CONGA: THE WORLD'S FIRST 42 FOOT DIAMETER 28 MW GEARLESS SAG MILL

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ABSTRACT

In 2010 Newmont made the decision to purchase a 42 foot (ft) Semi-Autogenous Grinding (SAG) mill from Metso and a 28 Mega-Watt (MW) Gearless Mill Drive (GMD) from ABB for the Conga Project in Peru. The test and study work showed that a single line 42 ft SAG mill circuit gave the most favorable project economics in comparison to an equivalently powered single line 40 ft SAG mill circuit. This paper does not address the process design or the project economics, but instead focuses on the key aspects of the SAG mill design, GMD design and the associated component manufacturing. This paper also addresses, where applicable, the potential reliability differences between the initially proposed 40 ft SAG mill and the finally accepted 42 ft SAG mill.

KEYWORDS

SAG mill, 40 ft, 42 ft, gearless mill drive, GMD, SAG manufacture, reliability

THE PROJECT

The Conga Project is located in Peru adjacent to Newmont's existing Yanacocha operations. The Conga Project has been in various development stages for approximately the last 15 years. In the last 5 years, test and study works were performed to determine the optimal mill circuit configuration and mill sizes. The results of these studies showed that a single line 40 ft SAG mill circuit gave the best project economics. Further work was followed up to optimize the 40 ft SAG mill size with the results showing that a slightly more expensive 42 ft SAG mill with equivalent power to the 40 ft SAG mill enhanced the project economics. After assessing the potential reliability difference between the 40 ft SAG mill and the equivalently powered 42 ft SAG mill, Newmont made the decision in 2010 to purchase a 42 ft SAG mill from Metso and a 28 MW GMD from ABB.

THE MILL

Needless to say "reliability" is a key word at every stage of the project. Although mill structure failures have not occurred in large GMD SAG mills, the mill design was not exempt from a reliability survey. This survey, or assessment was carried out by Metso partly in conjunction with Newmont, and included the following phases:

* A survey of engineering company mill specifications, looking mainly for obsolete areas;
* A survey of manufacturing facilities currently involved in 40 ft mills; and
* An overall survey of the design of the major mill rotating components.

A summary of the survey results is provided below.

Mill Specification Survey

In an overview of 7 engineering company specification documents, over a variety of projects over the last 2.5 years, all specifications were found to be essentially "dead documents", with any engineering personnel interested in serious updating of the technology descriptions having long since retired. Some of the obsolete items found are listed below:

i. "Do not use any process not previously used on mills". Considering this statement is from 1980, no new fabrication (welding, etc.) technology has been allowed for 31 years. One may wonder how the stainless clad mills were ever built under this specification statement.

ii. "Use only the single wire welding processes". This statement comes from 1983. Tandem wire procedures have long since been perfected, and save both time and money in mill fabrication. They have been used on mills since 1990.

iii. The fracture initiation (ΔK_{TH}) values, where given, come from 1986, and are drawn from an old document (Speidel 1981) for a different class of iron, and inappropriate r (tension to compression) ratio. Since then, both design companies, and foundries, have done testing (specified by ASTM) to obtain more appropriate values, matching the iron classes.

iv. "Map all dross", more recently co-opted to "no dross". The wording for this arises from 1987, when larger SGI castings started to be made, and were substituted for grey iron. The wording came from experiences with the Kennecott 34 ft SAG mills, where large dross areas were encountered on the head internal conical surfaces, for which <u>no machining</u> had been planned. Since this was a relatively new flaw (to mining) in 1987, the specifications were re-written to plan for stock allowances to remove dross in machining, and map what might remain. It is useful to note that the Kennecott 34 ft mills (and a number of other large mills with unmachined cones) continue to run today, after 24 years, justifying the reasoning to accept those castings "as is". Since that time, much testing has been done on dross, at the foundries, and at Metso, so that this flaw is now well understood.

v. Inappropriate use of BS7608 (1993) fatigue limits combined with "peak stress" terminology. BS7608 explicitly states, on p. 30, "Hence the hot spot stress is considerably lower than the peak stress, but provides a consistent definition of stress range for application with the design S-N curves." This is most often misused in reference to ground weld surfaces. BS7608 is a code for the design of various welded <u>structures</u>, not mills. In being an empirical code drawn from testing, it does not analyze individual weld ripples and crevices, but rather includes them in the test data by using as-welded specimen which satisfies visual criteria. The code considers diversity in these geometries by using statistical S-N curves. As such, the code idea of grinding weld surfaces requires no defined shapes or a minimum radius, etc., and thus provides only a small (in stress terms) improvement to the hot spot allowable stress. For further explanation, refer to Figures 1 and 2. If the smoothly ground weld in Figure 1 has just one small shallow area, where, due to the grinder slippage, there is a slight 12mm radius depression, the peak stress here could more than double. This is NOT what the code considers in ground welded structures. The local peak stress here is analogous to the local dimple stresses not considered in as welded conditions. The basic definition of "hot spot stress" holds for ground welds also.

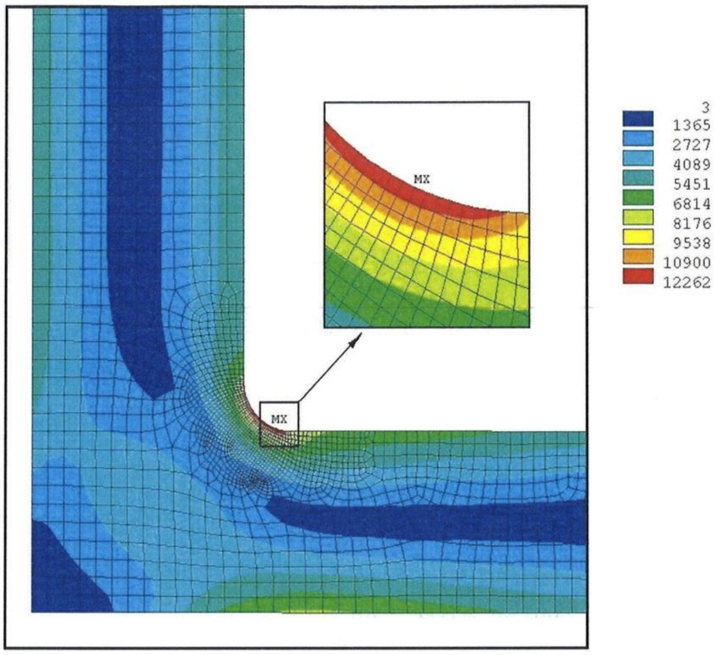


Figure 1 – FEA of ground weld

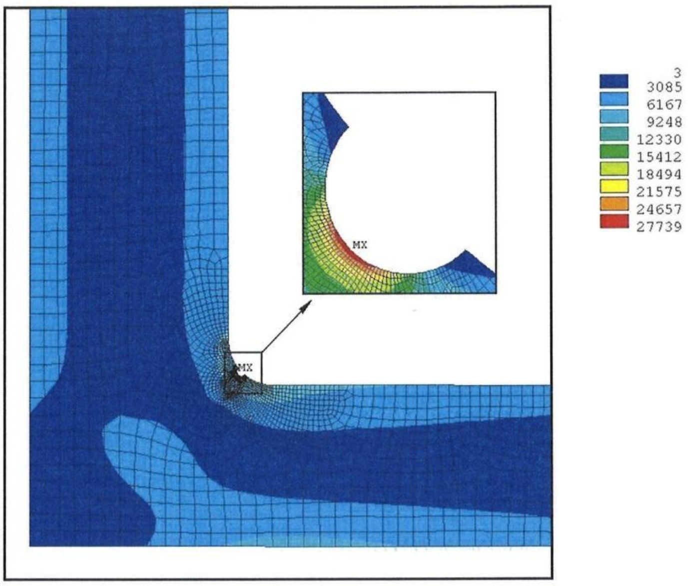


Figure 2 – FEA of ground weld with overgrind

vi. "Design…shall include a ball charge of a least 3%...greater than the maximum operating (sic) ball charge…, but not less than 18% of the total volume." This states that AG mills are designed at 18% ball safety, mills operating at maximum 12% balls get 6% ball safety, while operations at maximum 18% get 3% ball safety. The original statement was that all mills should be designed at 3% ball safety over their maximum operating load.

Some of the obsolescences listed above overlap into the choice of consultants. There are almost no consultants in the mill industry that actively pursue 'hands on' research in the materials and flaw sensitivity areas. Yet the original formulations were developed in the 80's. Since then, a large amount of research has been performed in these areas, as they apply to mill constructions. This new state of the art has to be considered. Churchill once stated:

> "However beautiful the strategy, you should occasionally look at the results."

This may be paraphrased for mill analysis:

> "If your theory tells you all the 20+ year old successfully operating mills failed 10 months after start up, you need a new consultant."

Manufacturing Facilities Survey

In direct contrast to the unchanging areas of mill specifications, the survey of manufacturing facilities found some interesting items which might be related to a change (relaxation) of surveillance. In the days of the first gearless mills of the '80s, and thru the first 40 ft mills, extensive fabrication kick-off meetings were held, where all processes were discussed. Perhaps because this has become familiar, such is no longer the norm. Because of this, and the retirement of experienced personnel, some interesting fabrication changes were discovered.

i. At one European foundry, head machining is subcontracted. In a review of these capabilities, a change in the machining procedure was discovered. Whereas the usual head machining is accomplished in one set-up, without moving the piece, in this case two machining set-ups were being used. Where previously this required picking up the assembled, partly-machined head, and turning it over as a unit, in this case, 40 ft heads were being completely disassembled, and turned over segment by segment, and then being reassembled. No written procedure of how the original machining cut inter-relationships were to be reestablished, before commencing further cutting in the new assembly, were produced. Therefore, this machining method was not accepted by Newmont and Metso for the Conga 42 ft mill. One of the authors (VS) had experience with this kind of reassembly, for <u>measuring purposes only</u>, and established tolerances in one position were not being duplicated in the reassembly, after days of effort. In light of specification item (i), it is interesting that this change was missed by inspectors.

ii. The lack of capability audits seems to originate with company buyers. The possibility of 20% + price reductions seems to overcome all quality and design audit requirements, even for large mills. This has allowed such undesirable fabrication practices to enter the industry as pictured in Figures 3 – 5. Figure 3 shows uncontrolled heat correction for a large shell. Figure 4 shows "vibratory stress relief" being applied to a large shell. If this method is to work, room temperature material yield stress must be exceeded for a large number of cycles, which reduces the shell operating fatigue life by the same amount. Figure 5 shows significant weld overlay being added to critical steel head flanges, to make up for errors in estimating casting shrinkages. This is compounded by the fact that specifications have not incorporated the detailed changes required to evaluate the flaw sensitivity of Chinese steel castings. The experiences gained with ductile irons cannot be directly applied to these new materials.

Figure 3 – Uncontrolled heat straightening

Figure 4 – Vibration “stress relief”

Figure 5 – Weld overlay on flanges

This cost pressure has triggered a cost cutting competition also in western mills, which has resulted in both fabrication and design changes. In the latter area, previous increases in allowable stresses were only pursued after detailed field experience. Currently, they are being pushed into larger mills with much less study, as illustrated in the examples below:

Table 1 - Changing design stress

SAG Internal Weld Design

Mill	Size	Design Stress	Age of Operation
Los Bronces	10.36m	58.5 MPa	23 years
Bata Hijau (sea water)	10.97m	48.2 MPa	14 years
Esperanza (sea water)	12.2m	69 MPa	6 months
Conga	12.8m	53 MPa	-

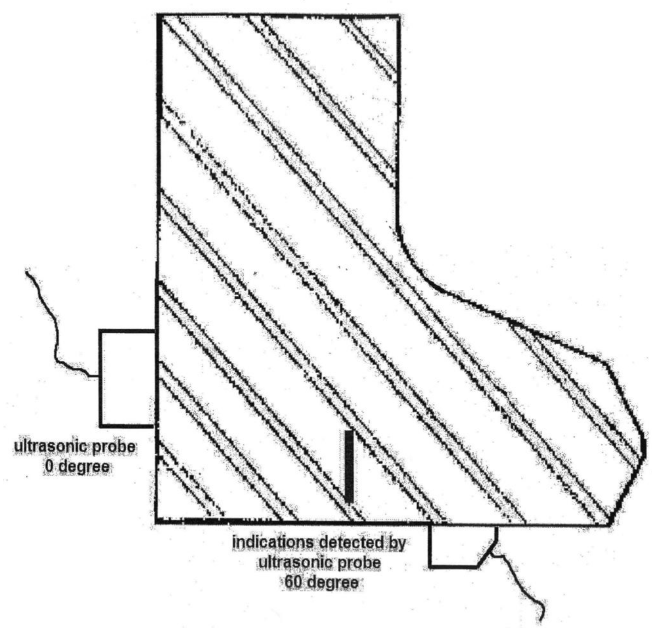
Ball Mill External Weld Design

Cadia	6.7m	37.8 MPa	14 years
Conga	7.26m	38 MPa *	-
Toromocho	7.82m	51.4 MPa *	-

* Strain gage correlation has been applied

For the Conga mill design, experience defined stresses were used.

iii. The last several years have <u>reintroduced</u> plate welding problems. Previous plate ordering specifications were no longer working to eliminate lamination and void problems. This comes about from greatly increased use of the continuous casting process in the steel industry. This process generally produces cheaper plate, but with poorer characteristics at greater thicknesses. This is complicated by the fact that individual steel makers use different thicknesses to separate the slab (continuous casting) from ingot making methods. For example, for Arcelor Mittal (North America) this boundary thickness is about 112 mm, whereas Dillinger may use continuous casting methods up to 160 mm thickness. This is further complicated in that the reduction ratio for some of these slab processes may be significantly lower than 3. Thus, for the Conga mill, the fabricators were warned of these possibilities, and requested to have discussions with their plate suppliers. One of the problems that can arise from this omission is shown in Figure 6. The figure shows part of a contour flange, which passed all straight beam ultrasonic tests, but where center-line plate defects were discovered by angle beam inspection of adjacent welds. Since this cannot be eliminated by standard ultrasonic inspections accepted by steel mills, it must be eliminated by a change in ordering specifications.



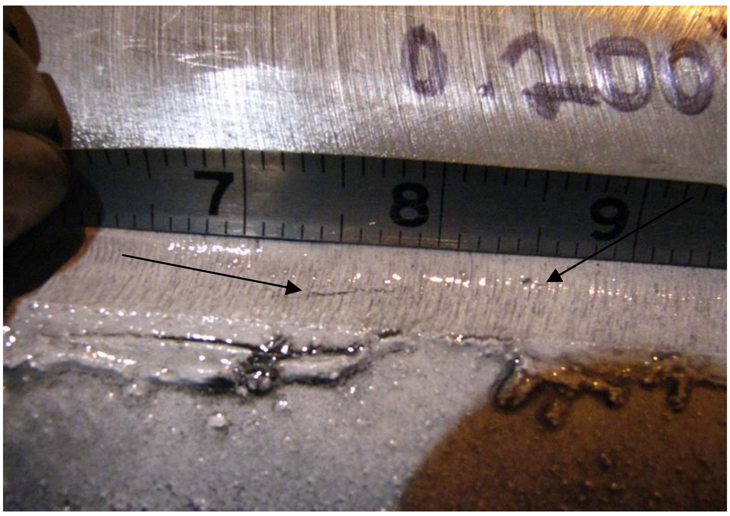


Figure 6 – Flaw location in contour flange

Major Mill Rotating Component Design Survey

The key driver with this survey was to design the 42 ft SAG mill heads and shells for maximum reliability by using the existing proven 40 ft SAG mill design concepts. In performing the Conga detailed design, several questions were asked:

1. How can we keep to the known design art as much as possible, minimizing "prototyping"?

2. Are there any recent design developments to be considered?

In answering the first question, the mill components were rated as to risk: large castings were rated as higher risk than shell fabrication, and so forth. The challenge was then to make the components have no greater risk than a 12.2m (40 ft) mill. This was accomplished in the following way:

- The 12.8m (42 ft) mill head castings were designed to be of no more weight than 12.2m (40 ft) heads, and of no larger diameter;
- The shell fabrication, while 0.6m (2 ft) larger in diameter, used plates of similar thickness as found on 12.2m (40 ft) shells; and
- The contour flange was designed deeper, but only of slightly thicker plate.

In this way, the mill construction "prototyping" was limited to manufacturing the shell at the 12.8m (42 ft) diameter. The machining of the components was accomplished on the same machines as for 12.2m (40 ft), and purchasing of parts was not affected, except to the level of control of plate purchasing that was noted earlier.

In answering the second question, a survey of design details was done. Two interesting items were uncovered:

(i) Segmentation of larger ball mills had produced a stress concentration point, associated with welding, as shown on Figure 7. While this point had been modeled (finite elements), an instrumentation program for validation had not been done. This was performed on two mills during 2010. The strain gauges verified the existence of a significant stress multiplier at the noted point. The strain gauging program also verified a known fact, that the standard FEA model produced very conservative results in this area. However, combining both results still showed that the noted stress concentration point could not be ignored. Therefore, design variables were adjusted for mills of this segmentation.

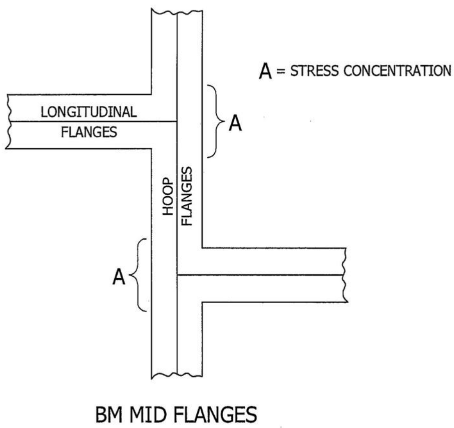


Figure 7 – Stress concentration point

(ii) In the general information search, a new proposal to the ASME code was uncovered. In piping welds, tests had shown that reinforcing weld fillet overall profiles could have significant fatigue life effects. It was shown that if the leg along the pipe is 2x that of the flange leg, the fatigue life could improve significantly (up to 37%). Some consideration of this was being proposed for the ASME code. Conveniently, Metso standard welding on large mill flanges had always utilized such leg dimension bias, and thus extra safety was verified for standard methods. For the mill, being a "large pipe", items (i) and (ii) become inter-related. Since item (ii) indicated extra conservancy (but in the early stages of study), no numerical advantage of this was incorporated into the present designs.

THE GEARLESS MILL DRIVE

The gearless motor (also called wrap-around motor or ring motor) is a very large synchronous motor. The poles of the motor are directly installed on a pole flange on the mill shell; this means the mill body becomes the rotor. The stator of the gearless motor is then wrapped around the mill. Figure 8 shows a picture of the 16.5 MW ABB gearless motor installed on the 32 ft diameter Metso SAG mill at Newmont's Yanacocha mine in Peru.

Figure 8 – Yanacocha gearless motor

The gearless motor is fed by a cyclo converter, which is an extremely compact and efficient drive system, opening the door for several advantages such as variable speed and frozen charge protection. With this innovative concept, the gearless mill drive (GMD) eliminates all critical mechanical components inherent within a conventional mill drive system, such as ring gear, pinion, gearbox, coupling or air clutch, motor shaft and motor bearings. Eliminating such components increases the efficiency and the availability of the mill.

Brief History of Gearless Mill Drives

The world's very first GMD was a 6.4 MW GMD delivered by ABB (BBC, before the merger with Asea) for a cement mill. This GMD started operation in 1969 and is still in operation today after more than 40 years. In the 1980s, the GMD was introduced to the mining industry as a reliable drive system for SAG mills. Early SAG mills had a diameter of approximately 32 ft, later increasing to 34 ft, 36 ft, 38 ft and 40 ft and were quite reliable. In the last decade some issues occurred with the larger GMDs which resulted in unscheduled downtimes. Subsequently, improved design and operational practices have been implemented in the last several years. Despite these issues many large mills have been ordered with some already commissioned and in operation. Currently, the largest GMDs in operation are the two 22.5 MW GMDs for the two 38 ft diameter x 45 ft length AG mills at Boliden's Aitik copper concentrator above the Arctic Circle in north Sweden and the 22.4 MW GMD for the 40 ft SAG mill of Esperanza in Chile. Besides these large GMDs in operation, ABB last year delivered a 28 MW GMD for the 40 ft SAG mill on the Toromocho Project in Peru, which will be installed next year at an elevation of 4,600 meters above sea level (masl) or over 15,000 ft. Not only ABB, but also another GMD supplier has delivered a 28 MW GMD for a 40 ft mill for an iron ore project in Australia. There is not only a clear trend in the global grinding industry for large diameter mills with high power GMDs, but also for mills requiring GMDs with high power density. The GMD power density, as defined in this paper, is a qualitative measure calculated by taking the mill rated power [MW] and dividing by the mill diameter [ft]:

$$\text{GMD power density} = \frac{\text{mill rated power } [\text{MW}]}{\text{mill diameter } [\text{ft}]}$$

Figure 9 shows that the power density of the GMDs has continuously been increasing during the past 15 years for both the SAG and ball mills.

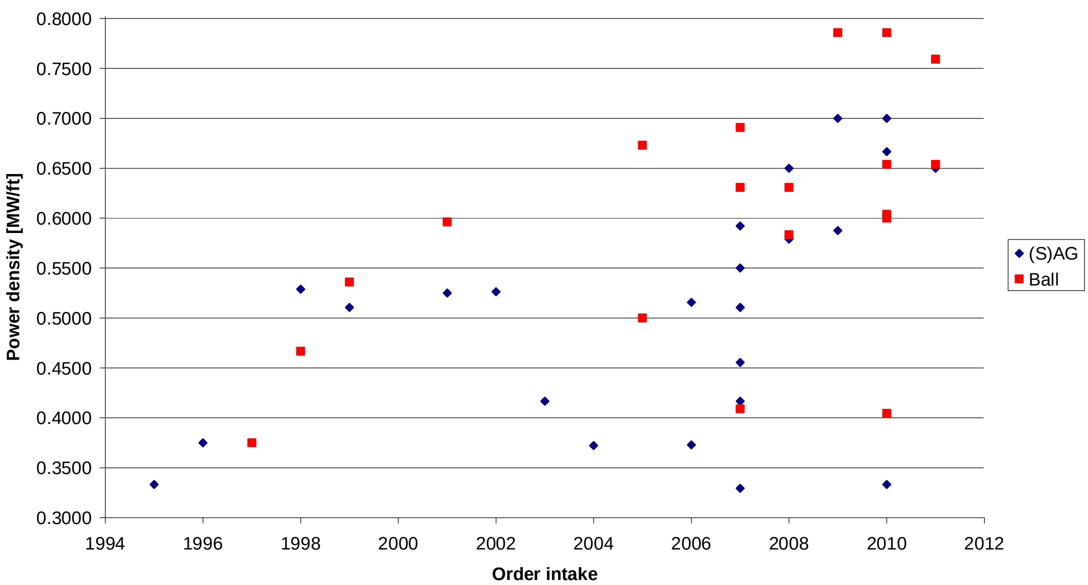


Figure 9 – Power density of ABB GMDs in the mining industry

There are several reasons for this trend of increasing power density values. For example, mills are getting longer and ball charges are getting higher. Most likely this is also driven by the fact that the ore bodies today are having lower ore grades and the need to maximize production rates. The trend of larger mills with higher power requirements and higher power density values naturally impacts the GMD design.

The GMD for the Conga Project

Since the step was made to go from 38 ft to 40 ft mills, the mining industry took more than a decade to go to 42 ft mills. The Conga SAG mill drive requirements are as follows:

- Diameter: 42 ft
- Rated power: 28 MW
- Rated speed: 8.86 rpm (74% critical speed)
- Maximum speed: 10.0 rpm
- Rated torque: 30,178 kNm
- Starting torque: 150%

The power density of the Conga 28 MW GMD is 0.67. Figure 9 shows that this power density is not the largest value or an industry first. In addition, the Conga concentrator will be located at a relatively high elevation of 4,100 masl, but again not the highest elevation or an industry first. All these important parameters (the 42 ft diameter, the 28 MW rated power, the power density, and the site elevation) have certain impacts on the GMD design and overall reliability.

<u>42 ft Diameter</u>

As already mentioned, some relatively large GMDs had problems for various reasons. The main goals for this first 42 ft diameter GMD are that no known past issues will resurface again and to design where the potential for new issues are eliminated. The starting design reference is based upon the 28 MW GMD for the Toromocho 40 ft SAG mill for which several design review have been performed.

It has to be noted that with increasing diameter, the first possible resonance frequency (4-node bending mode) is decreasing if no counter measures are taken. The correct design philosophy is obviously to stay below the first possible resonance frequency, especially considering the fact that the stator structure has a height of more than 20 meters. In order to define the resonance frequencies, a finite element model of the stator is created. The risk is the finite element model is for some reason not reflecting reality and consequently the calculated resonance frequencies could be wrong. In the last decade, the finite element model has been verified with a tapping test in the workshop on almost all GMDs delivered by ABB. On some occasions the tapping test has even been performed on site. On the 28 MW GMD for the 40 ft SAG mill for Toromocho, the finite element model was verified with a tapping test in the factory. On some GMDs site strain gauge measurements have been performed also to verify the model. Tapping tests in the factory and field will be performed on the Conga GMD along with site strain gauge testing. ABB has also performed the overall system study on several projects. This study analyzes the overall stiffness and resonance components of the soil, foundations, mill bearings, mill, rotor, magnetic pull between stator and rotor, and the stator. ABB will perform the system study on the Conga SAG mill. A 3rd party system study will also be performed to verify ABB's system study. The past experiences with the tapping tests, strain gauge tests, and overall system studies have been incorporated into the design considerations of the Conga SAG mill GMD.

<u>28 MW Rated Power</u>

Before the Conga Project, ABB received two other orders for a 28 MW GMD, but with a smaller mill diameter of 40 ft: Toromocho in Peru and Boszhakol in Kazakhstan, which both have been manufactured and delivered. So the Conga GMD has exactly the same power rating as for the Toromocho and Boszhakol Project. Naturally this high power requirement has several impacts on the design. The standard ABB GMD design is typically realized with a 12-pulse cyclo converter, but this is only available up to approximately 26 MW rated power. In order to reach more than 26 MW, either the stator voltage or the stator current (or both) have to be increased. Several years ago, ABB performed the basic design for high power GMDs up to 36 MW. ABB decided then to stay with the same proven electrical concept of the gearless motor. In order to reach the 28 MW, only an extra leg with thyristors had to be added resulting in an 18-pulse drive system as shown in Figure 10.

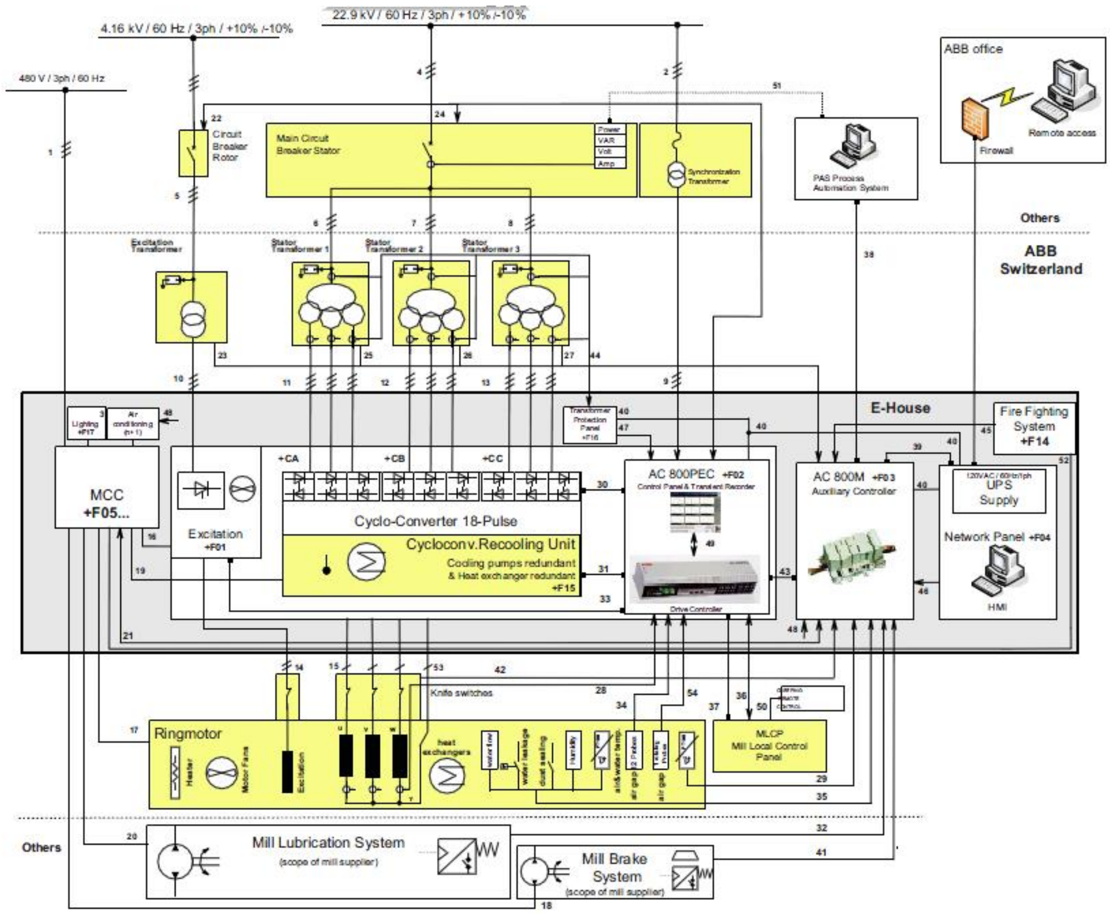


Figure 10 – Block diagram of the 18-pulse GMD

The advantages are as follows: available true motor differential protection, relatively simple winding design, minimized number of thyristors, just one cyclo converter instead of two cyclo converters which would require a kind of load sharing and reduced total harmonic distortion. Although the Conga 28 MW drive system is large, the basic design concept is proven and is being used on other projects.

Power Density

The 42 ft diameter Conga SAG mill GMD power density value of 0.67 is not an industry first or a new record. The 40 ft diameter Toromocho SAG mill GMD has a higher power density value of 0.70 at the same rated power of 28 MW. The 22 MW GMD for the 28 ft diameter Toromocho ball mill has an even higher power density value of 0.79. The power density has quite an impact on the design. More power means more active material in the motor. This means the motor size must increase, but unlike conventional electric motors the motor cannot be increased in radial direction ("increasing shaft height"). Basically, the gearless motor can only increase in the axial direction. In other words, a higher power density value results into a wider motor (in axial direction). For the stator this means that both the stator windings (due to the iron length) and the magnetic core lamination package are longer. For the rotor this means the pole units are getting longer. The poles will be single pole units without critical welding where every single pole can be adjusted slightly in order to have a perfect run out. The nominal air gap around the circumference is about 17 mm and an imperfect run out could lead to undesirable oscillating mill bearing pressures.

A wider motor can also have consequences on the mill design, especially on the last row of liner bolts as access to these bolts must still be ensured in order to be able to replace the liners. This challenge is visualized in Figure 11 below and requires close cooperation during the design phase between the mill supplier and the GMD supplier. Often the last row of liner bolts are mounted under a certain angle.

Figure 11– Challenge to access the last row of liner bolts

In addition to the challenge of removing the last row of liner bolts, a wider motor also challenges the conventional cooling design concept of the gearless motor. Typically the gearless motor has an internal axial cooling system where the cooling air flows in axial direction through the lamination package. This means there are certain limitations to the maximal length of the lamination package because otherwise the cold air to cool the motor will already have become too warm before it reaches the other side. Therefore a radial cooling concept is used for all the gearless motors with a high power density value: in this case the cooling air flows in radial direction through the lamination package. Exactly the same cooling concept is used on other large synchronous machines such as low speed diesel generators and hydro generators. It has to be noted that apart from this modification from axial to radial cooling, the cooling principle of the GMD has not changed. The cooling boxes with the water-to-air heat exchangers are still located at the bottom below the stator windings which means there is no cooling water at all around the circumference. If a leak occurs water cannot reach the stator windings and cause a serious problem. The Conga GMD will use the proven radial cooling design concept.

<u>Site Elevation</u>

The Conga mine site is located at an elevation of 4,100 masl, and this naturally places additional demands on the design. The high altitude has an impact on the efficiency of the cooling air. Furthermore, if not handled correctly, the high altitude could have an accelerated ageing effect on the electrical insulation. All these important parameters have been considered in the Conga GMD design. In addition, the extensive experiences gained with GMDs at altitudes over 4,000 masl have also been used in the design. The 28 MW GMD for the 40 ft SAG mill of the Toromocho Project has been delivered and will be installed at an even higher altitude of 4,600 masl (over 15,000 ft) in the Peruvian Andes. Approximately two years ago, several high altitude insulation tests of a stator part complete with windings were conducted in Switzerland in a hypobaric chamber, simulating conditions found at 5,000 masl. These tests were also witnessed by several customers. The test setup is shown in Figure 12. All tests were satisfactory passed.

Figure 12 – Insulation tests in hypobaric chamber simulated at 5,000 masl

CONCLUSIONS

Newmont, Metso and ABB have given special attention to the important fact that the Conga SAG mill will be the first 42 ft diameter SAG mill in the world. Reliability assessments were done concerning mill specifications, manufacturing facilities, critical component designs, and power limitations. The assessments bare out that the Conga SAG mill will be an industry first in diameter, but not necessarily an industry first in rated power, overall design, and component manufacturing. The mill and GMD are scheduled to be delivered in the middle of 2012 and go into operation in late 2014, early 2015. The successful operation of the world's first 42 ft SAG mill will be the culmination of a continuing tradition in the mining industry of building larger equipment to enhance project economics.

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