Medium Voltage Drive Application at U. S. Steel Lorain Tubular Operations, No. 3 Seamless Mill

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In 2006, the No. 3 seamless tube mill at U. S. Steel Lorain upgraded the constant speed synchronous motor powering the High Mill. This paper reviews details of the application process required for the mill upgrade, particularly the differing torque responses.

In 2006, a project was developed to address the reliability of the main drive motor for the High Mill in the No. 3 seamless mill at United States Steel Corporation (U. S. Steel) Lorain Tubular Operations (LTO), Lorain, Ohio. LTO is a unit of U. S. Steel's Tubular Products Division. The project included replacement of the existing 2,000-hp, 64.3-RPM synchronous motor with an appropriately sized 6-pole induction motor and variable speed medium voltage drive system. This equipment was commissioned in October 2007.

Process Overview

U. S. Steel Lorain Tubular Operations' No. 3 seamless mill produces finished pipe with outside diameters (ODs) in the range of 10.625–24 inches and wall thicknesses in the range of 2.25 inches down to 0.330 inch, depending on OD. Commissioned in 1930, the mill produces oil country casing, coupling stock and tube hollows, along with standard and line pipe. Figure 1 illustrates the product flow through the hot end of No. 3 seamless mill.

As shown in Figure 1, the High Mill (or plug rolling mill) is the third step in the hot rolling process. Depending on the finished OD, round billets with one of three discrete diameters (10.5, 12.25 or 13.5 inches) — ranging in length from 6 feet, 6 inches to 16 feet, 4 inches and weighing between 1,800 and 7,766 pounds — are heated in the rotary hearth furnace to a discharge temperature range of 2,200–2,300°F. The first piercer produces a pierced shell from a round billet. The second piercer further elongates the shell, increases the OD and reduces the wall thickness. The two piercers are similar in design and are single-pass cross-rolling processes, meaning the shell is rotated as it is formed over the mandrel.

The High Mill is a two-pass, single-direction, transverse-rolling process. The purpose of the High Mill is to produce the proper shell length through wall reduction. This is accomplished by rolling the shell over a machined plug located between two machined semicircular work rolls, positioned one above the other. Two passes are generally required, with the shell being rotated 90° between passes in order to roll out the first pass overfill. Approximately 60% of the wall reduction is taken on the first pass, with the remaining 40% taken on the second pass. Typical rolling temperature ranges are 1,880–2,000°F.

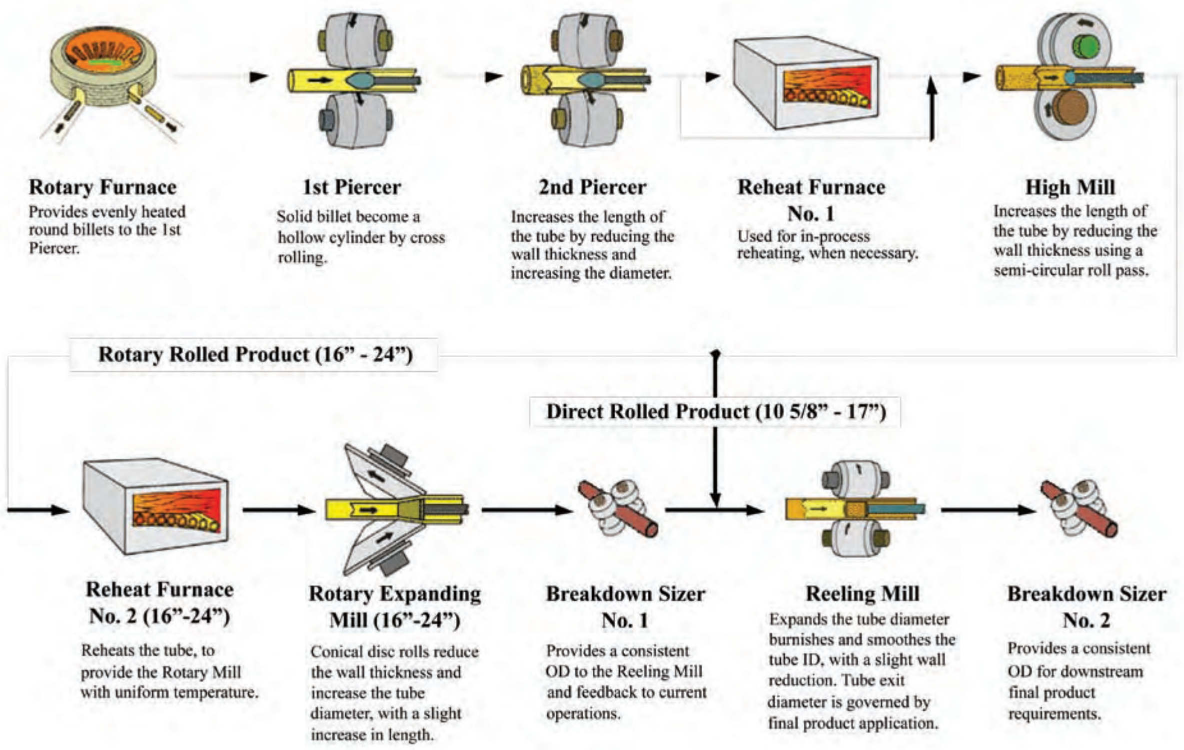
Because of the non-reversing nature of the mill, and the two-pass requirement to remove the first-pass overfill, a means is provided to return the shell to the entry side of the mill. This is done by a DC motor-driven stripper roll running counter to the work rolls. After the shell has completed the first pass, the work rolls open, the plug is discharged, and the bottom stripper roll raises and reverses the shell. Figures 2 and 3 illustrate the High Mill geometry and roll pass design, respectively.

Prior to 2003, the work roll gap was set utilizing electromechanical screws combined with an air-cylinder-engaged wedge arrangement. Also prior to 2003, the plugs were manually inserted. Two projects were completed in 2003: one replaced the gap adjust system with hydraulic cylinders, and the second provided an automatic plug

Authors

Michael A. DeCarli (left), TM GE Automation Systems LLC, Salem, Va. (michael.decarli@tmeic-ge.com), and **Richard M. Baker** (right), East Region Engineering, United States Steel Corporation, Mon Valley Works – Irvin Plant, Dravosburg, Pa. (rmbaker@uss.com)

Figure 1

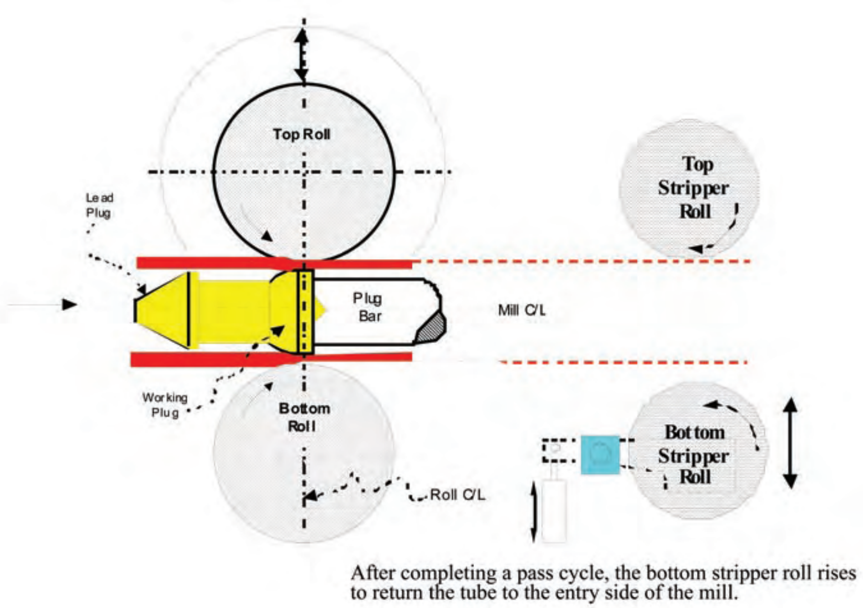


Product flow through breakdown sizer No. 2. Source: U. S. Steel Tubular Technology Course, 2007.

changer. Figure 4 illustrates the plug changer cycle.

The hydraulic capsule and control system (Figure 5) provided increased accuracy for setting the work roll gap, provided quick open and return capability, and enabled implementation of a time-based "taper control" feature to adjust the roll gap in order to compensate for end-to-end shell temperature variation.

Figure 2



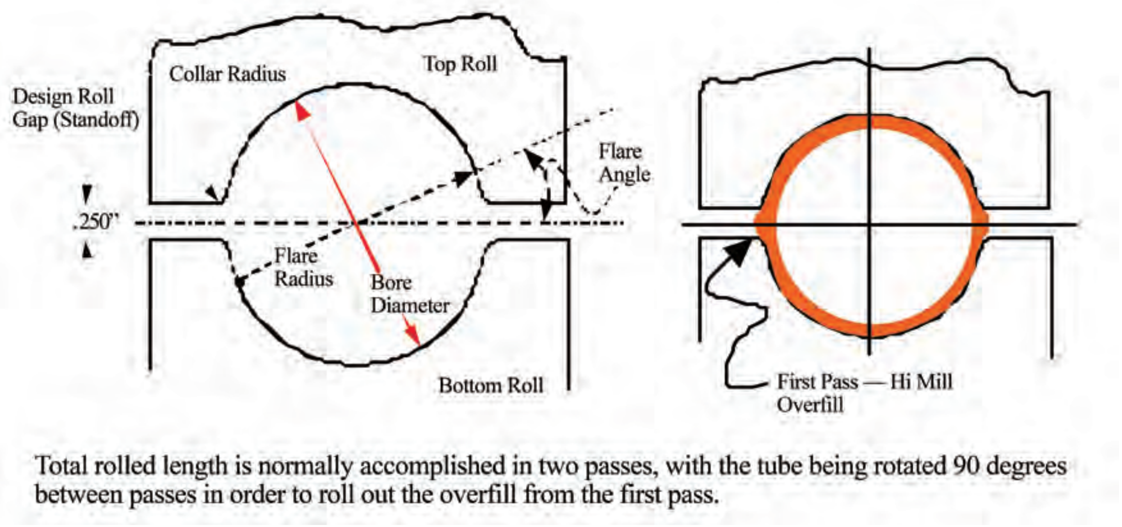
High Mill geometry. Source: U. S. Steel Tubular Technology Course, 2007.

High Mill Motor — Historical Information

The electromechanical configuration consisted of the high-inertia, fixed low-speed synchronous motor, coupled through a direct-drive pinion stand to the work rolls. The bottom work roll is directly driven, and the top shaft is geared to the bottom shaft in the pinion box. The motor stator was powered from the 2,300 VAC power system with reactor start, and the rotor DC excitation was derived from a small motor-generator set, connected through slip rings on the motor shaft.

In 1952, a program was implemented at what was then known as U. S. Steel Lorain Works to convert all electrical machinery operating on the 25-Hz power system to a 60-Hz system in order to eliminate the necessity for 25-Hz power in the

Figure 3



High Mill roll pass design. Source: U. S. Steel Tubular Technology Course, 2007.

plant. That conversion program included the upgrade by Elliott Co. of the original 2,000-hp, 25-Hz High Mill main drive motor.

The motor was modified from its original configuration with 46 rotor poles (23 pairs) to a design with 112 poles (56 pairs) to keep the speed approximately the same. Equation 1 illustrates the basic relationship between the synchronous speed (in RPM) of a three-phase AC motor and the applied stator frequency and pairs of rotor poles:

$$\text{RPM} = \frac{60 \times \text{Applied Frequency (Hz)}}{\text{Pairs of Rotor Poles}} \qquad \text{(Eq. 1)}$$

Using Equation 1 for the High Mill main drive motor before and after the redesign for operation at 60 Hz:

Synchronous Speed (Original Design) =

$$\frac{60 \times 25}{23} = 65.217 \text{ RPM}$$

Synchronous Speed (Modified Design) =

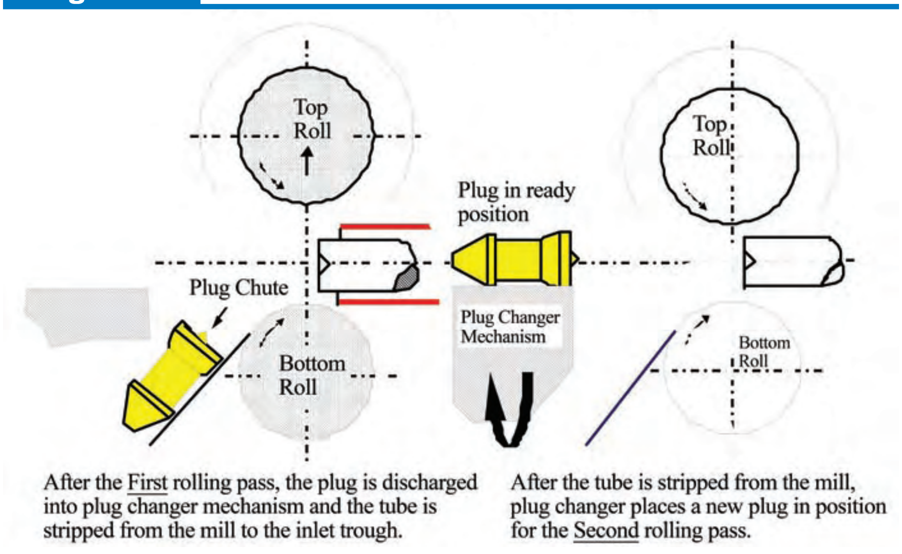
$$\frac{60 \times 60}{56} = 64.286 \text{ RPM}$$

Table 1 summarizes the pertinent motor data.

After the motor was re-commissioned, it had a well-documented history of occurrences of synchronization loss (stall or pullout), electrical and mechanical failures, and incremental design modifications to improve the reliability. The failures internal to the motor were typically associated with rotor/stator coils damaged due to overheating. The overheating resulted from frequent restarts required to clear the mill following a motor stall as the result of a "cobble." Over time, the stalls and frequent restarts led to distortion in the stator laminations and caused variation in the air gap between the rotor and stator.

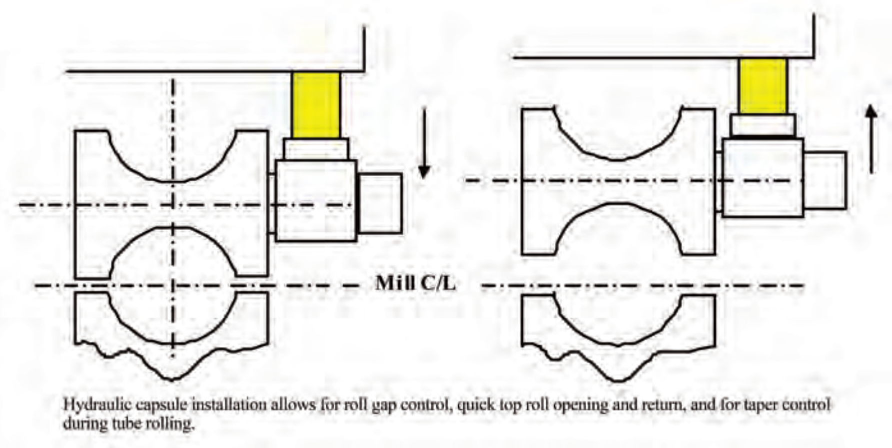
A forced ventilation system was installed, which provided some improvement in the area of overheating. However, there was no practical way to alleviate the mechanical stresses placed on the rotor poles and mounting bolts resulting from the repetitive impact loads during normal operation, in association with the

Figure 4



High Mill plug changer cycle. Source: U. S. Steel Tubular Technology Course, 2007.

Figure 5



Top roll hydraulic capsule. Source: U. S. Steel Tubular Technology Course, 2007.

unique combination of large rotor diameter and high number of poles.

Alternative Analysis

The primary objective of the project was to increase the reliability of the High Mill main drive motor, and no increase in throughput was anticipated. That being the case, the peak and RMS power requirements would be the same after the project as before. Prior to project approval, significant time and effort were spent analyzing various alternatives, not only for the type of motor and mechanical components, but also for the type of power conversion to be specified.

Table 1

High Mill Motor Data

Horsepower (hp)	2,000
Manufacturer	Elliott
Frame	SH337
RPM (25-Hz operation)	65.2
RPM (60-Hz operation)	64.3
Stator VAC	2,300
Stator FLA	502
Stator coils	294
Stator weight	72,000 pounds (approx.)
Rotor volts DC	125
Rotor amps DC	157
Rotor poles (25-Hz operation)	46 (23 pairs)
Rotor poles (60-Hz operation)	112 (56 pairs)
Rotor weight, including shaft	75,000 pounds
Rotor Wk^2	1,750,000 lb-ft^2 (approx.)

The primary unknown was the peak torque presented by the process to the mechanical and electrical equipment. In order to determine the load characteristics, shaft torque, vibration signatures, and electrical signals such as kilowatts, stator voltage and current, and rotor excitation current were recorded over a period of several months. That data collection and analysis are discussed in the "Application Considerations" section, which follows.

Even though the High Mill rolling process, from a main drive perspective, is a single-speed, non-reversing application, it was decided that the benefits provided by the adjustable speed and reversing capability justified including those features and the associated electrical equipment in the project scope.

DC and cycloconverter options had been eliminated early in the process. The DC motor/drive option was eliminated for several reasons, including initial and life-cycle costs and size restrictions for motor installation. The cycloconverter option was eliminated, primarily due to the advent of modern power semiconductor technology and the associated control.

Additional analysis was required for the motor type and speed and whether to include an intermediate gearbox. Four alternatives were proposed:

- Synchronous motor, no reducer.
- Synchronous motor, with reducer.
- Induction motor, no reducer.
- Induction motor, with reducer.

The evaluation team included U. S. Steel operations, maintenance, engineering, quality and safety representatives, along with representatives from an outside engineering company. An evaluation matrix was produced, the category weights and ranks were independently scored, and then a meeting was held to review the results.

Fourteen categories were agreed upon, broken into three areas: General, Maintainability and Costs. The top five category weights were:

- Maintainability.
- Risk to quality.
- Ease of changeout (time to repair).
- Constructability (production impact to install).
- Complexity (equipment and components).

The low-speed, direct-drive operation, although proven from the process standpoint, would require the combination of a large number of poles and low operating frequency, which was determined to present a less desirable combination than adding a gearbox and increasing the motor speed accordingly.

There was considerable discussion concerning what risks were presented by the combination of an induction motor with an intermediate gearbox. One concern was the lack of sufficient stored energy presented to the rolling process from the mechanical components, including the motor rotor, potentially resulting in a speed drop on impact that would be detrimental to the process. This risk was mitigated by the sophisticated features available in modern microprocessor-based, adjustable-speed drives.

Another concern was the addition of a mechanical component in the drivetrain, with its associated ancillary systems. This risk was mitigated not only by advanced design and quality requirements in the gearing component specifications, but also by providing comprehensive vibration and temperature monitoring instrumentation, along with a full complement of spare gearing components.

The overwhelming choice of the evaluation team was the induction motor/intermediate gearbox combination.

Application Considerations

Motor Type — As mentioned earlier, the existing synchronous motor had both mechanical and electrical (overheating) issues due to the repeated large-peak impact loads resultant from the High Mill rolling process. In general, a fixed speed synchronous motor is not well suited to impact load applications. A characteristic of all synchronous motors is that the load angle between the rotor and the rotating flux in the stator is proportional to the load on the shaft. This angle is labeled "δ" in Figure 6.

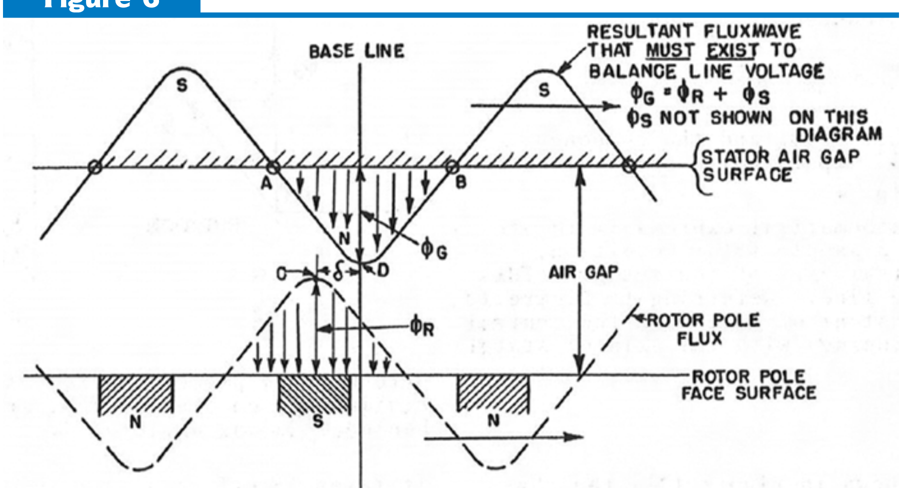
Each time the motor is impacted by a shell entering the roll bite, the impact causes the rotor to respond by instantaneously increasing the torque angle. This step change in rotor position causes instability in the motor and results in the rotor torque angle and shaft speed oscillating at the natural frequency of the motor and drivetrain. In this particular application, the oscillation would continue for the entire rolling time of the shell. The magnitude of the oscillation would be gradually damped by the amortisseur (or dampening) windings, friction, and other electrical and mechanical losses. The currents induced in the amortisseur windings cause heating of the field poles and the field windings. This oscillation, or ringing, caused corresponding electrical transients in the system that can be seen in the graph of Figure 7.

The general rule is that the higher the inrush current, the better the damping factor. From the available motor data, the design appears to be about a rather modest 3.9 inrush (2,680 KVA/10,500 KVA), probably out of concerns about starting. This correlates with the relatively low damping shown in Figure 8.

If the impact load was greater than the transient motor pull-out torque, the torque angle would exceed 90° and the motor would "slip a pole" or "pull out" of synchronization, resulting in a mill cobble, not to mention enormous torque transients in the motor. In an effort to address the increased in-bar torque requirements while not over-exciting the machine during non-rolling periods, a variable excitation (field forcing) system was implemented. A sensor detected an incoming shell prior to mill entry and boosted the motor field strength. This boost increased the pull-out torque of the motor and reduced the possibility of cobbling the mill. However, a negative side effect of the increased field strength was a reduced damping coefficient for the stator current oscillations. Figure 8 illustrates the comparative oscillations in stator currents under normal field strength operation (recorded Sept. 13, 2004) and boosted field strength operation (recorded Feb. 7, 2005).

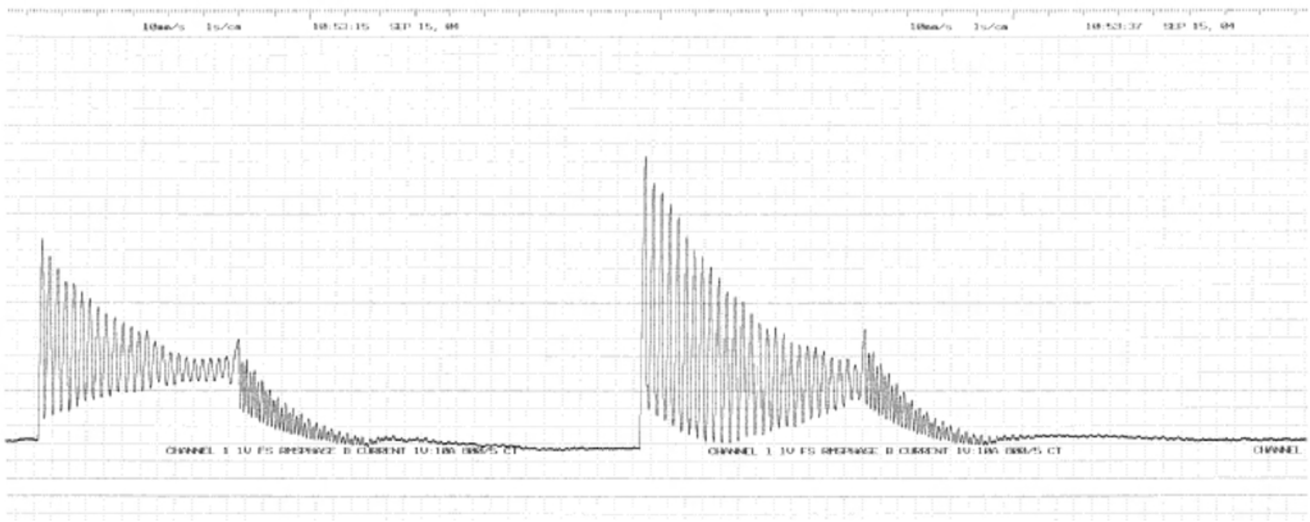
It is possible to apply a synchronous motor with a variable frequency drive for this type of impact application, and this is routinely

Figure 6



Synchronous motor torque angle.

Figure 7



Synchronous motor current oscillations.

done in new, high-power hot mill main stand installations. A motor designed specifically for mill-duty application has amortisseur windings designed to minimize the natural mechanical oscillations that follow impact. The drive control is tuned for high-performance control of the motor load torque angle to eliminate the oscillation. The speed regulator of the drive must sense the rapid increase in torque angle and respond by lowering the stator frequency to prevent the motor from bouncing back to its previous speed once it has overcome the increase in load torque. This variable speed drive system would thus be designed to overcome the natural characteristic of the synchronous motor. Even though this application is not speed-critical, consistent linear speed of the piece through the mill, particularly across the range of roll diameters, allows for better operation of the roll gap control.

The load in this application was in the range where induction motors are typically applied today, so a new synchronous motor was not considered to be the best choice for this application. In addition to the increased complexity, the drive system for a variable speed synchronous motor is generally more expensive than that of an induction motor because a separate transformer, power converter and controller are required for the synchronous motor field control. With today's high-performance drive systems, there is no difference in speed response between induction and synchronous motors used in mill applications.

An induction motor is better suited for this type of application because the fundamental torque response characteristic of the induction motor is different from a synchronous motor. An induction motor has a natural characteristic that matches impact loads very well. Torque is produced in an induction motor only when there is a difference between the rotor and stator flux, resulting in "slip." As an induction motor is loaded, the rotor slows down, increasing the difference between the rotor and stator flux frequencies. As the slip frequency increases, the output torque smoothly increases. The induction motor is not constrained to rotate at the synchronous speed, as the synchronous motor must. The fixed-speed induction motor will naturally droop or operate at a lower speed as load increases.

Motor Rating — The 2,000-hp, 64.3-RPM rating of the synchronous motor was adequate for the products historically rolled on the High Mill. The peak torque produced by the synchronous machine with increased field excitation was 480% at pull-out. U. S. Steel wanted to duplicate the torque capability of the existing motor in the new motor and drive system. However, the new motor must be able to produce the peak pull-out torque of the synchronous motor as a frequently applied overload. Because 480% overload torque is not a common motor design characteristic, it was decided to apply a 240% frequently applied overload on a motor rated for 4,000 hp.

Several options were investigated, and the most cost-effective solution was to use a higher-speed motor coupled to a gearbox. A 300-RPM motor (six poles, operating at approximately 15 Hz) coupled to a 4.6956-to-1 gearbox was selected for the application. The gearbox design and rating were predicated on the recorded load characteristics, and a custom specification was generated that addressed the performance requirements and quality procedures necessary to provide long-term viability for the gearing components. The existing 1-to-1 pinion stand, along with the remaining shafts, couplings, etc., were not replaced.

Motor Construction — The existing synchronous motor was a drip-proof, self-cooled machine located in the mill area adjacent to the stand. The motor internals were open to the harsh, dusty environment of the mill. The exposure of the motor internals to the mill environment made maintenance more frequent and shortened the life of the motor, so this design was not considered for the new motor. A totally enclosed induction motor was applied. It was decided that an air-to-air heat exchanger would require frequent cleaning because mill dust would tend to foul the heat transfer surfaces. A water-to-air heat exchanger was used, as it would perform well in the mill environment, did not require external ducting and would allow a long service life. The standard top-mounted heat exchanger unit was able to be used because there is sufficient overhead clearance at the mill.

Motor Auxiliary Systems — There was no significant change in the overall mill control as a result of this new drive installation. The new drive enabled the operator to reverse the motor to clear cobbles, and the new drive control permits varying the speed of the motor as required by different roll diameters. The new converter and inverter were added as drops on the existing ControlNet™ control network for alarm and status bits, and a simple analog speed reference and digital "Run" signal were supplied from ControlLogix® I/O control architecture for drive control. The analog reference signal was deemed sufficient for this application because the control of the motor was to be quite basic.

Motor Mounting — The 300-RPM motor and 4.6956-to-1 gearbox had to be located in the same footprint as the existing synchronous motor. The existing synchronous motor was an unusual shape due to its low operating speed and unique original design. The motor had the large diameter and relatively short length typical of a low-speed synchronous motor. The motor required a large pit below the mill floor to accommodate the large-diameter rotor with a comparatively short shaft height. It was decided that the new motor would not reuse the existing pit. Instead, a standard-design induction motor with bracket-type bearings was installed above the motor pit for the synchronous motor. The use of a bracket-type bearing motor allowed easier and faster installation, with a shorter disturbance in mill production because there was no need to assemble the motor parts and align the stator and rotor on-site.

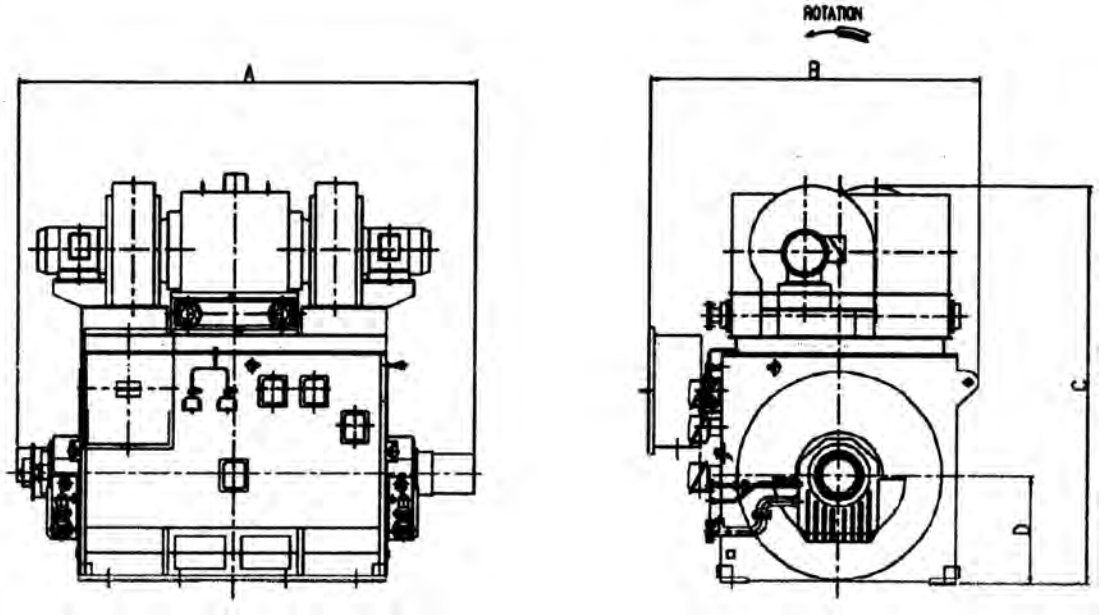
Typically, the external utility connections are separated so that main and auxiliary electrical terminal boxes and the cooling water connections are located on opposite sides of the motor. This isolates the electrical terminal boxes from water leakage or heat exchanger maintenance. However, because this motor mounting location prevented access to both sides of the motor while the mill was in operation, the motor was designed with all piping and electrical connections on the same side of the motor. An outline drawing of the induction motor is shown in Figure 9.

Drive System — There was no possibility of controlling the speed of the existing synchronous motor. One of the benefits of this upgrade was to enhance the controllability of the motor powering the High Mill. To accomplish this task, a regenerative, reversing drive was applied to the motor. The normal stopping mode for the mill was a coast stop, which required a long period of time (minutes), until friction and windage losses finally stopped the motor. A dynamic braking stop provided the only other stopping method. The new drive system allows the motor to be stopped at a specified rate through regeneration to the AC line. The process does not require rapid deceleration/acceleration, so the drive is currently set up to stop the motor in under 10 seconds.

Reversing the motor was limited to a "Reverse Run" function through the 2,300 VAC air circuit breakers and starting reactor. There was no reduced speed or "jog" capability. As mentioned earlier, in normal operation, the processed shell is returned to the entry side of the mill by opening the works rolls and using the stripper rolls. There are some cobbles where the stripper rolls do not have enough power to remove the piece from the mill. In that event, the Reverse Run function would be used. The new drive and motor allow reduced-speed operation in either direction, not only for cobble removal, but also for spindle spotting prior to roll changes.

Drive System Harmonics — U. S. Steel required a new drive that would meet the current and voltage harmonic requirements of IEEE 519. Ordinarily, this would result in increased complexity for the drive system, either through the addition of external filters, or the use of a multi-winding transformer with a diode source. The diode source would require some separate provisions to allow for rapidly decelerating the motor. The final drive system configuration was a simple two-winding transformer and IEGT PWM drive. There are no external filters, but the system is able to comply with the harmonic voltage and current limits of IEEE 519 through the use of a patented fixed pulse pattern control (FPPC) in the PWM converter.

Figure 9



Induction motor outline.

Drive/Electrical Room — Because of the mill layout, there is no space close to the motor where a drive or other electrical equipment could be located. U. S. Steel requested that the drive and electrical switchgear be housed in a pre-fabricated, pre-wired, outdoor enclosure, which was referred to as the Power Control Center (PCC). The benefits of this philosophy are well-known, as it allows for pre-shipment testing and configuration of all the enclosed equipment and shortens the on-site installation, commissioning duration and costs. This enclosure was shipped in one piece and installed on an elevated steel structure, allowing bottom-entry of all power, control, signal and communication cabling. The PCC was installed prior to the outage, and as much field wiring as possible was interconnected, so as to minimize the outage duration. Figures 10–13 provide details of the installation.

Results

Figure 14 shows the result of applying a variable speed drive with an induction motor. The figure shows the speed reference (scale not shown), speed feedback (scale on right, in %), and motor current (scale on left) for two passes of two different shells through the mill. The top line shows the speed reference of the drive, which is constant. The middle line shows the actual motor speed as measured by the shaft-mounted tachometer. It can be seen that the shaft speed slowed about 4% when the impact load was applied, and the motor speed increased about 4% when the load was suddenly removed as the piece left the roll bite. These speed excursions could be further mitigated by several control techniques, but the response was deemed suitable and no additional tuning was done. The bottom trace shows the motor current, which is much smoother than that observed with the synchronous motor and with little or no mechanical oscillations observed.

Conclusions

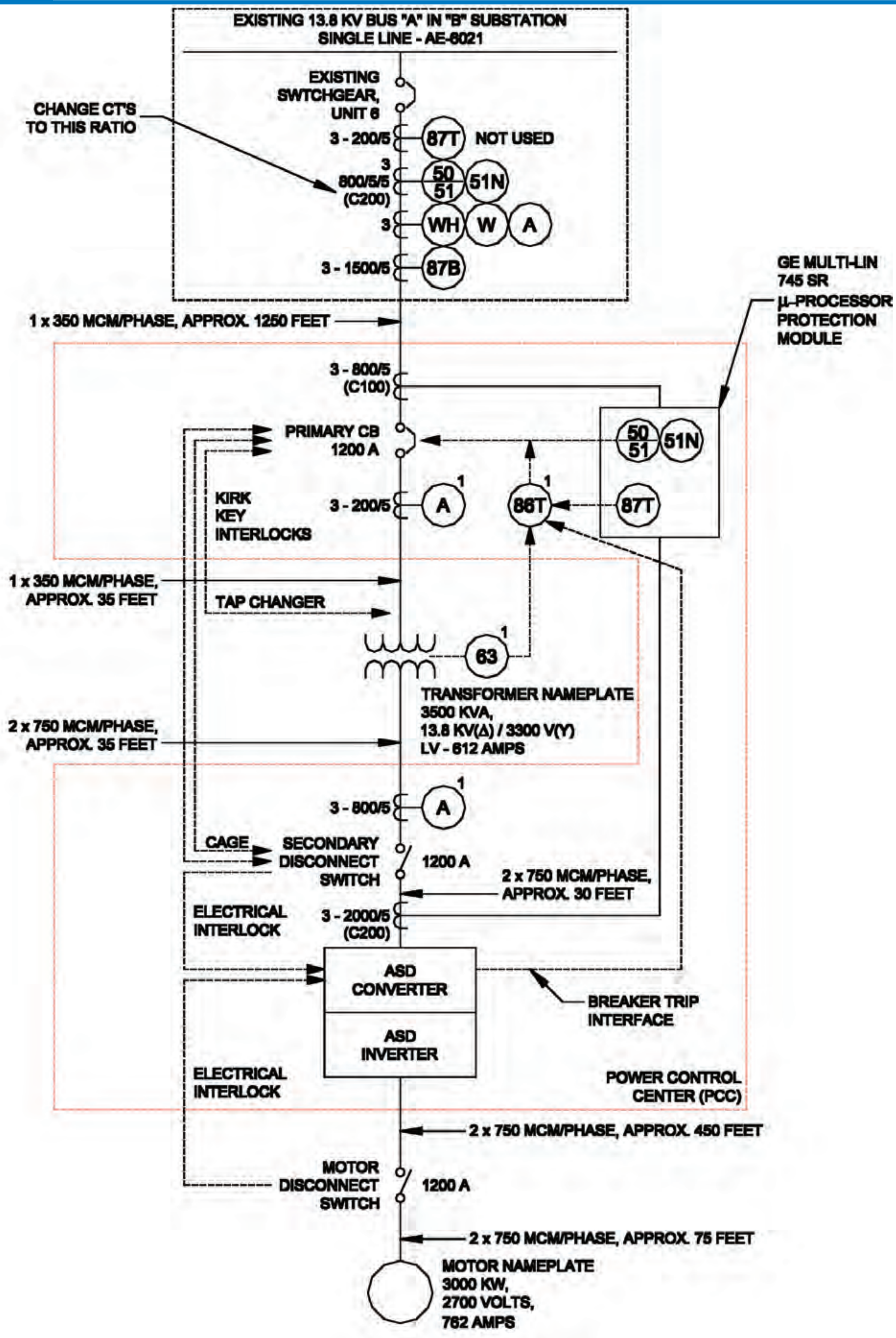
The main goal of this project was to improve the reliability of the High Mill main drive AC motor. Although only time will tell, an appropriately-sized modern induction machine with a TEWAC (totally enclosed water-to-air cooled) enclosure, which is well-suited to the harsh mill environment, should provide the increased reliability.

The alternative analysis and resultant decision to replace the low-speed synchronous machine with a combination induction machine/gearbox arrangement have not had any detrimental effect on the process, and appear to have eliminated underdamped torque oscillations. This should lead to less wear and tear on all drivetrain components.

The induction motor, gearbox, and drive system power, control and ancillary equipment were installed and commissioned safely, and the High Mill was restarted on schedule at pre-shutdown quality and production levels.

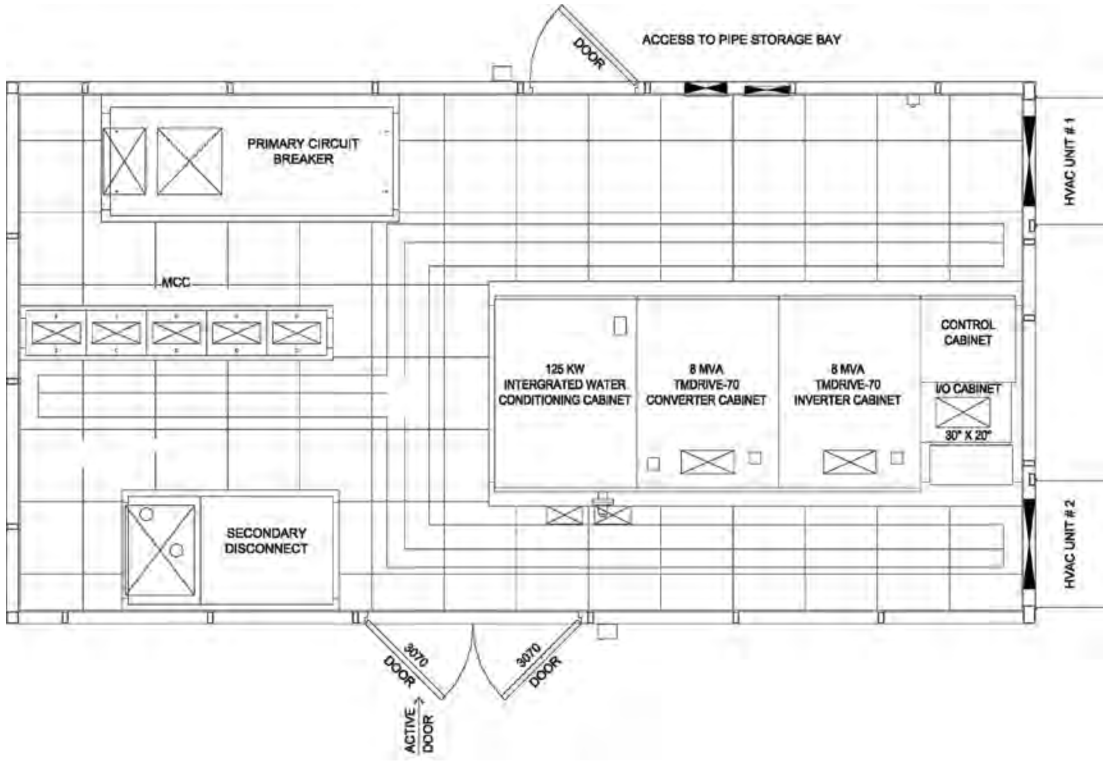
The full-reversing, full-regenerative, adjustable-speed drive technology and extended motor speed range allow further enhancements, such as work roll diameter compensation, to be implemented. Roll diameter compensation, in association with the existing hydraulic roll gap taper control, has the potential to improve the wall thickness variability and improve the quality of the High Mill and downstream operations.

Figure 10



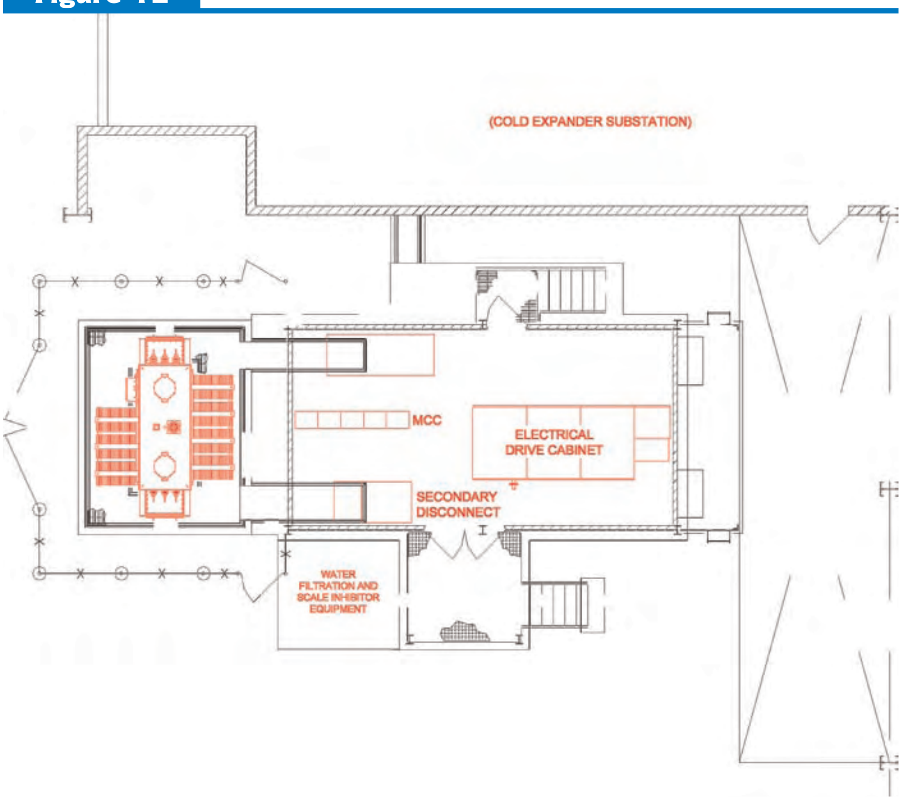
System single line.

Figure 11



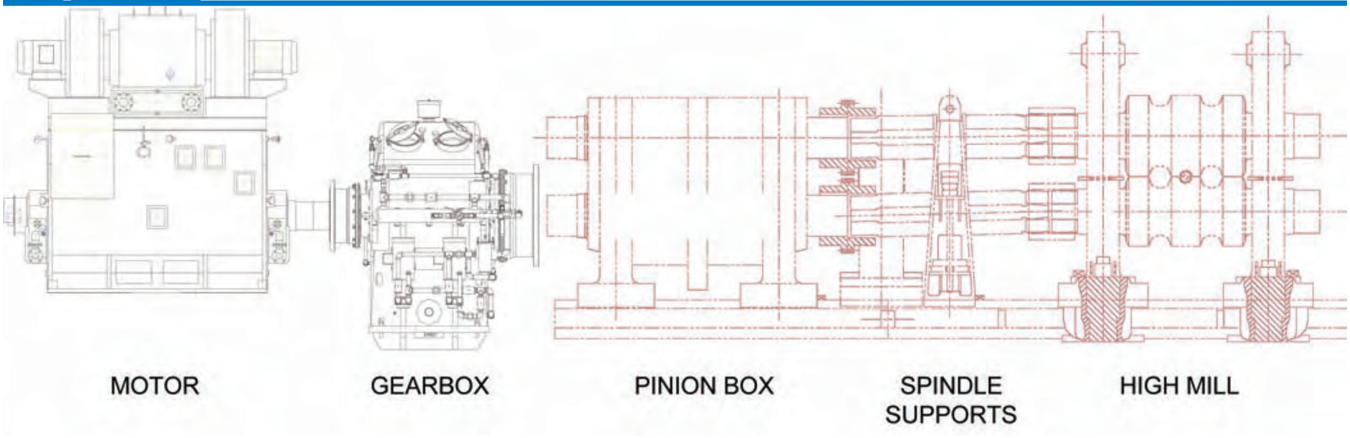
PCC layout.

Figure 12



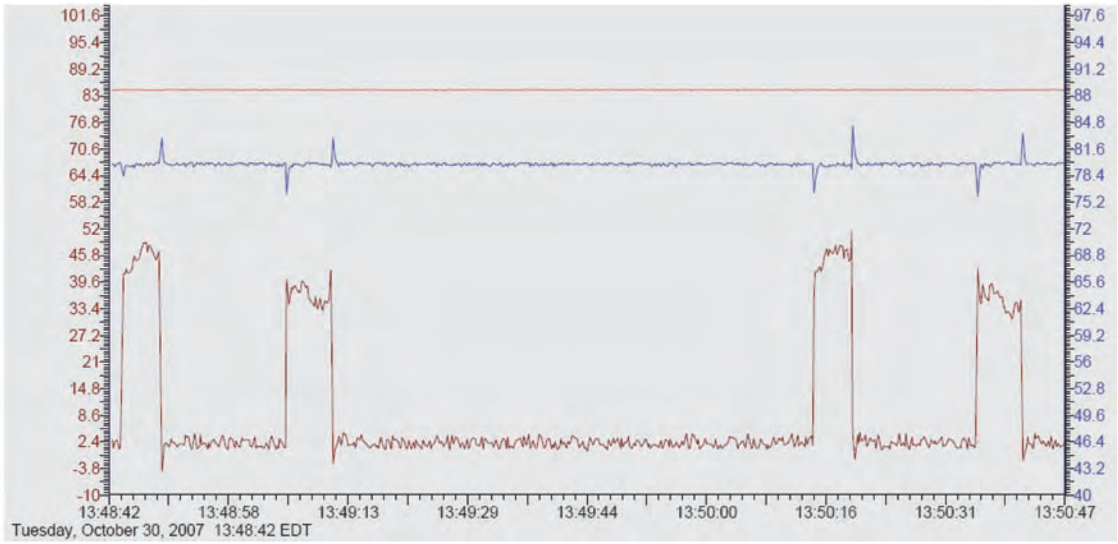
PCC area plan.

Figure 13



Mill elevation looking north.

Figure 14



Speed reference (top), speed feedback (middle) and motor current (bottom), as recorded for the induction motor.

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