Mining technologies

Comparison of alternative converters with regard to their application for gearless drives for grinding mills

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Abstract

Gearless drives for grinding mills use cycloconverters. This is the state of art. The cycloconverter delivers variable frequency to the Ring Motor of the gearless drive, changing its speed by variation of frequency. Cycloconverter technology has been in existence for more than 50 years. Over these years many types of variable frequency converters have been developed, but none has replaced the cycloconverter in the application for gearless drives. Most of those converters did not provide sufficient power for this application, but converters sizes are increasing year by year and have now reached the power range of gearless drives.

This paper compares the actual available technology of variable frequency converters with regard to their possible application for gearless drives for grinding mills.

1. Introduction

Since the late sixties, the development of larger autogenous, semiautogenous and ball mills in the mineral ore processing and cement industries, has involved enlarging the traditional drive system incorporating low speed motors, driving mills via a mechanical drive train with single or dual pinion and girth gear. This solution comes up its economic and design limits with increasing drive sizes. Today, mills are powered by up to 20,000 kW and mills with up to 32,000 kW are in the engineering stage.

In this megawatt power range cycloconverters are the preferred technology for driving the motor. In the meantime further types of variable frequency converters have been developed, but none replaced the cycloconverters in the application for gearless drives.

The paper describes the actual available technology of variable frequency converters with regard to their possible application and explains the backgrounds into why cycloconverter still remain the best solution for gearless drives for grinding mills.

The following converter topologies [fig.2] are considered in this paper:

Figure 1: Gearless driven grinding mills

Figure 2: Medium voltage converters for high power applications
2.1. Cycloconverter

The most common drive, as shown in [fig.3] for Ring Motors, uses a star connection circuit in non-circulating current configuration. Three anti-parallel thyristor bridges are connected separate secondary transformer systems. Each of these bridges feeds one motor phase that is not isolated electrically from the other phases.

![Cycloconverter Circuit](image)

The motor phase voltage is formed from sequences of three phase line voltage by sinusoidal modulation. [fig.4] In effect, three symmetrical voltage systems are applied to the motor winding.

![Output current and voltage of a cycloconverter](image)

The main advantages of cycloconverter drives compared with a conventional gear drive are:

- very high power ratings
- very simple and robust
- low maintenance and high reliability
- wide speed range with high efficiency at all operating points
- excellent dynamic performance and surge load capability
- low starting current
- no contribution to short circuit current
- no mechanical connection
- between motor and mill clock and counterclockwise rotation of the mill

The main disadvantages of the cycloconverter are:

- poor power factor of about 0.8
- creation of harmonic currents, which cause harmonic voltages in the power supply network.

For this reason the cycloconverter requires power factor correction and harmonic filters in power supply networks with low short-circuit capacities.

2.2. Voltage Source Converter

The voltage source converter (VSC) consists of a line-side rectifier, a voltage DC link and a motorside PWM-inverter, which produces a variable voltage with variable frequency at its output.

The basic version of the VSC [as shown in fig. 6] is equipped with a 6 or 12-pulse diode bridge. This configuration does not allow regenerative operation of the drive.
The motorside inverters of voltage source converters either use IGBTs (Transistors) or IGCTs (Integrated Gate Commutated Thyristors). Both types of semiconductors are used in the power range below 10 MVA. In the higher power range at 10 MVA and above the IGCT is mainly used because the power from a single semiconductor is much higher compared with IGBTs. A single converter consists basically of 12 IGCTs, 12 free-wheeling diodes, 12 line side diodes and reaches a power rating up to approximately 12 MVA continuous power.

For higher output ratings several converter units must be connected in parallel [as shown in figure 8].

The voltage source converters in the upper power range are based on fuseless design and on water-cooling.

The parallel connection of two converters allows a 24-pulse supply to be generated by an additional phase shifting of the primary-side windings for the two transformers.

The advanced version of the voltage source converter is equipped with an active front end (AFE). The AFE consists of the same power circuit as the motorside inverter. It operates together with the transformer like a motor inverter, but in breaking mode at constant speed driven by the load. The transformed primary voltage is like the motor EMF at the motor side.
Figure 9: Converter with active front end

The major feature of the AFE-converter is regenerative operation feeding energy back into the supply system. The converter therefore needs more semiconductors and controls.

The main advantages of the basic version of voltage source converter drives compared with cyclo-converters are:
- high power factor of about 0.95 over the complete speed range
- generation of low harmonic currents, which cause only low harmonic voltages in the power supply network.
- normally no need for filter circuits

Disadvantages of the voltage source converters compared to cyclo-converters are:
- current derating at motor frequencies smaller than 3 Hz, because of increased influence of phase current amplitude for thermal load of semiconductors
- lower short time overload capability compared to thyristor drives
- higher number of part count
- larger footprint (space requirement)
- drive with diode front end design cannot feed back energy into the supply system.

2.3. Robicon Perfect Harmony

In the Robicon Perfect Harmony [as shown in Fig. 10] a series of low voltage cells are linked together to build the medium voltage power output of the drive system.

Fig. 10: Typical power schematic of a Robicon Perfect Harmony drive

The low voltage cells consist of several voltage source converters with diode rectifier bridges and IGBT inverters.

The output power of the drive is scaled simply by series connection of the low voltage cells.

A single converter with low voltage cells attains an output voltage of 7.2 kV and a power rating of approximately 15 MW. A further increase of power is possible by connecting converters in parallel.

The integral transformer with phase-shifted secondary windings provides 18-pulse or better input harmonic cancellation with a power factor above 0.95 under any operating conditions. This eliminates the need for input harmonic filters or power factor compensation.

The quality of the output voltage is quite close to sine-wave shape that motors of literally any type – old or new, low-speed or high-speed – can be operated without additional stress. Issues related to dV/dt, overheating and increased torsion vibrations do not arise.

The Robicon Perfect Harmony is available in air-cooled or water-cooled version.
The converter availability can be increased by the ability to bypass any one cell during operation while maintaining the full output voltage.

In case of a cell failure the converter output is blocked, the faulty cells gets by-passed and the torque recovers after approximately 250 ms. By designing one additional cell per motor phase the drive can maintain full power in spite of a faulty cell.

The main advantages of the Robicon Perfect Harmony drive compared with the cycloconverter are:
- high power factor of about 0.95 over the complete speed range
- generation of low harmonic currents, which cause only low harmonic voltages in the power supply network
- normally no need for filter circuits
- increase of availability by additional cells and cell-bypass

Disadvantages of the Robicon Perfect Harmony drive compared with the cycloconverters are:
- current derating at low motor frequencies
- lower short-time overload capability compared with thyristor drives
- higher number of parts
- very larger footprint (high space requirement)
- less flexibility in converter cabinet arrangement due to need for integrated transformer design
- drive with standard cell design cannot feed energy back

3. Operation modes of the gearless drive
Apart the normal operation, the gearless drive provides inching and creeping operation for maintenance of the grinding mill.

The rated speed of the gearless drive is defined by the diameter of the mill and the lowest percentage of the mill critical speed at which the drive has to provide the rated power.

The rated speed of the gearless drive corresponds to a rated converter frequency of 6 Hz to 9 Hz. The rated frequency is defined by the rated speed and the circumference of the mill where the rotor poles of the gearless drive are to be installed.

Variation of speed is provided by variation of frequency, also for start and stop procedures.

To start the grinding mill, the gearless drive has to provide 130% to 150% of rated torque to lift the material. The converter therefore has to provide the corresponding 130% to 150% of overload current for each start.
The gearless drive provides inching with a speed of 10% of rated speed, corresponding to 10% of rated frequency of the converter (0.6 to 0.9 Hz), depending on design.

The creeping mode of a gearless drive is realized with 3% of rated speed, corresponding to 3% of rated frequency. This is approximately 0.2 Hz. This frequency is so low that it can be called variable direct current.

4. Comparison of converter drives for application

gearless drives for grinding mills

A number of criteria should be considered when assessing possible drive converter systems, for example:
- required space (dimensions)
- efficiency
- reliability / availability
- line impact (harmonics, reactive power)
- investment costs

of all components of the drive, which are different for the alternative converters.

These are:
- transformers,
- harmonic filters with power factor
- compensation and
- the converter itself.

The selection of the converter has minor impact on the Ring Motor.

For comparison purpose a representative application was defined with one gearless driven 27,000HP SAG Mill and two gearless driven 16,000HP Ballmills installed at 3000 m above sea-level with the following technical data

**SAG-mill Gearless Drive**

- Power: 20,000 kW
- Motor speed: 9.26 rpm
- Motor frequency: 6.8 Hz
- Site altitude: 3000 m
- Starting torque: 150%
- Starting duration: 30s
- Normal operating speed: 7 to 10.5 rpm
- Corresponding frequency: 5 to 7.7 Hz
- Inching speed: 0.9 rpm
- Inching frequency: 0.68 Hz
- Creeping speed: 0.28 rpm
- Creeping frequency: 0.2 Hz

**Ballmill Gearless Drive**

- Power: 12,000 kW
- Motor speed: 11.7 rpm
- Motor frequency: 7 Hz
- Site altitude: 3000 m
- Starting torque: 150%
- Starting duration: 30s
- Normal operating speed: 8 to 12.3 rpm
- Corresponding frequency: 4.8 to 7.4 Hz
- Inching speed: 1 rpm
- Inching frequency: 0.6 Hz
- Creeping speed: 0.3 rpm
- Creeping frequency: 0.18 Hz

4.1. Cycloconverter solution (CCV):

The selected cycloconverter solution consists of 2 x 6-pulse cycloconverter. At the line side the converter acts as a 12-pulse system [fig.14].

The cycloconverter is delivered in a transportable E-house, with cabling installed and completely tested together with the other electrical equipment [fig. 15]. This work in the factory reduces installation and commissioning time at site.

Figure 14: Cycloconverter electric diagram 12-pulse configuration

The cycloconverter is delivered in a transportable E-house, with cabling installed and completely tested together with the other electrical equipment [fig. 15]. This work in the factory reduces installation and commissioning time at site.

Figure 15: Transportable E-House with cycloconverter
The space required by the cycloconverter part of the transportable E-House is as follows:
- approx. 31 m² for the SAG-mill drive,
- approx. 62 m² for the two ballmill drives.

The power losses of the cycloconverter are:
- approx. 150 kW for the SAG-mill drive,
- approx. 80 kW for each ballmill drive.

The power losses of the CCV-transformers are:
- approx. 240 kW for the SAG-mill drive,
- approx. 110 kW for each ballmill drive.

The reliability of today’s cycloconverters is very high and their availability is about 99.9%.

As indicated above, the main disadvantage of a cycloconverter is the creation of harmonics and the low power factor. The power factor compensation and harmonic filters needed for the application considered here are installed in open air on an area of 480 m².

The investment cost comparison forms part of the evaluation sheet in a later chapter of this paper.

For comparison of the alternative converter solutions it is necessary to consider the space required inside the concentrator building, as well as outdoors.

Also the transformers between converter and power supply must be taken into consideration, because they are different for the alternative converters.

4.2. Voltage source converter solution

It is technically possible to operate a gearless drive with a voltage source converter (VSC). The version with rectifier diode input is sufficient, since regeneration of energy is not requested by the grinding process.

The voltage source converter is designed for a rated frequency of 50 Hz to 60 Hz. At low frequencies a derating of current is necessary because the duration of current flow through the IGCTs of the active half-wave is extended.

The current derating reaches the low value of 70% of rated current at converter output frequencies less than 3Hz down to 0Hz. A derating for site altitude is also taken into consideration in the comparison.

In our example for the SAG-mill drive a combination of 5 standard VSCs of 10MVA rated power is required.

Five parallel converters with a nominal power of 10 MVA each are necessary to meet the application-specific requirements. The nominal power of the inverters is relatively high, because several derating factors have to be considered:
- current derating for low speed operation
- voltage derating for altitude of 3000 m
- consideration of 150% peak torque/current for startup

The output of the VSC is connected in parallel for feeding the three phases of the Ring Motor. Output reactors are included in the parallel connection to avoid circulating currents between the converters [fig. 16].

![Figure 16: Combination of five VSC](image)

Each of the 10MVA converters consists of cubicles with the dimensions: (LxWxH): 6 m x 1.6 m x 2.54 m

![Figure 17 Standard VSC 10 MVA](image)

The space requested by the Voltage Source Converter solution is:
- 30 m x 1.6 m equivalent to 126 m² for the SAG-mill Gearless Drive and
- 18 m x 1.6 m equivalent to 151 m² for the two ballmill Gearless Drive.
The dimensions of these VSCs are too large to install the VSC in a transportable E-house, so the corresponding benefits are lost. The VSC must be installed at site in a clean electrical room in the concentrator building. Cabling and testing together with the other electrical equipment must be performed at site or at least repeated. The power losses of the voltage source converters are
– approx. 180 kW for the SAG-mill drive,
– approx. 110 kW for each ballmill drive.

The power losses of the VSC-transformers are
– approx. 140 kW for the SAG-Mill drive,
– approx. 90 kW for each Ballmill drive.

The availability of a voltage source converter is about 99.8%. The advantage of a VSC is that there are no harmonic filters and power factor compensation, so no outdoor space is required. The only equipment, installed outdoors are the transformers of the VSC, which need an area of
– 60 m² for the SAG-mill Gearless Drive and
– 72 m² for the two ballmill Gearless Drives;
The investment cost comparison forms part of the evaluation sheet in a later chapter of this paper.

4.3. Robicon Perfect Harmony drive
It is technically possible to apply a Perfect Harmony drive at a gearless drive. The Perfect Harmony solution selected consists of three standard units for the SAG-mill Gearless Drive and two standard units for each ballmill Gearless Drive. The outputs of the units are connected in parallel to provide the phases of the motor.

The space required by the Perfect Harmony solution is
– 30 m x 6.5 m equivalent to 195 m² for the SAG-mill Gearless Drive and
– 60 m x 6.5 m equivalent to 390 m² for the two ballmill Gearless Drives.

The transformers of the Perfect Harmony solution can be installed outdoors and need an area of
– 125 m² for the SAG-mill Gearless Drive and
– 250 m² for the two ballmill Gearless Drives;

Also the Perfect Harmony converters are too large to be installed in a transportable E-house, so the corresponding benefits are lost. The Perfect Harmony converters must be installed at site in a clean electrical room in the concentrator building. Cabling and testing together with the other electrical equipment must be performed at site or at least repeated.

The power losses of the Perfect Harmony Converters are
– approx. 190 kW for the SAG-mill drive,
– approx. 115 kW for each ballmill drive.

The power losses of the transformers of the Perfect Harmony solution are
– approx. 400 kW for the SAG-Mill drive,
– approx. 240 kW for each Ballmill drive.

With redundant cells installed, the availability of the Perfect Harmony can attain nearly 100%.

The main benefit of the Perfect Harmony is that there are no harmonic filters or power factor compensation, so no space is required outdoors.

Figure 18: Water cooled Perfect Harmony Drive
4.4. Evaluation of the collected data
The characteristic data for the comparison are set out in the evaluation sheet

<table>
<thead>
<tr>
<th>Equipment:</th>
</tr>
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<tbody>
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<td>One (1) SAG-mill Gearless Drive 20,000kW and Two (2) ballmill Gearless Drives 12,000 kW, each</td>
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<table>
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<tr>
<th>Estimate of Price, Space, Losses and Availability</th>
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<tr>
<td>Required Space, Indoors</td>
</tr>
<tr>
<td>Required Space, Outdoors</td>
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<tr>
<td>Required Space, Total</td>
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</tbody>
</table>

5. Conclusion
The main disadvantage of the cycloconverter solution, namely the need for harmonic filters, results in a high value for outdoor required space. However, indoors the cycloconverter solution requires 66% less space than the voltage source converter and 84% less space than the Perfect Harmony solution. Since indoor installation requires higher investment than outdoor installation, this compensates for the disadvantage of harmonic filters. All other criteria favor the cycloconverter solution or show the cycloconverter as equally good. Besides lower investment and higher availability the installation in a prefabricated E-house and pre-commissioning at the supplier’s factory are decisive benefits of the cycloconverter solution. Due to its advantages in low-speed and low-frequency operation the cycloconverter remains still the best solution for gearless grinding mills. The development of other converters, driven by the increasing demand for high power converters, may eventually result in a converter that can compete with the cycloconverter in gearless drive applications.
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