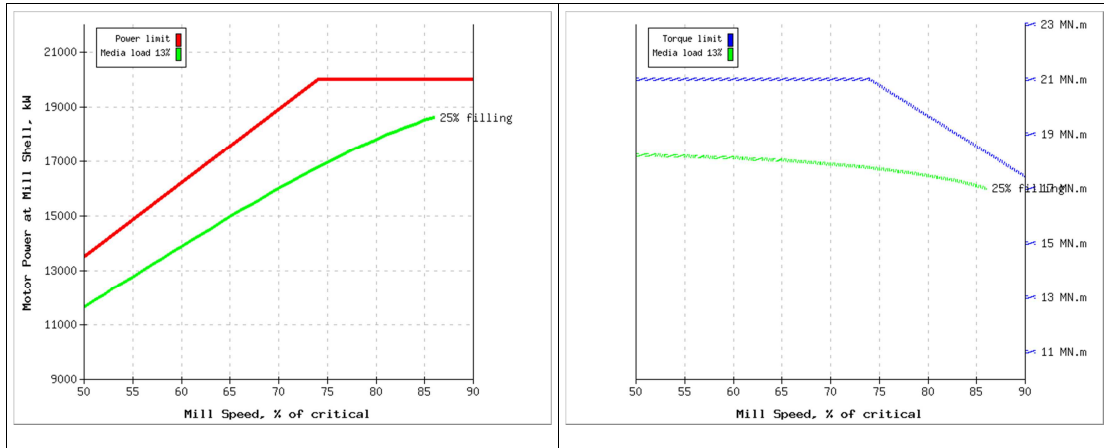
Figure 3– Power & torque diagrams for the Cadia SAG mill

Any time a process line (green) touches or exceeds the corresponding motor limit (the red or blue lines), the motor is at risk of tripping due to high current, depending on the conditions. Safe operating of a mill and motor means that the process lines should appear below the red and blue lines across the whole range of speeds that are of interest. In this example (13% vol ball load and 25% vol filling), the operator can safely operate across the whole speed range of 50% to 85% of critical speed.
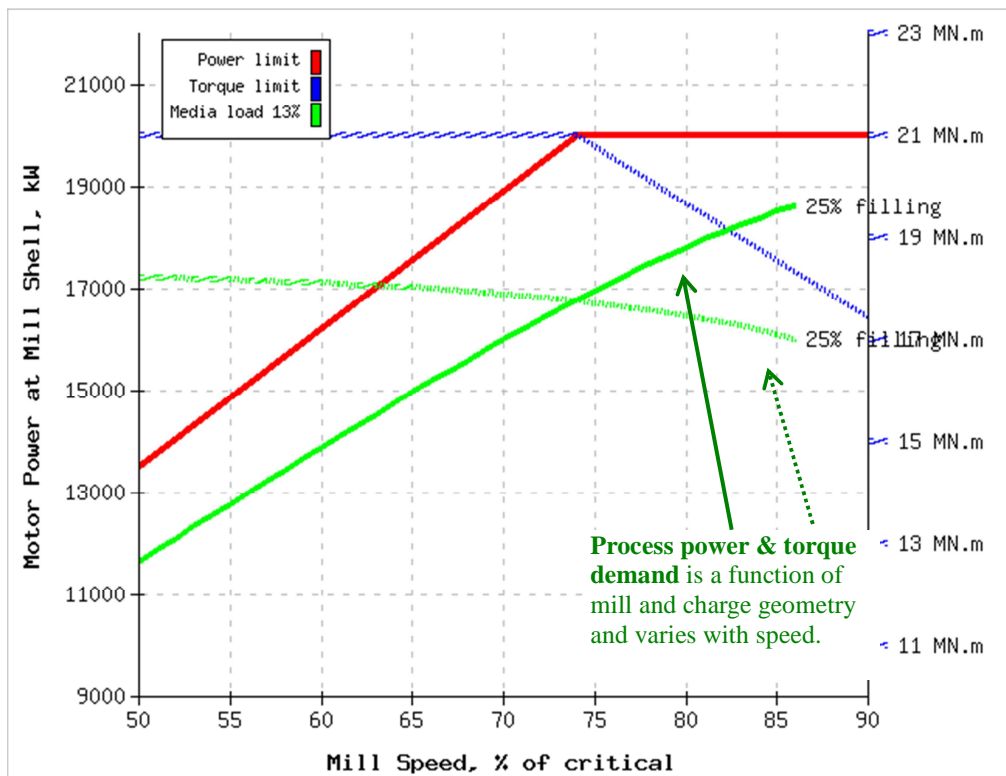

Figure 4 – "Tent" diagram for the Cadia SAG mill described in Figure 3

Combining these two diagrams into a single nomograph results in a "Tent" diagram described by Barratt & Brodie (2001). The Tent diagram superimposes the two motor maxima (Figures 1 & 2) plus the process power and torque demand in a single diagram (see Figure 4). It is important to note that the motor torque capability (dashed lines) on a tent diagram only compare to the process torque draw (dashed lines), and similar for the power (solid lines). A dashed line crossing a solid line, or vice-versa, is of no significance.

Definitions of mill speed

Process engineers commonly refer to the speed of a mill as "percent of critical speed", ϕ_C, or "percent" for short. SAG mills commonly operate at speeds between 70% and 80% of critical. Unfortunately, such a designation is meaningless to motor manufacturers who need the speed as either ω, Hertz (rev/sec) or ϕ_{RPM}, RPM (rev/min). The conversion between percent of critical speed and RPM is a function of the diameter of the mill and thickness (wear) of the liners, and a relevant form of the conversion equation is given in Equation 2 (adapted from Amelunxen et al, 2013 and neglecting the effect of the ball diameter).

$$\phi_{RPM} = \phi_C \times 42.2 \times (D - 2d)^{-0.5} \qquad\qquad (\,2\,)$$

where,

ϕ_{RPM}	is the mill rotational speed, revolutions per minute
ϕ_C	is the mill rotational speed, fraction of critical speed (eg. 0.72 for 72%)
D	is the mill nominal diameter inside the shell, m
d	is the mill liner nominal thickness, m

The process engineer is responsible for determining the mill diameter and liner wear conditions that the mill rated speed should be designed for. The definition of mill speed that the process engineer should specify to the motor designer (or vendor) is mill speed as ϕ_{RPM}, revolutions per minute.

The motor designer (or vendor) will convert the specified rated mill speed into the speed of the motor, ω_{rated} as Hz, which for a Gearless Mill Drive is simply $\phi_{RPM} \div 60$. For a gear driven mill, the motor speed is a function of the mill speed ϕ_{RPM}, and the gear ratio of the mill bull gear and the drive pinion.

CASE STUDY N° 1: CHANGING PINION ON A FIXED SPEED MILL

A common way of changing the speed of a mill that is driven by a fixed-speed motor is to change the pinion to a new design with an additional tooth. This additional tooth results in a different gear ratio resulting in a different rated mill speed ϕ_{RPM}, even though the motor speed ω_{rated} (both rated & operating) is unchanged.

Example: A small SAG mill with dimensions $(D - 2d) = 27$ foot effective diameter, $L = 14$ foot effective grinding length and 15° cone ends operates with 12% by volume ball charge and 25% by volume total load. The mill is equipped with single fixed-speed synchronous motor that drives the mill at $\phi_{RPM} = 11.1$ RPM ($\phi_C = 0.753$, 75.3% of critical) via a pinion with 20 teeth and a bull gear with 200 teeth (10:1 gear ratio) giving a motor speed of 111 RPM, $\omega = \omega_{rated} = 1.85$ Hz. The mill will draw 4457 kW at the mill shell, equivalent to 4525 kW measured at the motor output (see Figure 5). It is observed that 90.5% of the

available 5000 kW of motor power (measured at the motor output) is being consumed, so a pinion change is proposed to increase the speed of the mill with the intention of drawing more of the available power.

Changing the pinion to 21 teeth changes to gear ratio to (9.5:1). The motor speed does not change, 111 RPM, $\omega = \omega_{\text{rated}} = 1.85$ Hz. The new gear ratio means the mill is now turning at $\phi_{RPM} = 11.655$ RPM, $\phi_C = 0.791$ (79.1% of critical speed). This new speed the mill will draw 4627 kW at the mill shell, equivalent to 4698 kW at the motor output (see Figure 6). This is 94.0% of the available motor power.

Mill geometry and filling are unchanged, so the process power demand curve (the solid green line on the Tent Diagrams, Figures 5 & 6) is the same in both, but the effect of the pinion change is to "climb" farther along the process power draw curve from the original position (the green dot) to the new mill speed (the red dot). The tent diagram torque axis changes because the new gear ratio changes the torque observed at the mill shell (the motor sees higher torque, the mill sees slightly less).

The higher speed would require adjusting the mill's lifter design to properly drop the balls into the mill charge and not throw balls into the liner above the toe of the mill charge.

Table 1 – Operating conditions for 12% ball charge, 25% total load with different pinions

		Rated	20 tooth	21 tooth
Power, motor output	kW	5000	4524	4698
Power, mill shell	kW	4925	4457	4627
Torque, motor output	kN·m	430	389	404
Torque, mill shell	kN·m	4237	3834	3791

Tent diagram for 28′ Ø × 14′ EGL
Motor cumulative output power 5,000 kW. Usable shell power 4,925 kW.
Liner thickness: 6.00". Ore density: 2.6 t/m³.

Motor speed 1.85 Hz
Mill speed 11.1 RPM

Operating point for 20 tooth pinion

Tent diagram for 28′ Ø × 14′ EGL
Motor cumulative output power 5,000 kW. Usable shell power 4,925 kW.
Liner thickness: 6.00". Ore density: 2.6 t/m³.

Motor speed 1.85 Hz (unchanged)
Mill speed 11.6 RPM (+5%)

Operating point for 21 tooth pinion
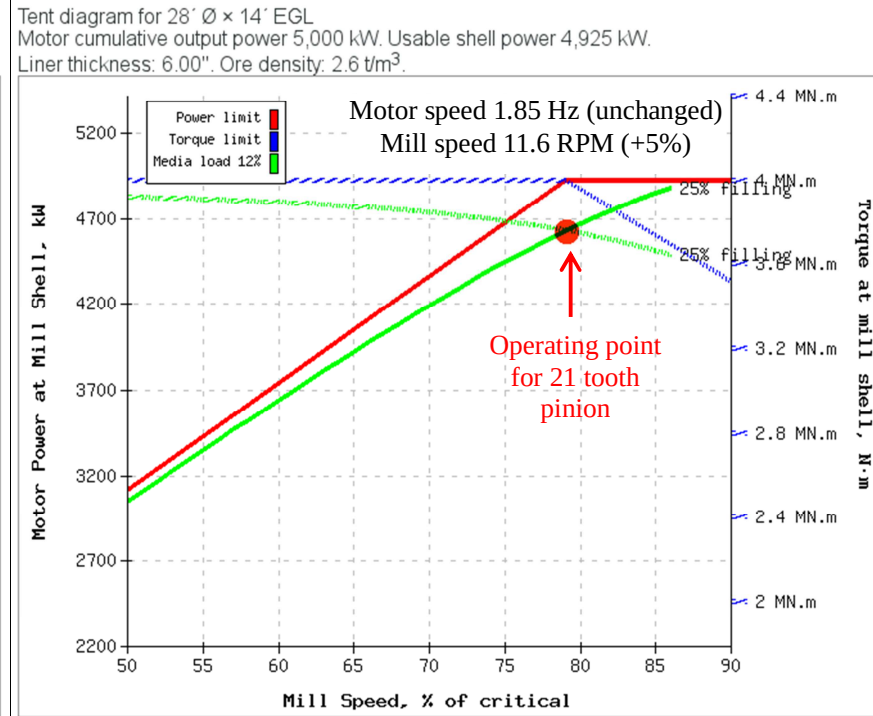
Figure 5 – "Tent" diagram for the 20 tooth pinion

Figure 6 – "Tent" diagram for the 21 tooth pinion

CASE STUDY N° 2: SPECIFYING GREATER RATED SPEED ON A GEARLESS MILL DRIVE

The inherent variable speed nature of a Gearless Mill Drive provides flexibility in operation for the operator, but does not release the designing process engineer from considering a single speed for optimum mill performance. The specification of the speed at which both the power and torque are their maximum values should be made to seek out the maximum possible power and minimum possible torque considering the likely mill operating conditions (filling, liner wear and ball charge).

Dunne et al. (2001) state the initial design of the Cadia Gearless Mill Drive called for 20 MW at a 9.02 RPM rated speed. The tent diagram assuming volumetric loadings of 13% balls and 25% total is given in Figure 7 and it demonstrates that the motor can go up to 85% of critical speed without encountering any motor limitation.
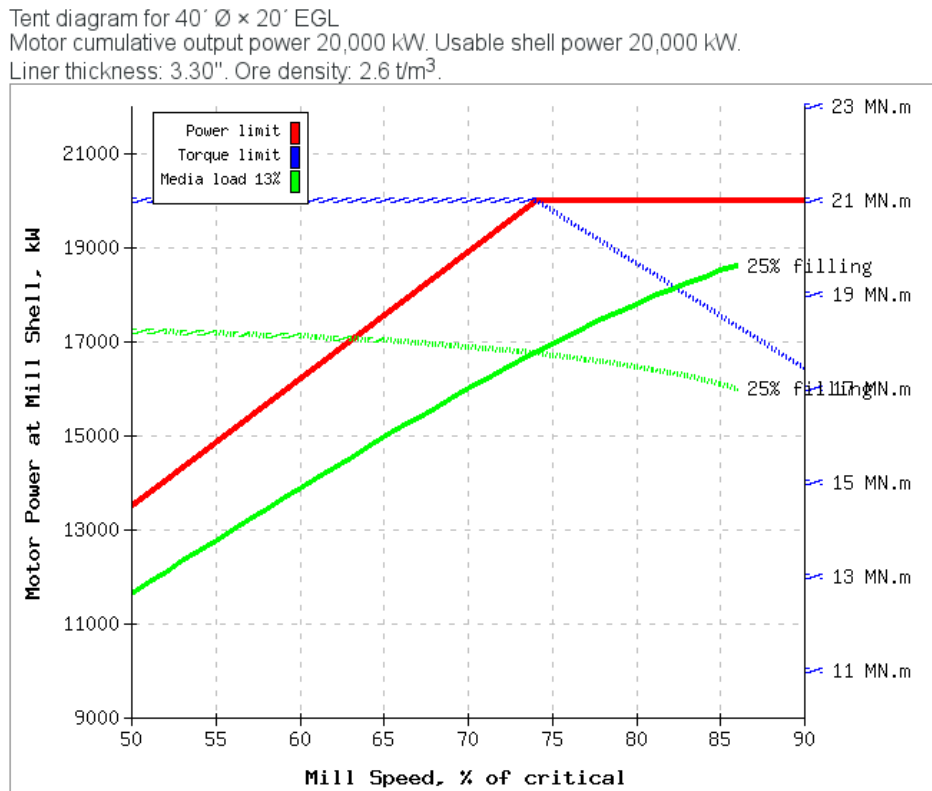

Figure 7 – Tent diagram for Cadia, normal operation

Suppose that the mill operator wanted to increase the power draw to 19.25 MW (96.3% of available power). This can be accomplished by a combination of increasing the ball charge and/or increasing the motor speed. Increasing the ball charge (to 18% vol.) at 9.02 RPM results in the process curves on the tent diagram shifting "upwards" as shown in Figure 8. The motor now shows a limit at 78% of critical speed where simultaneously the solid green line intercepts the red line and dotted green line intercepts the dotted blue line.
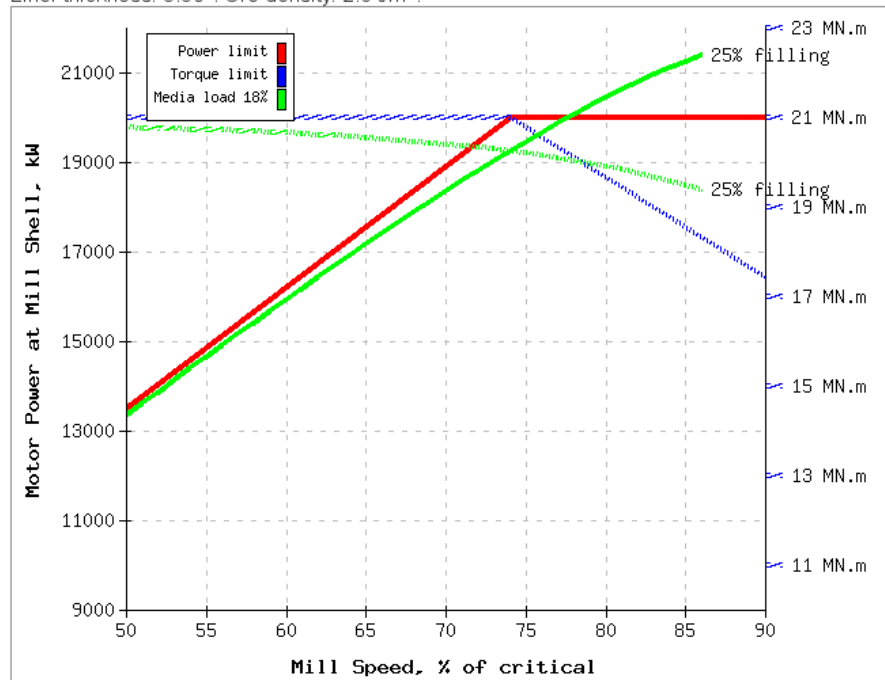
Figure 8 – Tent diagram for Cadia, operating with a higher ball charge

Table 2 – Operating conditions for Cadia SAG mill at 9.02 RPM rated speed, 25% vol filling

		Rated	13% vol balls	18% vol balls
Power, motor output	kW	20,000	16,750	19,250
Torque, motor output	kN·m	21,174	17,740	20,380

Consider if a different rated design speed had been selected for Cadia, 9.6 RPM instead of 9.02 RPM. This change would have the effect of shifting the "knee point" to the right on the tent diagram and lowering the overall motor torque, as shown on Figure 9. Operating at this higher speed means the same power draws observed at 18% vol. ball loading in Table 2 can be achieved at a much lower ball charge (16.25% vol.), as shown in Table 3.

Table 3 – Operating conditions for Cadia SAG mill at 9.6 RPM rated speed, 25% vol filling

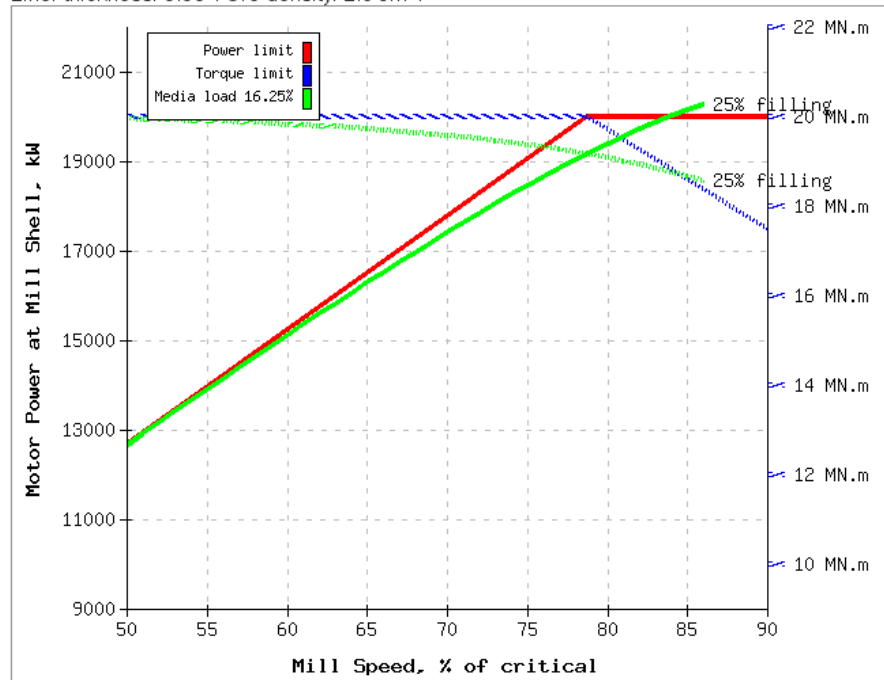|		Rated	13% vol balls	16.25% vol balls
Power, motor output	kW	20,000	17,600	19,300
Torque, motor output	kN·m	19,894	17,500	19,200

Figure 9 – Tent diagram for alternative Cadia design at 9.6 RPM

The higher mill speed can provide the same increase in power draw as Table 2, but at a lower ball charge of 16.25% vol. and a lower torque (therefore, lower capital cost). To make this higher speed a maintenance-friendly way to take advantage of a lower ball charge does require the lifters are correctly re-designed for the higher speed (eg. DEM modelling).

This reduction in ball charge will result in lower annual ball consumption and, as a result, lower operating costs. According to the linear wear equations presented by Morrow & Sepulveda (2015), the reduction in wear due to abrasion and corrosion (which is more than half of the total media wear in SAG milling) is simply equal to the change of ball volume within the mill (18% to 16.25%). The higher speed suggests a 10% reduction in ball wear per tonne of ore processed.

CONCLUSIONS

Process engineers should specify mill motors using the form "*X* kW motor output power at a mill rated speed of *Y* RPM". Avoid giving rated speed in units of *percent of critical* because that is a meaningless quantity for motor manufacturers.

Specifying a faster rated mill speed results in lower motor rated torque and a lower capital cost.

Operating at higher speeds, for a given process power demand, permits a lower ball charge than is possible at lower mill speeds. Achieving the same power draw with a lower ball charge means that operating cost savings are possible (due to the lower ball charge) with higher speed designs.

NOMENCLATURE

D mill diameter inside the liner, m

d mill liner nominal thickness, m

J_{balls} ball filling level, as a fraction of the total mill volume (e.g. 0.10 for 10%)

J_{total} total filling inside a mill, as a fraction of the total mill volume (e.g. 0.30 for 30%)

L mill effective grinding length, m

P motor output power measured at the output shaft (pinion) or mill shell (gearless), W

P_{shell} power measured at mill shell (both pinion and gearless drives), W

P_{rated} motor output power at the knee point (motor operating at rated speed), W

T motor output torque measured at the output shaft (pinion) or mill shell (gearless), N·m

T_{rated} motor output torque at the knee point (motor operating at rated speed), N·m

ω motor operating speed, 1/sec

ω_{rated} motor rated speed, 1/sec

ϕ_C mill speed, as a fraction of the mill critical speed (e.g. 0.75 for 75%)

ϕ_{RPM} mill speed, revolutions per minute

REFERENCES

Amelunxen, P., Berrios, P., and Rodriguez, E. (2014). The SAG grindability index text. *Minerals Engineering* (*volume 55,* 42–51) doi: 10.1016/j.mineng.2013.08.012

Austin, L. G. (1990). A mill power equation for SAG mills. *Minerals & Metallurgical Processing*; *AIME transactions Vol. 288,* 57-63.

Barratt, D. J., & Brodie, M. N. (2001). The "Tent" Diagram, What It Means. In D. J. Barratt, M. J. Allan & A. L. Mular (Eds.), *International Autogenous and Semiautogenous Grinding Technology 2001* (pp. IV368–IV-379). Vancouver, Canada.

Doll, A.G. (2013). A comparison of SAG mill power models. *Proceedings of the Procemin 2013 conference* (paper 44). Santiago, Chile.

Doll, A.G. (2012), *Technical Memorandum; Mill Motor Power Definitions* Rev. 5, dated January 12, 2012. Retrieved from https://www.sagmilling.com/articles/1/view/?s=1

Dunne, R., Morrell, S., Lane, G., Valery, W. & Hart, S. (2001). Design of the 40 Foot Diameter SAG Mill Installed at the Cadia Gold Copper Mine. In D. J. Barratt, M. J. Allan & A. L. Mular (Eds.), *International Autogenous and Semiautogenous Grinding Technology 2001* (pp. I-43–I-58). Vancouver, Canada.

Morrow, R. & Sepulveda, J.E. (2015). A mathematical model for the prediction of large diameter ball consumption rates in semi-autogenous grinding applications. *Proceedings of the 47th Annual Canadian Mineral Processors (CMP 2015)* (pp. 286–295). Ottawa, Canada.