# LCI'S AND SYNCHRONOUS MOTORS APPLIED TO ROLLER MILLS

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## 1. Abstract

A cement company concerned about high power-factor penalty costs requested an evaluation of the feasibility of using synchronous motors starting through LCI's to drive three new roller mills at a cement plant. The prior experience with roller mills centered about the application of wound rotor induction motors with either cascaded secondary resistance or liquid rheostat. By utilizing synchronous motors, there was the possibility of providing leading power factor to reduce the reactive power demands seen by the utility feeding the cement plant. It was theorized that, if sufficient power factor correction could be obtained, the payback period of the incremental additional cost of the synchronous motor drive system would be very short. After payback of the initial investment, all future energy savings gravitate directly to the bottom line as additional revenue. Several key concerns had to be addressed in evaluating the use of synchronous motors for these relatively high starting torque requirement applications. This paper discusses the electrical and mechanical evaluation leading up to the decision to proceed with this new application of synchronous motors started through an LCI.

## 2. Introduction

Roller mills, also known as vertical mills, are becoming more prevalent in modern cement plants. These mills have application both for raw material preparation and clinker grinding to final specifications. The increasingly competitive nature of today's business environment is pushing the mill OEM's to larger mills with greater throughput. Past applications have been powered by either fixed-speed motors or wound rotor induction motors with secondary control.

Process requirements will dictate the operating speed of the rotary grinding elements to maximize production with minimum energy expenditure. If this theoretical optimal operating point could be maintained, or accurately calculated, variable speed control would be unnecessary. The OEM that supplied the roller mill upon which this discussion is based postulates: *"The optimum grinding table speed in a roller mill is pinpointed by the equilibrium of the forces at a mass element located on the grinding table, but in spite of this some quite recent aspects show that it is appropriate to have a variable speed. With a variable speed grinding table drive, every newly commissioned roller mill could be set to it's optimum speed, the speed could be adjusted at any time to suit different mill feeds, and when the mill is being operated on line it would be easier to adjust its throughput to suit the rotary kiln."*

In summary, the following considerations support the benefits of utilizing a variable speed drive on a roller mill:

- The capability to implement fine speed adjustments at unit commissioning
- Speed adjustment for variable mill feeds
- Speed control for coordinated interaction between the mill and kiln (minimizing in-process material accumulation)

## 3. Implementation Options

The increasing emphasis on maximizing production and minimizing costs has resulted in larger roller mills. Some of the newest installations have mills requiring in excess of 5 MW of driving power. Both asynchronous and synchronous motors have been utilized. Many mills are powered by wound rotor induction motors (WRIM) with some form of secondary control. A benefit associated with variable secondary resistance, for a wound rotor induction motor, is the reduction in starting current. This can be significant where the power grid is weak. Synchronous motors started on an LCI offer this same benefit while, concurrently, minimizing power costs due to their inherently high efficiency and ability to provide leading power factor. Regardless of the type of motor applied, the extremely dirty environment forces some common construction details including totally enclosed air-to-air cooled enclosures and special seals to prevent entry of dirt into the bearings. The drive motor may be utilized singly or in combination with a gear reducer. Variable speed control options are as follows:

Wound Rotor Induction Motor – The secondary control options available, in order of their perceived preference, are:

- Cascaded secondary resistance
- Liquid rheostat
- Slip energy recovery

These three options are further explained in the 'electrical considerations' section.

Induction Motor with VFD – variable frequency drives induction motors include the following technologies:

- Gate turn-off thyristors (GTO's)
- Integrated gate bipolar transistors (IGBT's)
- Integrated gate commutated thyristors (IGCT's)

All of these devices are in common use. The benefits of the VFD are further explained in the 'electrical considerations' section.

Synchronous Motor with LCI – a unique application with the following characteristics:

- Unique torque-producing capability
- Higher efficiency
- Power factor control (when running on the LCI the power factor is lagging, similar to the WRIM)

These three elements are further explained in the 'electrical considerations' section.

### 3.1 Customer Preference

The customer initiated the request for a synchronous motor with an LCI starter for the two most prevalent reasons. First, the synchronous motor has the lowest operating cost of all of the alternatives due, principally, to the high efficiency and the capability to provide controlled leading VAr's to the power system (control the power factor angle). Second, a synchronous motor with brushless excitation and an LCI has very low maintenance costs – basically equivalent to an induction motor. The customer performed preliminary analysis that indicated the energy savings would offset the additional cost of this option in less than two years.

## 4. Electrical Evaluations

### 4.1 Wound Rotor Induction Motor

The most basic form of speed (and current) control for a wound rotor induction motor is to insert one or more fixed resistors in the rotor circuit as shown in Figure 1.

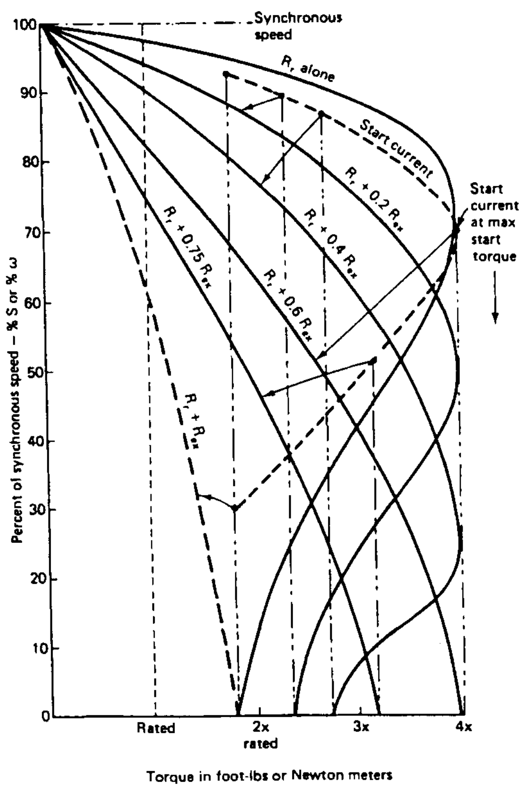


*Figure 1*

It is possible to operate at the represented speed torque curves by placing external resistors in the rotor circuit (via the 3 slip rings). This facilitates the following capabilities:

- High starting torque (curve of Rr + 0.4Rex)
- Inrush current control for weak power grids (curve of Rr + 0.75Rex)
- Accelerating high inertia machines (curve of Rr + 0.2Rex)
- Soft start capability (curve of Rr + Rex)

A contactor arrangement can be used to switch multiple resistances in & out of the rotor circuit to combine elements from Figure 1 and provide a customized motor acceleration profile. Adding secondary resistance means there is extra energy being dissipated due to the IR drop through the resistor. This adversely affects the efficiency, somewhat lowering it. Moreover, the motor power factor is unimproved, and is somewhat poorer than other alternatives. This is the least costly and most inefficient method of varying the motor speed.

Another method of wound rotor secondary control utilizes a liquid rheostat across the rotor slip rings to provide constantly variable resistance, see Figure 2 curve B.

The liquid rheostat has conductive plates with an electrolyte between them. The resistance can be varied by either changing the distance between the plates or by varying the level of the electrolyte – or both. In either case, there remains an IR drop through the rheostat resulting in heated electrolyte (which must be cooled) and poor overall efficiency. The power factor remains low just as with the cascaded resistance method of speed control.

Finally, the last evaluated control of wound rotor motors uses a solid-state slip energy recovery system as shown in Figure 2, curve A. A solid-state control is used to vary the secondary resistance. The IR drop power is routed to an inverter where it is conditioned and fed back to the incoming power system to minimize the losses. This provides variable speed operation while minimizing the heating losses of the previous methods. It is also the most costly of the wound rotor induction motor controllers. It also cannot be used to start the motor. A separate contactor or liquid rheostat is still required for that purpose.

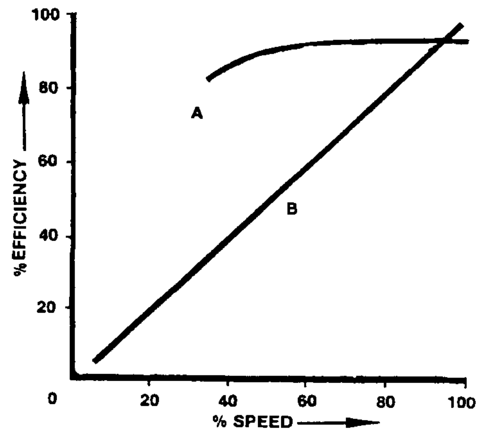


FIGURE 2

Motor efficiency using: A) slip power recovery system, B) only resistances. Example: (1000 HP motor speed range 1:3).

## 4.2 Induction Motor with VFD

The induction motor, by itself, has a speed torque curve similar to curve RR of Figure 1. A representative family of induction motor curves is shown in Figure 3

The most common induction motor has a speed torque relationship as shown by curve A of Figure 3. In ratings above 1 MW the induction motor also has very good efficiency and moderate power factor. The starting torque can be modified by adding rotor resistance, similar to the wound rotor motor examples previously discussed. The resistance is added by either changing the shape of the rotor bars or by changing the electrical conductivity of the bars – or a combination of both methods. Curve D of Figure 3 is an example of a high starting torque induction motor.

While the efficiency of the standard induction motor is very good, it still has significant losses stemming from the induction of the rotor excitation across the internal air gap between the rotor and stator. These losses become higher when special starting torque designs are needed due to increased heating in the rotor bars resulting from their added resistance.

The advent of variable frequency drives has dramatically changed the way we apply induction motors. The VFD allows us to start a load with 100% (or more) torque while limiting the starting current to rated full load values. This is accomplished without adding resistance to the rotor circuit, thereby maximizing the efficiency and minimizing the heating of the motor.

The VFD uses solid-state switching devices (GTO's, IGBT's or IGCT's) to provide variable frequency and variable voltage or current allowing the motor to accelerate without exceeding rated full load current while producing the torque required for acceleration of the load. The advantage is that, whatever the motor efficiency or power factor really is, the power system only sees the drive characteristics. Typically, an IGBT drive might have 97% efficiency and operate at a power factor exceeding 95%. If a voltage-source inverter is utilized, these characteristics are essentially constant between 20% load and 100% load. (Note, the IGBT and IGCT must be selected for the maximum torque required by the drive, and it should be acknowledged that in the case being studied the roller mill needed a minimum of 180% starting torque necessitating an oversized power supply to suit. The same requirements exist for the LCI, particularly transformer and reactor sizing)

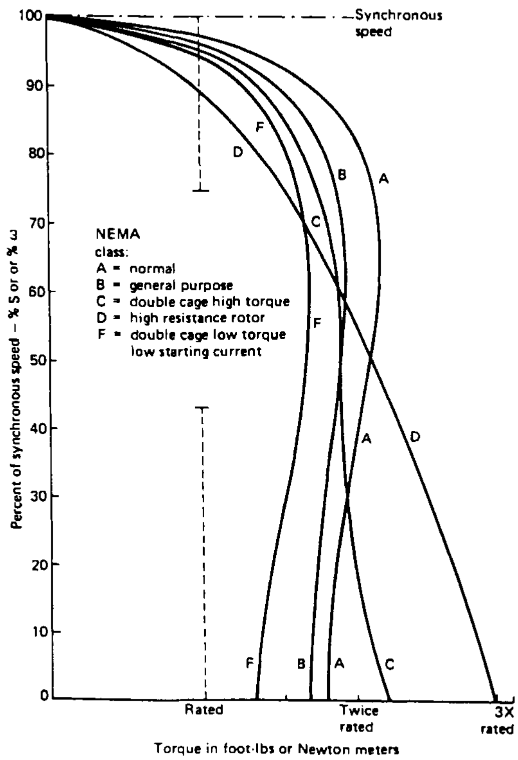


*Figure 3*

### 4.3 <u>Synchronous Motor</u>

Salient pole synchronous motors pose another unique set of characteristics. These motors get their rotor excitation from a separate source and can, therefore, operate at synchronous speed. The typical synchronous motor has a speed torque curve shown in Figure 4.

The individual poles have both a field winding and an amortisseur winding. The amortisseur winding is also called the damper winding and is a series of individual bars located near the outer perimeter of the pole face. These bars are shorted together by a shorting ring on both ends forming a squirrel cage winding similar to that of the induction motor rotor. When properly designed, low inertia loads may be accelerated to near synchronous speed utilizing just the amortisseur winding. At between 95% and 97% of rated speed, and with proper attention to phasing, power may be applied to the field winding allowing the rotor to pull into synchronism with the rotating flux wave of the stator. Once synchronous speed is attained, the excitation of the field winding can be adjusted to allow operation at unity power factor or leading power factor.

Since the damper winding is relatively small compared to a normal induction motor rotor bar, the synchronous motor has limited load acceleration capability. It is very difficult to get high starting torque or break-away loads having a high static friction which is referred to as "stiction". Also, a high starting torque design synchronous motor will have a high inrush current which may exceed the capacity of the power system. Again, increased resistance and/or larger bar sizes can be used to improve the starting characteristics. They never will, however, be as good as an induction motor for load acceleration at sub-synchronous speeds.

The advantage of the synchronous motor is that it has a huge field winding. The LCI requires application of excitation power to the field winding at zero speed. The variable frequency characteristics of the LCI can smoothly accelerate large inertia or constant torque loads while not exceeding rated amps on the stator or field. The starting characteristic of the LCI closely mimics the acceleration profile of the induction motor VFD.

Because the typical synchronous motor has salient poles on the rotor it does require careful application for constant torque loads. The torque produced by the rotor has two components – a direct axis component and a quadrature axis component. The direct axis component is formed from the flux directly through the central axis of the iron pole. The quadrature axis is the axis between field poles where the flux passes through air. With high starting and accelerating torque loads, such as roller mills without unloaders, high inertia fans, compressors and direct connected ball mills, the interaction between the direct and quadrature axis torque components can produce torque pulsations. Years of application expertise have led to the development of special controllers and software allowing the LCI to be finely tuned to minimize the effect of these torque pulsations while the load is being accelerated.

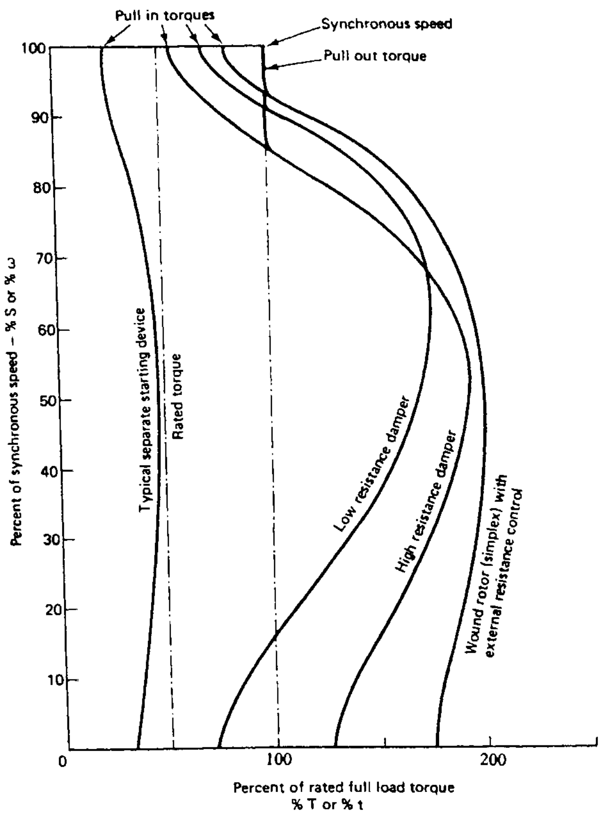


*Figure 4*

## 5. Other Considerations

### 5.1 Wound Rotor Induction Motor

The wound rotor induction motor has smoothly distributed stator and rotor windings giving a very good acceleration profile for a roller mill load. The most pressing drawback is the need to cool the secondary resistance source. Punched-grid resistors will require substantial quantities of cooling air. Liquid rheostats will require cooling the electrolyte – either by pumping it to radiators or to a liquid-to-liquid heat exchanger. A slip energy recovery system must be located in a clean electrical room, preferably near the motor. Wound rotor induction motors have been very successful in prior roller mill applications and will continue to be used for many years.

## 5.2 Induction Motor with VFD

Again, the smoothly distributed stator and rotor conductors yield a very smooth starting characteristic for this equipment. One advantage of the induction motor is that it is, generally, the smallest size motor for any particular rated power and speed. The use of modern variable frequency drives provides excellent speed control for the most demanding processes. The continued development of medium voltage solid-state devices, with very high efficiency and power factor, should ensure the continued use of induction motor drives well into the new millennium.

## 5.3 Synchronous Motor with LCI

When synchronous motors are applied to constant torque loads, by themselves, it is very hard to get a satisfactory starting profile. This is due to the difficulty in getting sufficient torque from the small amortisseur winding. Trying to adjust the torque through the use of high resistance bar alloys can result in pole face heating and other deleterious effects. Many loads can be very difficult to start due to the amount of torque required just to overcome the static friction at rest. Certain types of loads can be adversely impacted by the interaction of the quadrature axis and direct axis elements.

The LCI helps mitigate the aforementioned difficulties. The LCI, again, allows application of the field winding from zero speed and controls the amount of stator and rotor excitation, and the rate at which this power is applied, to provide a smooth starting profile. Driven equipment can be started and accelerated to rated speed (or any desired speed below rated speed) without exceeding rated volts and amps. This is particularly useful where power system grids are weak or the plant is at the end of a long transmission line.

A further advantage of the synchronous motor is the ability to provide leading power factor by adjusting the field excitation. This can only be accomplished when the synchronous motor is operated across the line. By providing leading power factor and supplying reactive power to the plant, the synchronous motor can correct for the poorer factor of many smaller induction motors.

**Why the Customer Requested Synchronous Motors?**

Our customer had made the challenge really interesting by requesting synchronous motors to drive three new roller mills – one raw mill and two finish mills for a 3,000 t/d cement plant. All three mills would be driven by synchronous motors of nearly identical ratings. One LCI would start all three motors in any desired sequence. Once the synchronous motors were started, the LCI would be bypassed to operate the motors directly across the line. As soon as the first motor was started and bypassed to the line, the LCI was available to start the second mill. The same process was repeated to make the LCI available for starting the third mill. All three mills could operate directly across the line or one could remain connected to the LCI for process control.

The reason synchronous motors were requested is the very high cost of poor power factor where the cement plant is located. When the motors are operating across the line, they would each be capable of supplying 2000 kVAr to the power supply system. This additional reactive power corrects the power factor for the remainder of the plant. The customer calculated that the incremental cost of the LCI system, vs. the lower cost wound rotor option, would be repaid in less than two years.

## 6. OEM Roller Mill Features

There were some features of the proposed roller mill that promised to overcome some of the perceived difficulties in applying synchronous motors. The two most important facilitating features are:

- The rollers could be vertically positioned by a hydraulic mechanism, which would help to unload the rollers for starting.
- There was an inching motor attached to the mill drive gearbox to allow low speed positioning and for clearing the mill when a jam occurred.

Of these two important features, the inching motor was the greatest help in applying the synchronous motor as a driver. Even with the above help, the mill still required 180% torque from the motor to overcome the “worst case” conditions in the mill.

The inching drive overcame the static friction (stiction) and would bring the mill up to about 5% of rated full speed. From this point, the LCI could accelerate the mill to full speed while not exceeding the power required by the mill (rated power). A special Mill Unit Controller (MUC) would manage the transfer of the synchronous motors to across the line operation.

### 6.1 The Role of the MUC

The Mill Unit Controller (MUC) has a sophisticated PLC for the primary intelligence. The MUC is uniquely suited to providing the appropriate sequencing to start the 3 motors from one LCI – as directed by the plant DCS system – and bypassing them to across the line operation. An example of a starting sequence is as follows:

- The MUC applies the LCI to one of the motors
- The motor and mill are accelerated to synchronous speed using only the power required to overcome the work done in the mill plus a small margin to accelerate the mill to full speed.
- The bypass contactor is closed and the LCI output contactor is opened, transferring the motor to the utility connection.

The coordination between when one contactor closes and another is opened must occur in a matter of milliseconds to prevent damaging torques or loss of synchronization with the line. The programming of the MUC, for this function, is critical to the success of the system. The MUC, therefore, programs the starting and acceleration ramps for the mill, coordinates and controls the transfer to the utility and, when required, commands the performance of the drive during adjustable speed operation. The MUC initiates the start sequence as directed by the plant DCS system and manages the switchgear transfers. The LCI, however, is responsible for the actual phase and voltage matching for the final transfer of the motor to utility operation.

### 6.2 Customer Benefits

The customer initiated the investigation that resulted in the application of synchronous motors to the three new roller mills in his plant expansion. His preliminary analysis indicated huge savings possible through correcting the power factor for the whole plant. Of the three roller mills in this case, one was a finish mill, where the optimum grinding speed had not been finalized The gearbox between the motor and the mill had been designed to carry three interchangeable gear ratios to allow the client to experiment with different grinding speeds. When the decision to use synchronous motors with LCI starters was made, it became possible to operate the finish mill on the LCI in order to determine the optimum grinding speed. The proper gearing could then be selected to suit this speed for best performance when the motor and mill are running directly on the utility.

## 7. Conclusion

While wound rotor induction motors have traditionally held an important role in powering roller mills, the inefficiencies and costs associated with their application has led to explorations for other means of providing variable speed operation of newer mills. Advances in medium voltage power electronics will lower costs for VFD’s applied to induction motors helping ensure their expanded use in new plant applications. Power providers who have not traditionally charged clients for low power factor are evaluating that option as costs escalate and grid limitations become known. Synchronous motors started through an LCI can reduce production expenses and dramatically lower plant-wide energy costs with significant impact on revenue generation.

## 8. References

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