AN INTRODUCTION TO COPPER EXTRACTION

ELECTRICAL ENGINEERING IN THE PROCESS INDUSTRY: THEORETICAL FOUNDATIONS AND PRACTICAL CONSIDERATIONS

ENG450 ENGINEERING INTERNSHIP

A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering

Name: David Stewart
Student Number: 12005178
Academic Supervisor: Gregory Crebbin
Industrial Supervisor: Bruce Larcombe

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ABSTRACT
The objective of this report is to provide an overview of copper extraction and demonstrate many of the practical applications and considerations related to low voltage motor selection and the implementation of a Control System to manage operation of a Ball Mill used in the copper extraction process.

This report is an accompaniment to work conducted during my Internship placement at Ausenco as part of ENG450 Engineering Internship. During my time spent in the Electrical division assigned to Kinsevere I have gained experience and insight into the daily operations required for practical engineering in the process industry, and some of these experiences are included where relevant within the body of this report.
DISCLAIMER
I declare the following to be my own work, unless otherwise referenced, as defined by the University’s policy on plagiarism.

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1 INTRODUCTION

During my Internship I was a member of the Electrical Engineering division at Ausenco and assigned to the Kinsevere Project. This project involved the design of a Solvent Extraction and Electrowinning process plant used for copper extraction. My internship was conducted during Semester 2 of 2008.

The following report focuses on two projects completed during my Internship. The first is a Load flow Study of all low voltage motors installed on site as well as drive and cable selections for each. The second is the implementation of a Mill Control System to control the operation of a 3MVA Ball Mill used for secondary crushing in the copper extraction process.

Included in this report is background information regarding the Kinsevere Project, the principles and processes involved in solvent extraction and electrowinning for copper extraction, and the electrical connection scheme being implemented. Also included is a detailed analysis of ac induction motors, and an introduction to the common loads and drive characteristics frequently present in industrial processing plants. In regards to the Mill Control System I have included an overview of the electrical connection scheme employed with the Ball Mill, a discussion of the peripheral processes required for operation, and explanations of key characteristics with a control system and the reasons for the control strategy used.

It was my intention to proved sufficient information to assist other graduate engineers, like myself, exposed to similar problems in similar circumstances. In this way the report is intended to be a guide for future engineering students exposed for the first time to the electrical concerns of practical engineering in an industrial workplace.
2 BACKGROUND INFORMATION

This section is intended to provide a brief introduction to the copper extraction process and the Kinsevere project. Additionally information is presented to provide a basic overview of the electrical connection scheme employed.

2.1 INTRODUCTION TO THE KINSEVERE PROJECT

The Kinsevere Copper Extraction Plant described in this report is a brown-field site located in southern part of the Katanga Province in the Democratic Republic of the Congo (DRC), approximately 20km north of the provincial capital, Lubumbashi.

![Figure 1: Location map for Kinsevere project](img)

The plant is a three stage development project with Stage 1 already completed and consisted of the installation of a Primary Crusher and Arc Furnace Mineral Processing Plant. The ore is supplied from an open cut mine producing 550,000 tonne of ore per annum (tpa) at a copper
grading of 7%. The existing facility is able to extract a 94% grade of copper at a throughput of 25,000 tpa. However this copper is required to be further treated before it is suitable for commercial use.

Due to the vast quantities of copper ore and the relative inefficiency of the Stage 1 plant, a Stage 2 upgrade has been initiated. The Stage 2 upgrade is expected to increase copper output to 60,000 tpa while raising the purity of the copper to 99.9%. This will be achieved by replacing the existing Arc Furnace plant with a new SX/EW plant, the principles of which will be explained in the next section. Planned upgrades for Stage 2 include the addition of a second primary crushing facility, a link conveyor between the existing crusher and the soon to be installed one, a secondary crushing facility in the form of a Ball Mill, numerous leaching and thickening tanks, a tailings disposal facility, and a Solvent Extraction and Electrowinning (SX/EW) plant. A brief but thorough introduction to the meanings of these processes is provided in the following section.
2.2 OVERVIEW OF COPPER EXTRACTION

The copper extraction process begins at an open cut mine where Copper Ore is blasted and removed via Excavators and Tip Trucks. The ore is fed to a Crusher where it is broken down to a specified maximum size and passed through to a conveyor. When the crushed ore falls onto the conveyor it is transported to a Ball Mill to have its particle size reduced further. During transportation the ore on the conveyor has grinding medium added to it, with the quantity added determined by the ores volumetric flow rate.

The Ball Mill is best seen as a large rotating drum on its side. The conveyor deposits crushed ore and the included grinding medium inside the Mill at one end. As the Mill revolves, the grinding medium smash and crush the ore into finer particles, until such time as the ore is of sufficient size to exit the other end. Grinding medium is not removed from the Mill but smashed to pieces and exits as part of the output feed. A cyclone separator is used on the Mill’s output feed to remove the oversized particles. These are returned back to the Ball Mill for further crushing. The sized particles are collected in leaching tanks where they are submerged in sulphuric acid to begin the leaching process (where copper ions dissolve into the acid solution).

The sulphuric acid and crushed ore mixture is now referred to as a Process Slurry. The Slurry is pumped first into a Thickener tank and then a Clarifier. The thickener tank is used to gravity separate the clay particles from the desired leached solution. Flocculants and Coagulants (artificial additives that promote amalgamation of fine particles into larger heavier ones) are added to the mixture to decrease the settling time. Once enough time has expired for the clays to sufficiently settle, the overflow (top part of the solution within the tank) is then pumped to the Clarifier. As a general rule Clarifiers will have a lower residence time and produce a thicker underflow solution. Flocculants will again be added and a settling time is allowed for. The end result is the Clarifiers overflow stream consisting of a High Grade Copper Leached solution. This solution is now referred to as a Pregnant Leach Solution and will be treated for copper extraction. The underflow stream of the Clarifier is pumped back to the original Thickener for further processing.
Returning to the original Thickener tank, let’s now address its underflow stream (the solution within the tank pumped from the bottom). Here we have a much lower concentration and further treatment needs to occur in order for high grade copper to be extracted. The underflow of the Thickener tank is passed through a series of additional Thickeners (five in total, referred to as CCD No.1 to No.5). More flocculants and coagulants are added and further separation occurs between the clay and copper impregnated leached solution. A second Clarifier is introduced and a Low Grade Copper Leach Solution is produced (also referred to as a Pregnant Leached Solution, often prefixed with either LG or HG).

The final two stages of the copper extraction process are Solvent Extraction (SX) and Electrowinning (EW).

The first stage (SX) is a two step process. First the Pregnant Leached Solution is injected with an organic solvent which has the beneficial property of attracting copper atoms to its molecular structure, especially in low acid - low copper leach solution. Copper ions transfer between the two solutions and once completed, we declare the organic solution to be loaded. This step is referred to as Extraction. Then the organic solution is contacted with a concentrated sulphuric acid. Copper is released from the loaded organic and the end result is a sulphuric acid solution containing very high concentrations of copper. This is referred to as Stripping. The final solution after Stripping is called a Strong Electrolyte and it is this which will be used in the Electrowinning process. The remaining solution, containing the now unloaded organic solvent, goes through a recycling process to be reclaimed for later reuse.

The Electrowinning process is essentially a series of cell batteries. Each cell is comprised of electrodes (in the form of removable anode and cathode plates), and is filled with the Strong Electrolyte solution (from the Stripping process). A potential DC voltage is applied to the cells and, much like the charge cycle of a battery, current flows. Current flows due to chemical reactions occurring within the electrolyte, and a consequence of this action is the accumulation of copper onto the electrode plates. When sufficiently coated, the plates are removed from the solution by a system of hooks and overhead crane and taken to a stripping and washing bay.
where the copper is removed, and the plates washed and returned (at a later date) for the process to be repeated.

Figure 2: General flow diagram of the copper extraction process
2.3 SUMMARY OF THE POWER SYSTEM

As this report has an Electrical Engineering perspective a quick introduction to the power system being implemented at Kinsevere will now be given. Firstly there are two 33kV overhead transmission lines supplying the site, fed from a 110kV/33kV substation. Each line terminates at its own switch room. The configuration between the two switch rooms is a split bus, serving as a contingency option for loss of supply of one incoming feeder.

Nine Motor Control Cubicles (MCCs) are located throughout the plant designated with the primary function of supplying power to all low voltage motors with power. At a MCC, depending on the total load connected, 33kV is stepped down to 525V by 0.5MVA, 1 MVA, or 2.5MVA transformers. Drives required for each motor and their protection circuits are stored within the MCC cabinets. Exceptions to this rule are Variable Speed Drives, which are mounted along an interior wall of the building housing the MCC.

Only a few cases exist on site where a medium or high voltage connection is required. The first is the Ball Mill which requires a 3MVA wound rotor induction motor. This is supplied from a 33kV feeder and connected at 11kV by a 3.5MVA dedicated transformer. A Liquid Resistance Starter (LRS) and a Slip Energy Recovery (SER) Unit will also be employed for this connection.

The other requirement for a medium to high voltage connection is at the Electrowinning plant, where there are two applications present. The first is a 1.5MVA hot water system used to heat the Strong Electrolyte solution, and again this will be supplied by a 33kV feeder to a dedicated 2.5MVA transformer with secondary voltage at 525V. The second application is the connection of two 12 Pulse Rectifiers connected at 33kV generating 180V DC in parallel. It is this DC voltage that will be applied to the cells of the Electrowinning plant.

A simplified single line diagram (SLD) indicating the major components introduced in this section, and the connection scheme employed, is shown in Figure 3.
Figure 3: Simplified Single line diagram of Kinsevere Electrical System
3 CHARACTERISTICS OF AN AC INDUCTION MOTOR

The predominant type of motor employed in a process plant is the ac induction motor, converting on average 70-80% of electrical power to mechanical energy. This is true in most process applications, and very much so in the Copper Extraction Plant being developed in Kinsevere.

Over 90% of motors used at Kinsevere are ac induction motors. The Squirrel Cage motor makes up the bulk of this percentage, with the Wound Rotor motor taking up the rest. Considering this fact, it seemed necessary to conduct a detailed analysis of the principles of ac induction to be conducted.

3.1 PRINCIPLES OF OPERATION

A three phase ac induction motor consists of sets of three phase windings on the stator with corresponding numbers of windings on the rotor (for a wound rotor). When three phase power is supplied to the stator windings a rotating magnetic flux is generated. To explain this process, consider a two pole three phase ac squirrel cage motor. The configuration of the stator windings is shown in Figure 4. A1 and A2 represent the start and end of a phase winding, B1 and B2 represents the second phase winding, and C1 and C2 the third, with each phase spaced 120° apart from each other around the stator i.e. A1 is 120° apart from B1. Coils are wound around the stator core in such a way that when a current flows in them, one coil produces a north pole while the other produces a south. (see Figure 4)

![Figure 4: Stator winding configuration of a two pole motor](image-url)
A quick detour will now be taken to explain a common reference to three phase supplies. According to AS3000 2007, installation wiring conductors should be clearly identified to indicate their intended function. The insulation for neutral conductors shall be Black or light blue, the insulation for earth conductors shall be green and yellow (with one colour not covering more than 70% of the surface area), and for multiphase supplies (three phases), the recommended identification colours for the active conductors are Red, White, and Blue. Because of this last fact, each phase of a three phase supply is generally referred to by their insulation colour.

When a three phase voltage is applied to the motor, the red phase is connected to the first stator winding, the white phase connected to the second stator winding, and the blue phase connected to the third. Figure 5 shows the red phase connected to winding A of the stator and the three phase voltages with respect to each other.

![Diagram](image.png)

**Figure 5: Three phase supply to the two pole motor [10]**

The applied ac voltage to the stator causes current to flow in the windings that produce a magnetic field. The strength and direction of this magnetic field is directly proportional to the magnitude and direction of the current in the windings, shown visually in Figure 6 and mathematically in Equation 1. As the current varies in response to the alternating supply voltage, the strength of the magnetic field also varies at that same frequency and this is seen in Figure 7.
Equation 1: Magnetomotive force

\[ \text{mmf} = N \cdot i \]

where:  
\( \text{mmf} \) = Magnetomotive force  
\( N \) = Number of turns around iron core  
\( i \) = Current

Figure 6: Visual impression of current and magnetic field strength [10]

Figure 7: Visual indication of varying magnetic field strength [10]

Because three sets of windings are on a stator, and each provided by a single phase of a three phase system 120° phase shifted from each other, at any given point in time the magnetic fields
of each winding differs. The result of these differing magnetic fields is a combining of the fields to produce a resultant magnetic field which rotates around the stator at a frequency given by Equation 2. It is this resultant field which will dictate the operation of a motor.

\[
\text{Equation 2: Frequency and rpm of a rotating magnetic flux}
\]

\[
f_{\text{Stator}} = \frac{f_{\text{Supply}}}{P} \quad \text{or} \quad n_{\text{Stator}} = \frac{n_{\text{Supply}} \cdot 60}{P}
\]

where: 
- \( P \) = Number of pole pairs 
- \( f \) = speed in Hz 
- \( n \) = speed in rpm

To demonstrate this feature, consider what this resultant field is doing with 30° increments of the supply voltage. Figure 8 shows three positions in time of a three phase system (a, b, and c) spaced 30 electrical degrees apart, and their corresponding voltage magnitudes for each phase (red, white, and blue).

![Figure 8: Three phase supply in 30° increments [7]](image)

At position a the red phase is at its maximum voltage and producing maximum current, therefore generating the largest magnetic field for stator A as possible. The blue phase and white phase at position a receive only half the maximum voltage magnitude, which is negative in polarity, producing a negative current. The resultant flux lines at this point in time is shown in Figure 9a.

At position b 30 electrical degrees later, the white phase is zero (producing no magnetic field), and the red and blue phases are equal and opposite. The resultant magnetic field and flux lines are shown in Figure 9b, and as indicated in the figure a shift in the north and south poles caused
by the resultant magnetic field has occurred by 30 mechanical degrees around the stator. A further 30 electrical degree increment in the supply cycle produces the resultant magnetic field and flux lines as shown in Figure 9c, and as before a shift in pole position by another 30° has occurred. It is clear from this analysis that the magnetic poles in the stator mechanically rotate around the rotor at the electrical frequency of the supply (that is for a two pole motor). This frequency is referred to as synchronous speed.

Figure 9: Resultant Magnetic Flux lines from three phase stator [7]

The magnetic field set up by the stator induces a voltage in the rotor proportional to the relative difference in rotation between the rotor and stator’s rotating magnetic flux. A simple way to think of this concept is by thinking of flux lines cutting a rotor bar. If the rotor were stationary (locked rotor) and the supply frequency was 50Hz then the number of times one flux line would cut one rotor bar is 50 times a second. The faster the rotor rotated the fewer times the flux lines would cut, and if the rotor were at synchronous speed it would move at the same speed as the rotating flux and no lines would cut at all.

If a wire moves through a magnetic field, a voltage is induced on the wire given by the vector calculation shown in Equation 3. In the case of an ac induction motor, it is more correct to think of the wire being stationary and the magnetic field moving past it. But regardless of how it is visualised, the principle still remains the same. If a circuit is completed in the rotor, current will flow. With squirrel cage rotors the circuit is completed by shorting rings at the each end of the
rotor bars, in a wound rotor motor the windings are brought out to the housing by slip rings and the circuit is required to be completed externally. In both cases, once the rotor circuit is complete, it is the number of times the flux lines cut the rotor bars that determines the magnitude of the current induced.

**Equation 3: Induced voltage in a conductor moving in a magnetic field**

\[ e_{ind} = (v \times B) \cdot l \]

where:
- \( v \) = velocity of the wire
- \( B \) = magnetic flux density vector
- \( l \) = length of the conductor
- \( e \) = voltage induced

To develop the rotor/stator interaction further, when current flows through a rotor bar a magnetic field is induced around the bar (Figure 6) that alters the flux distribution in the stator’s rotating magnetic field. Assuming the stator’s rotating magnetic field is clockwise, the flux redistribution results in a strengthening of the flux density on the left hand side and a weakening on the right, as shown in Figure 10. In consequence of this redistribution a force is exerted on the rotor bar to move it in the same direction as the rotation magnetic field. If the induced torque (force) is sufficiently high rotation of the rotor occurs and the rotor’s relative speed with respect to the stator’s magnetic field decreases. This will result in less flux lines cutting the rotor bars and therefore less current being induced, producing a weaker magnetic field around the rotor bars with less redistribution of the stators magnetic field and therefore resulting in less torque induced.

![Figure 10: Torque induced on a rotor][7]

The concept of relative speed is referred to as slip and is often expressed as a percentage shown in Equation 4. If a rotor is stationary its slip is equal to one (s=1). If the rotor is at synchronous
speed its slip is equal to zero \((s=0)\). At a slip of zero the induced voltage is zero and therefore the current is zero, producing zero torque. In reality, rotational losses of the motor due to friction and windage losses (hysteresis and eddy currents in the stator iron core) are always present, so if the rotor did reach synchronous speed it would do so only momentarily as the rotational losses would act to slow it down and induce torque in the rotor once again.

A point will be reached where the induced rotor torque matches that required by the rotational losses and at that point the motor will remain at a fixed speed. If a load were placed on the motor, then a lower speed would be reached where the induced torque again matches that required by the rotational losses plus the torque requirement added by the load.

**Equation 4: Slip percentage**

\[
\begin{align*}
    s &= \frac{n_{\text{sync}} - n_{\text{rotor}}}{n_{\text{sync}}} \times 100\% \\

    \text{where:} & & s &= \text{slip percentage} \\
    & & n &= \text{rotational speed in rpm} \\
    & & \text{sync} &= \text{synchronous}
\end{align*}
\]

When purchasing a motor the motor will be specified with a certain slip indicating the no load speed which it will run at and therefore the rotational losses of that machine. A method for determining the speed of a motor at any given slip is shown in Equation 5.

**Equation 5: Slip and rotor speed**

\[
    n_{\text{rotor}} = n_{\text{sync}} (1 - s)
\]

\[
    \text{where:} & & s &= \text{slip in decimals}
\]
3.2 Squirrel Cage Motors

In industry the squirrel cage motor is the basic workhorse of the induction motor family. Having a robust design it is reliable, has low operating costs, and is relatively cheap to construct.

The stator windings of a squirrel cage motor are wound on a laminated iron core inserted into semi-enclosed slots within the inner walls of the stator housing. Wire used in the windings is completely insulated from contact with itself when looped, from each phase, and from earth. Figure 11 shows a typical design.

![Figure 11: Sketch of a typical cage rotor motor stator [9]](image)

The rotor is positioned central within the stator with the minimum practical air gap between the outer rotor bars and inner stator windings. Rotor bars are either bare or lightly insulated solid aluminium or copper, and at both ends of the rotor bars are shorting rings used to complete the rotor circuit and allow current to flow. A typical design for a squirrel cage rotor is shown in Figure 12.

![Figure 12: Representation of a typical cage rotor design [10]](image)
As mentioned the no-load and full-load slip of a motor is determined by the rotational losses and rotational losses plus connected load respectively in the rotor circuit. As the rotational losses include \( i^2R \) losses in the rotor (\( R = \) Rotor Resistance) slip is therefore dependent on the impedance of the rotor circuit. Because a squirrel cage rotor uses shorting rings to short the rotor bars to allow current to flow the resistance of the rotor circuit will always remain the same. This is a disadvantage of a squirrel cage motor because the current through the rotor cannot be controlled.

Low rotor impedance is required when small no-load and full-load slip is desired. Also at higher slips the current in the rotor increases requiring a corresponding increase in current through the stator windings from the supply. Low circuit impedance is therefore also desired so operating currents are low. However higher rotor impedance reduces rotor current and provides higher starting torque. In general for a squirrel cage motor, higher rotor impedances produce greater starting torque, higher full load slip and lower starting currents. Figure 13 shows this relationship, the dashed lines labeled \( b \) are motor characteristics from a squirrel cage design with a higher rotor resistance than \( a \).

![Figure 13: Rotor resistance, starting torque, and starting current [7]](image)

The ideal characteristic for a squirrel cage motor would be an initially high resistance at start-up to reduce starting current and a lower resistance during operation to reduce slip. Figure 14 shows the torque-speed characteristics of both a high circuit impedance rotor and a low one with the
desired characteristic just mentioned indicated by a dashed line. Because the rotor characteristic of a squirrel cage motor is fixed, achieving this desired characteristic is a little tricky.

![Desired characteristic of a squirrel cage rotor](image)

**Figure 14: Desired characteristic of a squirrel cage rotor** [6]

Historically a squirrel cage motor would be designed to suit a specific application and a tradeoff would be made between starting torque and operating speed. When low slip motors were required the design of the motor would be as efficient as practical to minimizing losses, however this of course meant that the starting torque was reduced and therefore not applicable in other applications. When situations required high starting torques the resistance of the rotor circuit was increased and lower operating speeds would be dealt with.

There are specially designed motors available with high starting torques because the rotor bars are constructed in a concentric ring formation. This design allows higher currents to be induced in the rotor bars due to a reduced skin effect, and this then produces higher torque in the motor with the same magnetic field supplied by the stator. Comparing this with a standard squirrel cage rotor a higher torque design results in higher starting torque and lower current drawn from the supply. This implementation of rotor design addresses some of the limitations of a standard squirrel cage motor.

Changing the shape of the rotor bars is another way of overcoming the limitations of a squirrel cages motor, with the result of more or less achieving the desired characteristic shown in Figure 14. Rather than having circular or square rotor bars, specially designed cross sections are designed to increase eddy current losses during starting. This works on the principle that eddy
currents in the rotor can be approximated by an inductor in the rotor circuit. With the rotor at low speed the frequency of the flux generated in the rotor is high and as eddy currents are being approximated by an inductor the impedance of this rotor circuit will also be high. As the rotor increases in speed the frequency of the flux generated in the rotor reduces, reducing the impedance of the inductor and therefore lowering the rotor circuit impedance. The result of this interaction is to produce high rotor impedance at start-up and a reduction in the rotor impedance as the rotor approaches operating speed, therefore exhibiting a non-fixed rotor circuit impedance characteristic.

Implementation of a wound rotor motor can be the alternative for some applications where a fixed rotor characteristic is not applicable. Wound rotor motors have the ability to control the rotor circuit impedance externally by connection of resistances in series with the rotor circuit. However this option is more expensive due to the complexity of the rotor windings procedure and the required inclusion of brushes and slip rings to bring the rotor circuit out to the stator for access. The machine is also not as robust as a squirrel cage motor and requires higher maintenance due to the wear of the brushes, and although this wear was designed to be at a minimum the need for replacement added further costs to this implementation option.

Mechanically a fluid coupler can be connected between the load and motor. This allows the motor to run-up to speed while only perceiving a fraction of the load torque while starting. With a fluid coupling the motor shaft spins inside a compartment filled with a lubricant which causes the fluid to rotate, creating a vortex. At low speed the velocity of the liquid is low and so too is the frictional coefficient between the fluid and the stationary load shaft. This would result in less ‘grip’ on the load shaft by the fluid and therefore less torque imposed on the motor by the load. As the motor increased in speed the friction between the fluid and the load shaft would increase and the fluid coupling’s ‘grip’ would tighten, the motor shaft would then see more torque imposed by the load but by this time its speed would be approaching operating speed and the motor would be able to absorb it. And at high speeds it would be like the fluid coupling was not there at all and that the motor was directly coupled with the load.
Finally advances in variable speed drives have allowed squirrel cage motors to be used in applications where it would not otherwise be suited. Variable speed drives are to be discussed in a later section of this report.

### 3.2.1 Torque - speed curves

The torque speed curve of a motor allows for a quick evaluation of the suitability of that motor to a specific application. Some important characteristics to be identified when looking at a motor’s torque-speed curve are shown in Figure 15. The starting torque of a motor is a measure of how much torque can be provided by that motor when in a locked rotor position, this is given by the intersection of the characteristic curve with the vertical torque axis and is often expressed as a percentage of full load torque. The pullout torque of a motor is the maximum torque available from that motor, for a fixed rotor characteristic this value can only be achieved at a specific slip and is determined by the rotor characteristics. Finally the full-load torque is the rated torque of the motor given by the intersection of the curve with a 100% torque reference shown as a dashed horizontal line in Figure 15. At this intersection point, the mechanical speed axis will identify the operating speed of the motor when full load has been applied.

![Figure 15: Characteristics of a torque speed curve](image)

Because torque-speed curves are affected so drastically by motor design a need for standardisation of motor manufacturing was required for industry. In this way, if a motor for a
common applicable was required an order could be made for a motor which conformed to specific standards suited to that application. The most widely used classifications of ac induction motors are defined by the National Electrical Manufacturers Association (NEMA) and the International Electrotechnical Commission (IEC). The NEMA classification is adopted by American manufacturers while the IEC classification is widely adopted by the European Industry, however both classifications will specify similar requirements.

The NEMA standards for classification are shown in Figure 16. Design B is the most common type of ac induction motor in circulation, with Locked Rotor Torque (LRT) approximately 200% of Full Load Torque (i.e. at 100%) and a slip at full load of less than 5%. Standard squirrel cage motors exhibit similar characteristics to this classification with 3% slip common at full load and 300% to 350% of full load torque at pullout. Squirrel cage motors with higher torque designs such as the concentric rotor bars discussed previously will often exhibit torque-speed characteristic similar to Design C.

![Figure 16: Torque speed curves of NEMA standard motors [9]](image)

### 3.2.2 Voltage and frequency relationship

The relationship between frequency and voltage on flux generation is shown in Equation 6 and demonstrates that the flux generated in the stator is proportional to the voltage applied to the motor and inversely proportional to the applied voltage’s frequency. The magnitude of the current induced in the rotor is directly related to the magnitude of flux in the stator, which ultimately determines the torque induced. However as shown in Equation 6, this is controlled not
by the current in the stator windings but by the voltage impressed upon the stator windings by
the supply. This is true due to the relatively low voltage drop occurring across the stator
windings, and therefore the magnitude of the magnetic field induced in the stator is required to
balance proportionally with the magnitude of the voltage applied at the motor terminals.

When too much flux is generated in the iron core of the stator the core is driven into saturation. It
is undesired to operate a motor in saturation because small increases in load requires large
increases in current drawn from the supply to produce the small increase in flux required to
match the load, and if a large increase in load were applied a very large increase in current would
occur because a large increase in flux would now be required to equal the load.

Equation 6: Flux, voltage and frequency

\[
\phi \propto \frac{V}{f}
\]

where:
- \( \phi \) = Flux
- \( V \) = Voltage
- \( f \) = Frequency

A motor is manufactured to operate at a rated voltage and rated frequency, these values referred
to as the motors base values i.e. base voltage and base frequency. When operating at base values
the motor is designed to produce high magnitudes of flux with as comfortable a margin as
possible between this operating point and the point where the motor approaches saturation.
Because efficient motors require minimal losses, a reduced material list is often the solution and
as a consequence of this, these machines will generally operate close to their saturation point.
From Equation 6 if frequency was fixed and an excessive voltage increase occurred above the
base voltage the flux in the stator would increase and the motor would be driven into saturation.
And if voltage was fixed and an excessive frequency reduction occurred below base frequency
the flux would again increase and the motor would again be driven into saturation. Therefore for
any changes in operating point away from base values, corresponding adjustments must be made
to avoid saturating the motor and the unwanted effects that this will produce.
3.3 LOAD CHARACTERISTICS AND MOTORS DRIVES

In industry there are two common types of loads to which a motor is likely to be connected. The first is a constant torque load with a characteristic shown in Figure 17a. The second is a variable torque load with a characteristic of the form shown in Figure 17b.

The discerning characteristic of a constant torque load (Figure 17a) is that the same torque is present when at a stationary position as it is throughout the operational speed range. When you start a conveyor for example, in a stationary position friction caused by mass on the conveyor and gravity \( F = m \cdot a \) is the same friction as when it is moving. Common examples of constant torque loads in industry are conveyors, positive displacement pumps, traction drives, and compressors.

Variable torque loads on the other hand (Figure 17b) have torque requirements that increase with the speed of operation. A fan is a good example of this type of load characteristic. When a fan is started the impeller is initially stationary and the only torque required by the motor is the torque used to overcome the impellers moment of inertia. But as the speed of the fan increases the wind resistance also increases and the torque of the load increased accordingly, the increase in torque will generally increase with the square of the speed. Common examples of this type of load are centrifugal fans, centrifugal pumps, and blowers.

![Figure 17: Load Characteristics a) Constant Torque b) Variable Torque](image-url)
3.3.1 DOL drives

A Direct Online (DOL) drive for a motor will be housed in the Machine Control Cubicle (MCC) and is used to control the power supplied to a motor. It does so by opening and closing a contactor which will either break or make the supply circuit to that motor. Using a DOL drive to start a motor is like turning on a light switch i.e. bang! … and now the motor has power.

Except for when the stator’s iron core is in saturation, current in the rotor is proportional to current through the stator (in saturation, as alluded to previously, small increases in rotor current produce marked increases in stator current). Additionally torque is proportional to the square of the voltage applied to the stator terminals as shown in Equation 7. A consideration when selecting a DOL drive for an application is related to the torque / voltage relationship shown in Equation 7, and will be developed with an example case of starting a standard squirrel cage motor.

Equation 7: Torque and voltage

\[ \Gamma \propto V^2 \]

where: \( \Gamma \) = Torque   
\( V \) = Voltage

With a Direct Online (DOL) start of a standard squirrel cage motor, the start-up current at full load torque (FLT) is between 600% - 700% of full load current (FLC). Electrical designs for a motor circuit will usually allow 3% to 5% voltage drop at the motor terminals at rated conditions. Taking 3% as the conservative voltage drop at FLC, during normal operation, the available torque from the motor based on Equation 7 would be 94% of FLT (dealing in p.u. values a 3% voltage drop provides 97% of rated voltage at the motor terminals with corresponds to 0.97^2 of rated torque equaling 0.94). This would normally be accommodated for by the selection of a slightly oversized motor for the application.

The issue occurs when considering the voltage drop at start up due to the 6 to 7 x FLC required. If the motor was connected to a constant torque load application for example, at the moment of
contact from the DOL, full load torque would be required and therefore 7 x FLC would be drawn. The voltage drop at the terminals would then correspond to 21% (7x3%) and the voltage at the terminals would be 79% of rated voltage, using Equation 7 this would results in 65% (0.79^2) of FLT available at start up. To select an oversized drive to accommodate this starting torque reduction would not be practical and alternative methods of connection must be considered, many of which have been addressed in previous discussions during this report.

### 3.3.2 VVVF drives

The basic operation of a Variable Voltage - Variable Frequency (VVVF, pronounced ‘triple-V-F’) drive is to first rectify the supply voltage into a DC voltage and then through high speed semiconductor technology invert this DC voltage to an AC voltage at any desired frequency. These forms of drives are often designed to control both voltage and frequency across the entire operating range of the application. With this ability VVVF drives can be used with motors to control applications which the motor may not have otherwise been suited to, such applications are those requiring specific speed control and loads possessing constant torque characteristics without the need to oversize the motor.

In the case of constant torque loads it is desired to maintain a constant level of flux in the stator across the entire speed range of the motor. Referring back to Equation 6, at low frequencies of operation the flux increases in the stator windings, and at very low frequencies of operation the magnitude of this increase would most likely drive the motor into saturation. To avoid this from occurring, an equal decrease in voltage is required to maintain a constant level of flux in the stator and avoid saturation. Figure 18 shows the desired linear relationship between voltage and frequency with the base voltage and base frequency indicated by the dashed lines.
A control strategy such as the one employed in Figure 18 by a VVVF drive is referred to as constant V/Hz control and a conveyor is a good example of where this type of application is required.

As mentioned in the previous section entitled **Load characteristics and motor drives** two common loads can be connected to a motor. If we consider the case of a constant torque load, an obvious advantage of VVVF implementation is the controlled starting speed of the load by control of the synchronous speed of the motor from the VVVF drive. Another less obvious advantage of VVVF implementation is presented to the engineer when accommodating for variations in initial load likely to occur. If we take the example of a conveyor once again, there are two extreme conditions in initial load which can occur and that is the cases of a loaded and unloaded conveyor. Comparing both situations, the torque required for a loaded conveyor is considerably higher than the torque required for an unloaded one. For a standard squirrel cage motor the starting torque is less than the maximum torque available, so the selection of a motor for this application would have to be based on the starting torque available and the worst case scenario likely to occur, and in this example that would be the torque required for a fully loaded conveyor. Regardless of the likely operating conditions i.e. the conveyor may only start loaded once in a 100 times, the motor must still be selected for loaded conditions. However because the VVVF’s produces a constant torque characteristic from the motor at magnitudes equal to pullout torque (maximum torque at 300% to 350% of FLT usual) the motor can be selected for standard operation with the ability to handle these worst case scenarios if they occur.
Variations from this control strategy may be required when operating at low frequencies and requiring full torque. This is because the principle which constant V/Hz control is based on (Equation 6) assumes the voltage drop across the stator windings is negligible compared to the voltage supplied. However with a constant V/Hz control, the lower the operating speed of the motor the lower the voltage supplied to the stator by the VVVF drive, as can be seen by in Figure 18. With low voltages such as this the voltage drop across the stator windings becomes less negligible, and because a high percentage of voltage is being dropped across the stator winding the flux in the stator demonstrates a characteristic as shown in Figure 19. To overcome this issue modern VVVF drives are able to provide a voltage boost at these low operating speeds to account for the now significant windage losses. The resultant voltage boost control strategy implemented by a VVVF can be seen in Figure 20.

![Figure 19: Flux characteristic in constant V/Hz control][7]

![Figure 20: Voltage boost characteristic in constant V/Hz control][7]
The effect a VVVF drive has on the torque-speed curve of an ac induction motor is shown in Figure 21, and as can be seen in the figure a change in frequency below the base frequency causes a shift in the characteristic curve horizontally along the frequency axis. If increment steps between the frequencies were small enough the torque available from the motor would appear to be a constant value across its entire operational speed range, indicated by the dashed line in Figure 21. Because the VVVF drive is able to maintain a constant flux in the stator windings when operating at lower speeds, maximum torque can be reproduced at all frequencies. Therefore the torque characteristic produced in an ac motor using VVVF control is seen to be constant by the load with the magnitude of this torque equal to the pullout torque rating of the motor, which is often 200% to 300% of FLT.

![Figure 21: Effect of frequency change on torque speed curve](image)

As with constant torque loads and constant V/Hz control, variable torque loads can be addressed by a VVVF in a similar manner. For this situation the VVVF is simply required to employ a different control strategy in relation to the adjustments made to the voltage in response to frequency changes in the supply.

To end this discussion let’s look at how the VVVF drive can control starting currents. Figure 22 shows a block diagram depicting a standard connection of a motor and VVVF drive configuration. If for arguments sake the motor in this figure was started DOL, then 6 to 7 times FLC would occur when full load torque was connected. (When referring to FLC this is with
respect to the current drawn from the supply, which is an important distinction that will become clear shortly.) If instead a VVVF drive and constant V/Hz control was implemented, although the same torque is required at start-up and therefore the same current through the rotor, the VVVF supplies power to the motor at an initial low frequency and at a corresponding lower voltage. Less power will be consumed at start-up than in the DOL case where both high currents and high voltages are present. As a result of this constant V/Hz control strategy constant power consumed by the motor is maintained at a constant value, as power in is equal to power out, as well as the voltage supplied to the VVVF remaining constant, the current drawn from the supply by the VVVF is also constant. Fluctuations may occur due to voltage boosting techniques being employed, load changes, losses in the drive, or losses through heating, but as a general rule 200% to 250% of FLC during start-up can be expected.

![Figure 22: Schematic of a VVVF drive connection](image-url)
4 LOAD FLOW STUDY AND LV CABLE SELECTION

Approximately 250 drives are present in the process plant being designed at Kinsevere. This is one reason why the complete load flow study conducted for Kinsevere is not presented in this report. Additional to this reason I did not see it appropriate to display this information for public knowledge. So as a compromise I have included in this report extracts of the load flow study and LV cable schedule conducted for the two Tailings Area MCCs, the smallest MCCs present within the plant, and a screen capture of the Electrowinning Area MCC, one of the largest MCCs in terms of number of drives on site, shown small enough not to display information but included to provide to the reader an indication of scale. Additionally, listed in the next section is an overview of the results obtained from the load flow study, used to determine the size of the transformers ordered for each MCC.

4.1 LOAD FLOW STUDY

![Figure 23: Load flow list for Tailings Area MCC 72-MC-007 and 72-MC-008 (1 of 2)](image-url)
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<tr>
<th>CONNECTED LOAD</th>
<th>DIVERSITY FACTOR</th>
<th>LOAD FACTOR</th>
<th>OVERALL LOAD FACTOR</th>
<th>MAXIMUM DEMAND kW</th>
<th>MAXIMUM DEMAND kVAR</th>
<th>MAXIMUM DEMAND kVA</th>
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<td>0.8</td>
<td>0.8</td>
<td>5</td>
<td>4</td>
<td>6</td>
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Figure 24: Load flow list for Tailings Area MCC 72-MC-007 and 72-MC-008 (2 of 2)

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<th>MCC 1100: TO MAIN MCC 2200</th>
<th>MCC 1100: TO MAIN MCC 2200</th>
<th>MCC 1100: TO MAIN MCC 2200</th>
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<th>MCC 1100: TO MAIN MCC 2200</th>
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Figure 25: MCC load flow list from Electrowinning Area 60-MC-001
4.2 SUMMARY OF MCC LOADS

72-MC-007: Tailings Disposal Stage 2 Pumps
600W 382kVA ∴ 0.5MVA ordered

72-MC-008: Tailings Storage Facility
333kW 262kVA ∴ 0.5MVA ordered

60-MC-001: Electrowinning Area
1917kW 1977kVA ∴ 2.5MVA ordered

50-MC-002: SX Solutions Ponds Area
802kW 847kVA ∴ 1MVA ordered

15-MC-004: Grinding Area
2501kW 2294kVA ∴ 2.5MVA ordered

70-MC-003: Tailings Disposal
778kW 623kVA ∴ 1MVA ordered

10-MC-005: Crushing Area
417kW 532kVA ∴ 1MVA ordered

90-MC-006: Service Area
558kW 569kVA ∴ 1MVA ordered

4.3 LV CABLE SELECTION

An LV cable schedule was also performed and an extract of this cable schedule for Tailings Area MCCs can be seen in Figure 26, Figure 27, and Figure 28. Also presented in this section is an example calculation for the Mill’s Cyclone feed pump. The intention for this inclusion is to
demonstrate to the reader the required tasks to be performed when conducting this task in the future.

![Table](image1.png)

**Figure 26: LV cable selection from Tailings Area MCCs (1 of 3)**

![Table](image2.png)

**Figure 27: LV cable selection from Tailings Area MCCs (2 of 3)**
4.4 **EXAMPLE DEMONSTRATING METHODOLOGY**

The cyclone feed pump is a centrifugal pump required to pump the Mill output feed to the cyclone separator. The motor to be connected is a 400kW squirrel cage motor and the bus voltage at the MCC is 525Vac. A simplified process diagram of the cyclone feed pump is shown in Figure 29.
The first task is to identify the rated power of the motor, the supply voltage connected, and from manufacturer information, the rated power factor of the motor and its efficiency. From this information the operating current can be determined. At rated conditions indicated below, and power factor and motor efficiency values given in Figure 30, the rated operating current is:

\[
V_{source} = 525\, V \quad P_{rated} = 400\, kW \quad PF = 0.87 \quad eff = 0.96
\]

\[
I_{rated} = \frac{400 \times 10^3}{\sqrt{3} \times 525 \times 0.96 \times 0.87} = 520.6\, A
\]

![WEG Industrias S.A. Performance Under Load](image)

Figure 30: Manufacturers motor data for 400kW squirrel cage motor (WEG)

The length of the cable run from the MCC to the motor needs to be measured. This is achieved by use of a 3D modeling package known as NavisWorks. Ausenco has a team of draftmen and
women with the responsibility of inputting the design of the Copper Extraction plant into this three dimensional package. Dimensions are to scale and accurate measurements can be taken using the measuring tool provided, with the measured values returned in meters. Figure 31 shows a screen capture of NavisWorks overlooking the cyclone separator pump of this example. The building in the bottom left hand corner is the Crushing Area MCC (15-MC-004).

![Figure 31: Cable route and distance](image)

The total length of the cable run indicated in Figure 31 is 115m. As a design standard, LV power cables are to travel on cable ladders where possible. As can be seen by the cable route taken to the pump, this is not the most direct route possible, and a shorter route could be made by going underground directly to the right from the MCC. However it is undesirable to bury cables in the ground because of the potential of pests damaging the insulation (especially termites) and personnel digging in that vicinity unaware of the cable run below.

De-rating factors are applied to the operating current to account for variations in standard operating conditions from which AS 3008 has based their table data. The applicable conditions that are required to be de-rated for Kinsevere are the running of multiple cables along a
perforated cable ladder side by side and touching. The reason for this de-rating requirement is the increase in ambient temperature around the cables due to mutual heating. Figure 32 shows the de-rating multiple based on maximum grouping in one cable ladder equal to 3 cables side by side and two levels of cable run.

![Perforated Cable Ladder](image)

Figure 32: Table 24 from AS/NZS 3008.1.1:1998 [12]

Applying the de-rating factor gives:

\[
I_{\text{rated+derating}} = \frac{520.6}{0.8} = 650A
\]

Using Table 12 from AS 3008 (shown in Figure 33) it can be seen that the maximum current capacity of multi-core copper cable layed unenclosed and touching is 570A, which is insufficient for this connection. Therefore an alternative option is to lay two cables in parallel. The current rating for each cable then becomes:

![Table 24](image)
\[ I_{\text{rated}} + \text{derating} + \text{parallel} = \frac{650}{2} = 325 \text{ A} \]

From Figure 33 it can be seen that a 185mm\(^2\) cable is the required cable size for this application.

With the cable size now selected for the application the next task at hand is to determine the voltage drop at the terminals of the motor, and for this task to be completed the resistance and reactance of the cable must be determined. AS 3008 lists these impedance values in Table 35 and Table 30, these tables have been included in the report and are shown in Figure 34 and Figure 35.
As is seen in Figure 34 the resistance of a cable depends on the operating temperature of that cable. For the case concerning a voltage drop at startup, the temperature of the cable is taken as the temperature of its environment (ambient).

\[
Z_{R@45} = 0.112 \, \Omega/km \quad Z_L = 0.0744 \, \Omega/km
\]

\[Cable \ Length = 115m = 0.115km\]

\[
\therefore Z_{cable} = 0.112 \times (0.115) + j0.0744 \times (0.115)
\]

\[= 0.0129 + j0.0085\]

---

**TABLE 35**

<table>
<thead>
<tr>
<th>Conductor size (mm²)</th>
<th>Copper* a.c. resistance at 50 Hz, Ω/km</th>
<th>Aluminium a.c. resistance at 50 Hz, Ω/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor temperature, °C</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>1</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>1.5</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>2.5</td>
<td>0.18</td>
<td>0.21</td>
</tr>
</tbody>
</table>

---

Figure 34: Table 35 from AS/NZS 3008.1.1:1998 [12]
From an early calculation, during normal operation at full load current (FLC) the magnitude of that current is 325A. Therefore the voltage drop at the terminals is:

\[ V_{\text{drop}} = Z_{\text{cable}} \times I_{\text{FL}} \]

\[ = 325 \times (0.0129 + j0.0085) \]

\[ = 4.19 + 2.76j = 5.02 \angle 33^\circ \]

\[ \therefore V_{d} \% = \frac{5.02}{525/\sqrt{3}} = 1.6\% \]

According to AS3008 the design standard states a maximum of 5% voltage drop at the terminals. However at Kinsevere the allowable voltage drop is 3%. Using Kinsevere as the base it can be concluded that the voltage drop during operation is acceptable.
From Figure 30 a figure is listed labeled II/In. The value of this figure is 7.5 and the meaning of this figure is the percentage of full load current which will occur during startup. Therefore at start-up the designer must accommodate for 7.5xFLC. Therefore at locked rotor (start-up) the current through the cable is:

\[ I_{\text{start-up}} = 7.5 \times I_{\text{FLC}} \]
\[ = 7.5 \times 325 = 2438 A \]

\[ V_{\text{drop}} = Z_{\text{cable}} \times I_{\text{start-up}} \]
\[ = 2438 \times (0.0129 + j0.0085) \]
\[ = 31.45 + 20.72 j = 37.7 \angle 33^\circ \]

\[ \therefore V_d \% = \frac{37.7}{525/\sqrt{3}} = 12.4\% \]

From Equation 7 the start-up torque available to the motor is then:

\[ \Gamma_{\text{start-up}} = \left( \frac{87.6}{100} \right)^2 = 76.7\% \text{ of FLT} \]

For the case of the cyclone pump as per Figure 29, the load attached to the motor is a variable torque load (Figure 17b) and therefore loss of torque at start-up is not as significant. Therefore a DOL drive for this application would be acceptable. However a process requirement for this application is the ability to vary the flow rate of this pump. This can be achieved either through gearing or alternatively through a VVVF drive installed. The choice was made for the latter.

One final note on this situation is related to motor ratings and VVVF operation. A usual cooling method for squirrel cage motors is forced ventilation from a fan coupled to the drive shaft of the motor. When insulating this type of motor, manufacturers will account for the heat dissipation provided by the cooling system at rated speeds. If the operating speed of the motor is lower than
rated, the ability of the cooling system to remove heat from the windings is drastically reduced. Therefore when using a VVVF drive to reduce the operating speed of a motor for an application this must be referred the manufacturer so the reduced cooling ability is accounted for.
5 PROCESSES INVOLVED IN ORE REDUCTION

5.1 Crushers

The supply of crushed ore comes by truck transportation from a distant open cut mine site. Large Hallpacks transport the mined ore to a ROM bin situated close to the process plant. The ROM bin is effectively a large storage bin positioned in a raised location with an exit passage and chute at its ground level. Referring to Figure 36, the Crusher (3), also referred to as a Mineral Sizer, is fed from a sublevel conveyor (2) beginning at the base of the ROM bin (1).

![Figure 36: Schematic of ROM bin, sublevel conveyor, and Mineral Sizer](image)

The mechanics of a Mineral Sizer can be viewed as two parallel corkscrews rotating in opposite directions towards each other. These ‘corkscrews’ are driven by two 110kW three phase, squirrel cage, induction motors. Ore fed to the Mineral Sizer can only pass through to the conveyor when the particle size is small enough to fit through the pre-calibrated gap size. The Sizer used for the Kinsevere project is rated to output crushed ore with a diameter no greater than 625mm.
5.2 CONVEYORS

There are two main sections of the conveyor system employed in the Kinsevere Project. The first is a Tie-in conveyor, intended to selectively transport crushed ore from the existing Crusher to the new Process Plant. The second section of conveyor system is the Mill Feed Conveyor which takes the course from new Crusher to new Ball Mill.

The conveyor model employed in both situations is a belt conveyor: a long, continuous, rubber belt, looping the entire length of the conveyor, supported by rollers, with the ore sitting on top, and two drive motors positioned at each end of the conveyor to provide movement. Both conveyors are driven by three phase squirrel cage induction motors.

Figure 37: Site picture of a belt conveyor

5.3 BALL MILL

Briefly mentioned in the Copper extraction overview was the Ball Mill’s electrical connection scheme. The key electrical components are:

1. A 3MVA wound rotor induction motor
2. A Liquid Resistance Starter (LRS), and
3. A Slip Energy Recovery (SER) Unit
5.3.1 Wound rotor motor

The 3MVA motor is the main drive of the Mill during operation. It is an ac induction motor with a six pole stator and its rotor circuit brought out for resistance insertion. Connection to the stator is at 11kV and during normal operation the rated current is 160A. The principle of operation of this machine is the same as the squirrel cage motor and has been explained in depth in previous sections.

5.3.2 Liquid resistance starter

A simplified description of a LRS is a variable resistor placed in series with the rotor circuit. Initially the resistance is at its maximum and is gradually reduced as the motor starts up. Physically, the device is more like a battery i.e. terminals (electrodes) submerged in battery solution (electrolyte). How the LRS differs from a battery is it possesses the mechanical means to raise and lower its electrodes in and out of the electrolyte.

In essence, it is the amount of contact between the electrode and electrolyte which determines the resistance. Practically, as the rotor is three phase, the LRS has three electrodes, with the resistance being seen between the phases. Starting position is when the electrodes are fully submerged in the electrolyte and at this point the resistance is at its greatest. As the motor runs up to full speed the LRS raises its terminals, lifting the electrodes out of the electrolyte, and reducing the resistance. When in its maximum vertical position the LRS is completely shorted and effectively removed from the rotor circuit.

A major advantage of the LRS over other methods such as a staged resistances technique is its controllability of the resistance value during operation. For a staged resistance implementation the steps which occur when resistance change is requested are fixed at the minimum resistance size installed which can be shorted from the circuit. With a LRS implementation, the resistance change is smooth and analogue, based on the height of the electrode removed from the electrolyte. The implementation design for height adjustment of the LRS electrodes is via a worm drive configuration, a squirrel cage motor, and a VVVF drive controlling the speed of operation of the motor. In this method of height adjustment any desired resistance change characteristic during operation of the LRS can be programmed to occur.
Also, as the current is being controlled via resistance in the rotor circuit, a consequence of this method of control is the generation of heat in the resistors. For metallic resistance starters this heat would have to be absorbed by the resistors installed without causing damage, therefore high power ratings would be required and fast and efficient cooling methods included. However with the LRS, the mass of electrolyte can store this heat and dissipate it after the starting procedure via natural ventilation.

5.3.3 Slip energy recovery

A Slip Energy Recovery Unit is installed on the rotor circuit to control the speed of the Mill between 80% and 110% of synchronous speed, while also utilising the rotor current by feeding this energy back into the grid.
6 MILL OPERATION AND THE CONTROL SYSTEM

The control system of the Ball Mill is by far the most complex system associated with the copper extraction plant and was one of three projects identified for completion in my Project Plan. This chapter is intended to provide information about the Control System of the Mill and its peripheral processes. Before this discussion takes place, an overview of the Mill hydraulic system and the cyclone separator is required.

6.1 OVERVIEW OF THE PERIPHERAL PROCESSES

6.1.1 Hydraulic system

To visualise what the situation is, think for a moment of a front bicycle wheel. Here the frame supports a central axle from which the wheel revolves around. In this situation, the axle is stationary and internal bearings allow the wheel to rotate freely. For a Ball Mill, turn this concept upside down and weld the wheel to the axle. So rather than the wheel rotating around the axle, the axle rotates with the wheel. Now, add 100 tonne of downward pressure to the wheel and you’ll find movement virtually impossible. And any movement which does occur resulting in excessive wear on the axle and support frame.

In the lubrication system employed in Kinsevere, four slide shoe bearings are present at each end of the Mill, and a combination of high and low pressure pumps supply these bearings with oil. High pressure pumps provide hydrostatic lubrication. Fundamentally this works by way of a constant supply of high pressure oil providing an upward force which equals the downward force of the rotating Mill to float the Mill above the bearings. Low pressure pumps provide hydrodynamic lubrication. The necessary prerequisite for this form of lubrication is velocity. Hydrostatic lubrication must be present during starting and stopping (static meaning stationary) and hydrodynamic lubrication must be present when the Mill is in operation (dynamic meaning moving).

To avoid overheating issues with the lubrication oil, the temperature is regulated by a combination of heating and cooling facilities. For heating, two movable skids (one for each end)
support an oil tank storing the lubricant, with the aforementioned pumps mounted vertically on top. Heaters mounted within the tank switch on when the oil temperature falls below 30°C, and switch off when the temperature reaches 35°C. For cooling of the lubrication oil three chilling units provide chilled water to a heat exchanger. Circulation pumps move oil to this heat exchanger when the oil temperature exceeds 45°C and ceases operation when the oil temperature is below 40°C. The two systems work in tandem to regulate the oil temperature between 30 and 45°C.

6.1.2 Cyclone Separator

Although the Mill is effective in reducing particle size, it is not capable of ensuring all output is below this dimension. Consequently a Cyclone Separator has been installed downstream of the Mill so oversized particles can be returned to the Mill for further grinding.

The principal of operation of a cyclone separator involves a vortex of air inside a conical structure which is injected with ground ore from the Mill. As the air (infused with the ore particles of varying size) rotates upwards the vortex widens and the velocity reduces. From the reduction in velocity, heavier particles cannot overcome the effects of gravity and fall to the inner walls. Here they slide down the sides of the conical structure away from the vortex of air and fall out the bottom. The top feed of the Cyclone Separator ejects the finer, sized particles to be used in the leaching process. The bottom feed containing the heavier particles are returned to the Mill for further grinding.
6.2 MILL CONTROL STRATEGY

The Mill Control System is PLC based with various external sensors returning state information about the process and is used to make decisions regarding Mill operation based on a Control Strategy. Pressure, Temperature, and Level sensors are all present within the Mill and interconnected processes. Unity is the PLC system used at Kinsevere which comes with its own coding standard. Citec is the program used for the Human Machine Interface (HMI) and displays graphical information about the process conditions within the plant to the operator that is monitored and controlled by the PLC.

Citec and Unity are linked via tags. These tags are defined in Unity and are essentially stored variables generated by inputs to the PLC, and evaluations of these inputs in relations to defined set-points specified by the Engineer. Over 30,000 tags are currently present in the PLC, all related to a state of a process in the plant.

6.2.1 Coding conventions

Most of the coding in Unity is done using Function Blocks, with inputs on the left and outputs on the right. Although the location of elements on the screen does not matter to the computer, it aids the programmer tremendously. Therefore the visual layout of the code should be depicted left to right, with the visual positioning more or less mimicking the logical flow intended. Naming conventions for all inputs including sensors, alarm, and motor conditions follow the pattern (Area) (Type) (Sequential No) _ (Tag). An extract of code from the Mill Control System is shown in Figure 38 and will be used to explain the information conveyed by implementing the naming convention stated above.

Figure 38: Tag naming convention
'Area' is used to designate a location in the plant that serves a specific function so in one glance you can immediately narrow your search for an item to within a rough location. The two examples in Figure 38 are both A15 which indicates the location of this tag is Area 15, which is grinding i.e. the Ball Mill. Other examples of area naming are A10 indicating Crushing and A60 indicating Electrowinning.

‘Type’ describes the motor or instrument to which the tag is associated with. The first example in green of Figure 38 is TIT which identifies the sensor to be a Temperature Indicator Transmitter, the second example in pink is PDIT indicating the sensor is a Pressure Differential Indicator Transmitter. The meaning of ‘Indicator’ is that the device will have some sort of display mounted locally on the instrument, which in many cases will be an LCD screen or some other variation. Other examples of code words include PU for Pump, LIT for Level Indicator Transmitter, and PIT indicating a Pressure Indicator Transmitter.

‘Sequential No’ is a unique number with respect to ‘Type’. This means that no other device of that type will have the same identifier.

And lastly ‘Tag’ is used to convey the various state conditions of the device. These will be generated within the PLC based on sensory information. The example in green from Figure 38 is HW indicating that it is a High Warning. The example in pink is HHA which notifies that the tag is a High-High Alarm. Other examples include RUNUP indicating the motor has reach its running speed, CIA meaning Critical Interlock Alarm, and SEQRDY indicating that all starting interlocks are in their correct state and the Sequence is Ready to be started.

6.2.2 Interlocks

An Interlock is a certain condition that when detected will prevent or trip operation of a system. To achieve this, the motors concerned with that system have to be isolated from operating. Regarding isolation, in a general sense there are two different forms, Electrical and Electronic. An emergency stop button is an example of electrical isolation because when pressed a relay will open circuit the power supply to all motors concerned. Programmable Logic Controllers (PLCs)
utilise electronic isolation because the *software* written to control the PLC ensures Start signals are not sent, and Stop signals are.

Three forms of interlocks are used in the Kinsevere project:

- **Operation interlocks** are used to trip the motor during operation, hence its name. When an undesired state or condition has been detected from a sensor or motor protection device the motor will trip and cease operation. Once an operational interlock has been tripped, the drive concerned is locked out from restarting until the situation has been addressed.

- **Process interlocks** are used when the condition of an upstream process determines Mill operation, or the condition of a downstream process is dependent on Mill operation. Process interlocks will trip the drive during operation, however they are often not instantaneous but initiated after a period of time has expired. An example of this is the feed conveyor to the Mill. If this was detected to be empty or stopped, only once stopped for a period of time will the Mill have to stop operation, because there would still be charge in the Mill at the time the situation was detected.

- **Starting Interlocks** are all conditions which must be met before the Mill is started. They are specific conditions that if not present will cause damage to equipment or introduce safety concerns. A starting interlock can also be an operational interlock, but if it is not then it is no longer of concern once the mill is running.

### 6.2.3 Modes of operation

The different forms of interlocks are a good lead in to discussing the various modes of operation in the Mill Control System. All modes serve varying purposes and are affected by each interlock differently.

- **Local**: control is initiated by an Operator directly on site by a Local Control Station (LCS). All Starting, Process, and Operational interlocks are active.

- **Remote**: control is initiated by command signals from the Control Room by an Operator. The advantage of this mode of operation is multiple events can be initiated by one
command. As with the Local mode, Starting, Process, and Operational interlocks are all active.

- Maintenance: control can be initiated either locally or remotely. Maintenance mode differs in the fact that Process interlocks are bypassed. Reasons for this mode are to allow for positioning of the Mill via an inching drive to carry out repairs (this is a smaller alternative motor for the mill which can be clutched into the mill gearing), and the conducting of test runs without the requirement of crushed ore being supplied.

6.2.4 Alarms

Alarms are generated by a combining of one analog block (Figure 39a) and four alarm blocks (Figure 39b). Alarms are generated within the PLC and are based on:

- Four set points with two for high and two for low
- An analog input referred to as a process variable and identified by RAWPV
- A hysteresis value indicating a dead band within which the process variable can fluctuate within without generating a change in signal
- A timer value which must expire before the alarm is generated.

As seen in Figure 39a, the left hand side is where the programmer can enter all the information previously mentioned, and on the right hand side are the four signals sent to the Alarm blocks i.e. HH (Hi-Hi), H (Hi), L (Low), and LL (Low-Low).

The four signals generated by the analog block in Figure 39a are each suppliers of their own alarm block displayed in Figure 39b. One reason for feeding these outputs into an alarm block instead of using them directly is the alarm blocks’ ability to suppress a signal. On the left hand side of an alarm block in Figure 39b are two inputs labelled SUPP1 and SUPP2. These both stand for suppression and if this input is true than the alarm signal on the right will not be generated.
Another reason for using an alarm block is there are some cases where you would not like an alarm to disappear if the process variable is no longer outside of specified range. The alarm block provides an AUTORST input (Auto Reset) where if the signal at this input is true then the alarm will clear automatically, but if the signal is false the alarm will not clear until an ALMRST (Alarm Reset) signal has been generated by the operator.

Figure 39: Analog and alarm blocks
6.2.5 Start-up procedure

Within the PLC the function block used to represent the drive for the Mill is shown in Figure 40. For the remainder of this discussion we will be referring to this function block as the Mill drive, this clarification is required to avoid any confusion from previous discussions regarding DOL and VVVF drives. Also, when looking at the drive labels you will notice all labels on the left hand side end with an ‘I’ and all labels on the right end with ‘O’, this is just a reminder to the programmer that the labels on the left are Input (I) and the labels on the right are Output (O).

![Diagram of Mill drive in PLC](image)

Figure 40: Mill drive in PLC

The top two inputs on the left hand side of the drive in Figure 40 are used to control the process interlocks (PII) and critical interlocks (CII) interaction. The tags used to supply a signal to these inputs are A15ML001_PI and A15ML001_CI respectively. Conditions for these tags are generated in another location using a combination of AND, OR, and TON (Timers) function blocks, with each tag generated from sensory information supplied to the PLC. Figure 41 shows the section of code which generates both A15ML001_PI and A15ML001_CI’s Boolean values.
Figure 41: Critical and process interlocks for the mill

The process interlock A15ML001_PI shown in the top portion of Figure 41 is determined by two conditions, the first condition A15_Mill_Lube_STTCOMPLETE is there to ensure the Mill’s hydraulic system is up and ready before the Mill start sequence is initiated. The second input A10WCIT0031_LW is a tag generated from a weight-o-meter installed on the Mill Feed Conveyor. Within the PLC a Low Warning (LW) alarm is generated when the conveyor is empty. This event will trip the Mill but only when the conveyor is empty for a defined period of time. The time period shown in Figure 41 is 3 minutes (t#3m) but this value was used to facilitate debugging with the true time closer to 30 minutes.
The critical interlock tag A15ML001_CI can be activated by a number of different conditions in the Mill. The way in which this code is written is ANY tag listed as an input will cause the critical interlock tag to be false if a bad state is detected. A bad state for a tag can either be true or false because some interlocks require the tag to be false for a good condition to occur. On many of the tags attached as inputs in Figure 41 a circle appears between the tag and the function block, this is set by the programmer and indicates that the signal is negated i.e. a false tag will feed a true signal to the function block.

Because it would be hard for a person not familiar with the control system to understand all the interlocks shown in Figure 41, a summary of the starting conditions are listed below:

- Oil tank level above a critical value
- Oil temperature is within range
- Both High Pressure and Low pressure pumps are running
- Pressure in the lines of the high and low pressure circuits are above a critical value
- Differential pressure across the oil filters is not above a critical value (indication of a clogged filter)
- The auxiliary drive clutch is not engaged
- The LRS is ready in its maximum position.
- The mill is stationary

Referring back to Figure 41, starting interlocks are implemented by suppressing the tags defined to be a starting interlock with an OR function block and the running signal of the Mill (A15ML001_RUNUP). In this way once the Mill is running A15ML001_RUNUP would be true and therefore regardless of the conditions of the other tags the output of the OR block would also be true.
Of the tags shown in Figure 41 there are two tags labelled A15_MILL_STAND_STILL and A15_MILL_HYDRAULICS_OK. These tags are generated by a combination of other tags in another section of the program. The reason for the existence of these tags is the conditions which dictate their state are repeated in several locations throughout the program, so rather than repeating the code every time we have written it once and defined our own variables.

Generation of the tag A15_MILL_HYDRAULICS_OK is shown in Figure 42. The tags used as inputs are purely related to the hydraulic system of the Mill. As a quick note, from the Figure 42 several OR function blocks can be seen, this is to accommodate for the redundancy operation of the high pressure and low pressure pumps.

![Mill Hydraulic is ok tag generation](image)

The purpose of the A15_MILL_STAND_STILL is to ensure the Mill is not in motion when the signal to start the Mill is generated. The consequences of this situation occurring is not good,
with major mechanical damage to the motor and gearing system very likely. This tag is true when the Mill rundown signal has been received (A15ML001_RUNDN), and either the clutch of the gearing system is engaged, or the auxiliary drive is running. The RUNDN signal is an output of the Mill drive (Figure 40) and is true when the supply to the motor has been removed and a time period inputted at the RUNDNTMR input has elapsed (Rundown timer can be seen in the lower regions of the Mill drive inputs of Figure 40).

![Image](image-url)

**Figure 43: Mill standstill tag generation**

When a false value is generated by either A15ML001_PI or A15ML001_CI the Mill drive will generate a Critical Interlock Alarm (A15ML001_CIA) which will stop the Mill if it is running, or prevent the start sequence from being initiated.

For the start sequence to be initiated an operator is required to send a start signal to the Mill drive. If the Mill is set to maintenance mode (A15ML001_MAINT) or local mode (a false value at A15ML001_REMOTE) then the command to initiate the starting of the motor occurs by a true value at A15ML001_CMDSTT (command start). If the system is in remote mode then a true value will be present at A15ML001_REMOTE and the command to start the Mill will come via an operator initiating a starting sequence from the HMI in the control room and the A15ML001_SEQSTT (sequence start) tag being used. The start sequence is already written in the PLC but lays dormant until the signal is received by the HMI to initiate. The start sequence then goes through a series of steps in order to start the Mill.

How the HMI is able to initiate a start sequence is by the sequence function block shown in Figure 44. There are two sequences written for the starting of the Mill, the first is the Mill Lube
sequence and the second is the Grinding Sequence. Both sequences consist of action blocks and transitions. Within the action block a programmer can set the state of any tag defined in the PLC. For the starting of the Mill the principle action is to set the SEQSTT tags true for the many motors involved in the start routine i.e. all low pressure pumps and high pressure pumps are run by motors and have similar drives as the Mill’s drive shown in Figure 40, a SEQSTT tag exists for all these motors to start the motor when set in REMOTE mode of operation.

The sequence function block in Figure 44 will initiate operation in the Grinding sequence by activating the first action block defined for that sequence. For operation to exit the action block, transition conditions are written, and when the conditions defined for each transition have been met execution of the next action block in the sequence chain will initiate, with the commands defined in the previous action block no longer present.

As before when describing the critical interlocks for the Mill, an understanding of what is actually happening when looking at the code in each figure is difficult, so to simplify the understanding a summary of the basic operations of the Mill start routine will be presented. The first action of the start routine is to send SEQSTT (sequence start) signals to all the high pressure pumps. When these signals are received the associated drives for each pump will send a start signal to the pump motor drive (DOL) and three outcomes are then possible:

![Figure 44: Sequence function block enabling MHI interaction](image-url)
a. If all goes according to plan no critical and process interlocks will be present and the motors will start, returning a running signal (RUNUP) to the PLC which will be received by the drive before a time has expired defined by the RUNUPTMR input.

b. A critical interlock or process interlock is detected and the drives for the effected motors will throw a critical interlock alarm (CIA). This will result in the graphical representation of the motor on the HMI screen flashing red and alarms being generated.

c. No critical interlocks or process interlocks are received but the RUNUP signal is not received before the time defined by RUNUPTMR expires. This will also generate a CIA and the pumps will also flash red on the HMI screen.

If the last two conditions are detected the start routine is aborted.

When the high pressure pumps are running (RUNUP is true) the transition condition defined for this action is set to true and execution begins in the next action block in the sequence. The second action block will then send SEQSTT signals to the low pressure pumps to operate. As with the high pressure case, identical circumstances can occur, and the start sequence will only proceed if all the low pressure pumps’ RUNUP signals are received.

As a quick note, the transition conditions for both high and low pressure pumps only require one of the two pumps in a pump pair to generate a RUNUP signal. This is because each pump pair operates in a redundancy configuration and only one pump is required at any given time. Figure 45 shows the code for generating the high pressure pumps transition. When the HP_PUMP_RUNUP tag is true, execution of the next action block will be initiated which in the Mill start routine is the starting of the low pressure pumps.
Figure 45: Transition condition for high pressure pumps

And finally, the last operation for the start routine is to signal the mill’s main drive motor to start and this has the same three outcomes as the ones listed above.
7 DISCUSSION

As time was spent in my internship placement, I became aware that there was a lot of general knowledge and simple concepts which I did not fully understand. It may have been the case that the meanings were not clearly understood, or I had simply heard of these things in passing and assumed knowledge based on common reference. When I became aware of this I decided that if I did not know the exact meaning of an instrument, concept, or application, I would research it. In most situations this act was simply a confirmation of my ideas, but on occasions I found that my understanding was incorrect, either slightly or completely, or totally lacking. Because of this fact I have presented in this report explanations of common concepts and practical applications that, from my experience, on most occasions are not fully understood.

Another realisation I had during my internship, which I find important to mention, is related to engineering design. The best way to introduce this point is by use of a common expression: ‘there is always more than one way to skin a cat’ (apologies to all cat lovers). To address this, let’s look at an issue concerning start-up of a conveyor, and the prevention of personnel in close proximity to it.

One possible solution is the installation of barriers along the entirety of the conveyor preventing access. This is an effective solution. However in the case where access is required for maintenance the original issue resurfaces. To overcome this we can implement a lockout system, initiated by the maintenance crew and only removed by that maintenance crew. And again we have solved the new issue which surfaced, but what if access were required during operation? Another possible solution is to introduce proximity sensors along the entirety of the conveyor and prevent the start-up procedure from initiating if personnel are detected. Again this is an effective solution. In fact it could be considered ideal, but it is not. With this solution the complexity of the system is high: communication wires, PLCs, sensors, calibration, mounting, coding, all required. And what if a bird was sitting on a pole near the conveyor, or a dusty situation was present, would the sensors then trip?
These examples highlight two key points. Firstly, you can often get engrossed in a series of cascading, reactive, problem solving techniques. With the end result not applicable for normal operation. The second is it is very easy to overdesign a solution. The more complex a system is the more things can go wrong. At Kinsevere, to address this issue an early warning system is employed, with sirens that can be heard anywhere along the conveyor. The sirens sound for a predetermined time before the start up procedure is initiated. This option was considered sufficient as the likelihood of personnel not hearing this siren is remote. Additionally, emergency stop buttons are located along the entire length of the conveyor which will electrically isolate the motors from their supply.

And for my final discussion point, it is important for a graduate engineer who comes out of university not to assume they are now complete in knowledge in their field of study. Because in actual fact once you finish your degree you effectively start your apprenticeship, and it is only after years of learning and listening that you become capable of performing your work competently and reliably. If you do not put in the hard yards to bring your skills up to industrial standards at the start, you are in a sense being negligent in your actions. One of the ethical guidelines for Engineers states ‘one should not act outside of their discipline’, from this it can be implied that one should not act in areas where they are not competent. And this is the reason for the previous statement because one should not underestimate the responsibility bestowed on an Engineer to perform the tasks correctly.

7.1 Problems faced during internship

One of the problems which occurred was in relation to the Mill Control System. The Mill was a vendor package bought by the client before Ausenco’s involvement. When this package was bought very little vendor data was collected. Additionally the PLC program written for the Mill was not included with the purchase but instead a screen capture of an example program was supplied. This example program was not written in the same code language as Unity which is the code language accompanying the PLC’s purchased. As a result several weeks were required reading this code and understanding its operations.
Normal to Ausenco’s control system plan is a written functional description of the process which the PLC is to control. This was not submitted by the Vendor and as a result this needed to be inferred from the screen dumps of the code supplied with the package. Examples of these screen dumps are shown in Figure 46 and Figure 47. There are exactly 71 pages of code like these and at times it felt like I was reading hieroglyphics. Also, due to contract specifications, if the intended purpose displayed in the code submitted by the vendor was not followed exactly, contractual issues could occur if something did go wrong in the future. To avoid this from occurring it was essential that the program written performed the exact operation as the example program supplied.

Figure 46: Mill control system example code 1 from vendor
Figure 47: Mill control system example code 2 from vendor

An extract of the function description which was written is shown in Figure 48.

Figure 48: Function description developed
As a result, the time required to complete this task was understated. However this did not end up being an issue with the Mill control system as this task was completed successfully.

The second issue which I faced during my internship was basically I did not have enough time to finish the short electrical analysis of the process plant and perform power factor correction calculations based on results of the load study. This was due to a combination of factors, one was the additional time required for the Mill and another reason was that I was unaware of the sheer size of the plant and the number of drives, motors and transformers that existed. The third reason is related to this last point, and that is as a result of underestimating the size of the project I inadvertantly overstated the tasks to be completed for my internship. But, in saying that, I did get pretty close.

As a side note, a short circuit analysis was conducted using a computer package known as ETAP. However it was desired to perform this task by hand and for this reason results have not been included in the report. Additionally, also stated in my project plan was the conducting of an operator training program. However, because this was a proof of concepts project that did not get the go ahead to continue, I have not included it in the report.

**7.2 Future Work**

Incomplete tasks identified for completion in my project plan is a short circuit analysis of the electrical system and power factor compensation id required. As a result for future works it is recommended that these tasks are performed.
8 CONCLUSION

This report is a detailing of the task performed during my Internship placement at Ausenco. Accompanied with this information are the principles involved in copper extraction, an overview of the Kinsevere project and its electrical system, low voltage motor selection with respect to ac induction motors, as well as common drives characteristics and varying load applications. Extracts from the LV load flow study and cable selection are included for viewing and some not so common considerations have been added for interest. Additionally, the successful completion of the Mill Control system has been notified and the methods employed for this task have been explained, with extracts of code shown and common coding practices and styles discussed and justified.

Within the discussion section of this report I have included some thoughts and realisations I have had during my internship and identified some of the limitations and issues required to be resolved to complete the tasks defined. And finally for future works, I have identified a short circuit analysis of the power system to be conducted by hand, and based on results from the load flow study, any power factor compensation requirements to be addressed.
9 REFERENCES


