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OVERVIEW OF MV DRIVE TECHNOLOGIES IN MINES AND FUTURE SCOPE

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ABSTRACT

Typical mine has ore processing units at site for grinding of ore. This operation is done at site for making product cost effective. After grinding and processing, only useful material is transported for further processing. Grinding of ore is one of the most power intensive operation in mining. For grinding of ore, various mills are used operating at various speeds like ball mills, Auto-geneous mills, Non-Autogeneous mills and Gearless mills. Bigger the size of mill, more is the power requirement. Presently Synchronous motors are used for geared mills upto the power 9MW, while gearless mill use Synchronous motors upto 38 MW. The power converters in both the cases used are cyclo-converters because of certain advantages. This paper focuses on overview of Medium Voltage Drive (MV) systems for grinding of ores including motors and converters presently reported and alternate options available with latest developments in motors and power converters.

Index Terms: Cyclo-converter, multilevel Inverter, and Gearless Mill Drive

INTRODUCTION

For ore grinding operation in Mines, large Grinding mills are used driven by Induction and synchronous motors of max of 38 MW but for low speed. The reliable operation of the drive is essential to prevent business interruption loss which can be huge. Presently Gearless and Geared Grinding mills are used for the purpose. Geared mills use Induction motors and Synchronous motors but there is a limitation on gears for power greater than 9 MW. Moreover gears encounter maintenance problems. Gearless drives are being used where motors are coupled directly to Mill cylinder. Synchronous motors upto 38 MW and cyclo-converters are reported to be used. Cyclo-converters are inherently efficient and reliable but has problems related to harmonics. This calls for huge passive filter banks which not only consumes power but also occupies space. Though synchronous motors are ideal for operation because of unity power factor and good efficiency, it suffers few problems like effective starting and complex construction. There are other option like induction motor and PM motor which do not have these kind of issues. For power converter, modular multilevel converters are becoming viable option due to availability of power devices like IGBT and upcoming SiC devices.

GRINDING SYSTEMS IN MINES

Fig.1 shows the cross section of typical grinding mill having internal steel liners with lifters for lifting the load. The cylinder is filled with ore and set under rotation at low speed (0-10 RPM) decided by cylinder diameter and type of ore. While under rotation, the load builds a kidney form as shown. When charge climbs upwards, it tends to fall down under gravity resulting into crushing operation. The weight and speed of rotation decides the centrifugal force and various trajectories. The trajectory is set by adjusting speed of the cylinder to optimum value so that mill operates without any direct impact between charge, liners and lifters thereby avoiding damage. The trajectory impacting at the load toe gives optimum resulting into most effective grinding by steel balls inside the mill while in operation.

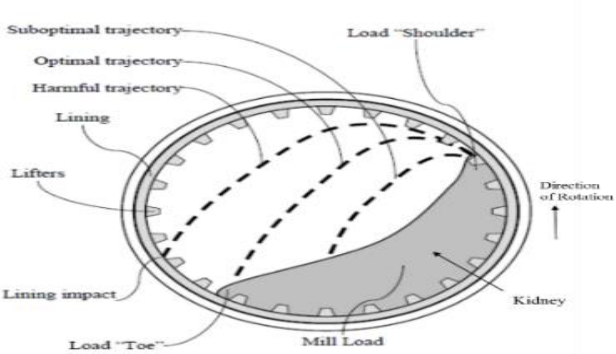


Fig. 1 Operation of Grinding mill [12]

For higher throughput, large diameter mills are being employed to use this impacting effect. The movement of the charge depends on several variables like geometry, viscosity, ore size-distribution and speed. In addition, the wearing of the lifters also plays a role because its geometry changes with time. There are also harmful effects because of the ball trajectories impacting in the lifters such as energy loss and accelerated steel ball wear etc. jeopardizing the life of lifters and affecting the availability of the mill. That is why variable speed is needed for high power mills so that perfect trajectories are manipulated. The useful range of operation speed is around 75% and 80% of the critical speed. The critical speed is defined as the speed at which a steel ball remains at the shell of the mill without falling when the centrifugal force equals its weight and is given by:

$$w = \sqrt{\frac{2g}{(D-d)}}$$

where, $g=9.81\ m/s^2$,
D= internal mill diameter
d=diameter of steel balls
w=critical speed

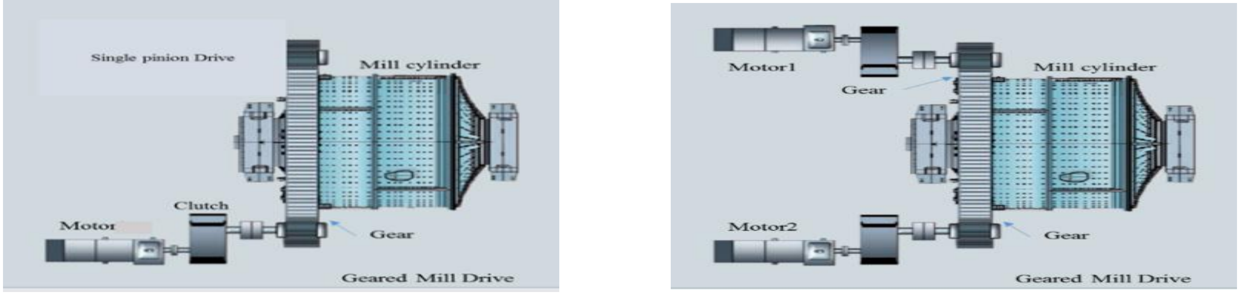
Practically, D>>d hence , d can be ignored. If D in meters, Critical Speed N_c in RPM as:

$$N_c = \frac{42.2}{\sqrt{D}}[rpm] \quad , \qquad (1)$$

A typical mill with D, 12 meters will have a critical speed of 12.2 RPM and operating speed 77% of the critical speed which is 9.3 RPM.

GEARED MILLS (SINGLE AND DUAL PINION MILLS)

A schematic of Geared drive is shown in Fig. 2. System shows single and dual pinion gear coupling to Mill drum with single and double parallel motors respectively. Single And dual pinion configurations can be powered by low speed synchronous motors (approx.60 - 200rpm) connected directly to the pinions driving the ring gear or by high speed asynchronous motors (approx. 750 - 1500 rpm) that require a reducer between the pinions and the motors.



a) Single pinion drive schematic b) Double pinion drive schematic

Fig 2. Schematic of Typical Geared Mill Drive system [6]

Today, the maximum power capacity per pinion is less than 9 MW because of limitations on gearboxes. Proper alignment and regular service are important for operation of gearboxes. Misalignment between motor and pinion is a major reason for wear in a clutch. However, the drive train not only has to be aligned statically but it also must be checked dynamically when running with a loaded mill.

GEARLESS MILLS (GMDS)

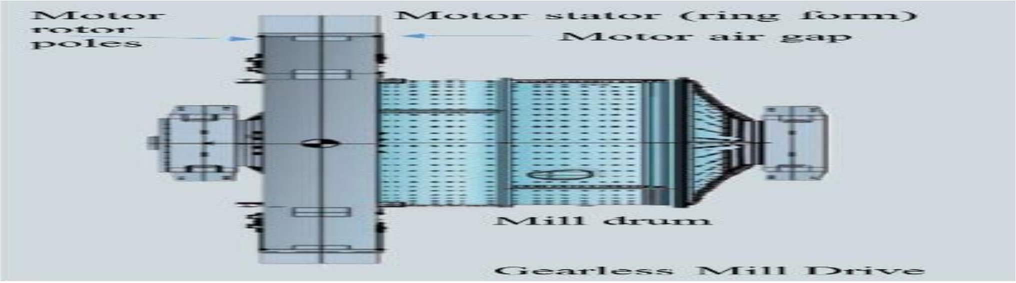


Fig 3 Schematic of Typical Gearless Mill Drive system [6]

The principle idea behind a gearless drive system is to reduce the number of components and diversity of parts. Fig.3 shows the general scheme of a mill with gearless motor drive and the rotor poles of the machine are bolted to the mill. The stator has a ring form, giving wrapped-around the mill drum. Typical value of the air gap between the stator and the rotor is in the range of 15-20 mm, +/- 3 mm. The motor is run with low speed (0-10 RPM) with variable voltage variable frequency converter to regulate the torque and operating speed of the mill. Nowadays GMDs up to 38MW for 42' ball mills are reported to be in production.

ADVANTAGES OF GMD

1) About 4% higher energy efficiency can be achieved with gearless drive technology.
2) No mechanical limits so high power is available at the driven component.
3) Smaller footprint of complete drive train.
4) The air gap of a GMD is large (15-20 mm). Therefore, the system is not sensitive to small misalignments between the stator and the rotor.

DISADVANTAGES OF GMD

1) Because of physical size, motor cannot be manufactured in one piece and made of many segments and hence calls for special design and assembly requirement.
2) Have drawback of being a bottleneck when one unit goes out of service, huge production loss is feared. Hence reliability and availability is a major concern.

TECHNICAL REQUIREMENTS FOR DRIVES IN A GRINDING MILL [13]

Modern grinding mill drives used in copper, gold, and cement industries employ Medium voltage motors with power electronic drives. The main requirements are as follows:

1) Drive with at least 120% starting torque without affecting the power network.
2) Operation of full system in harsh concentrator environment with wet grinding and high altitudes, commonly higher than >6000 feet above mean sea level.
3) Variable low supply frequency because of large diameter for speed 0-10 RPM.
4) High reliability and availability to keep business interruption loss (BIL) low.
5) Full output frequency and voltage control with four-quadrant operation capability.
6) Frozen Charge detection and management: At standstill, the material inside the mill tends to solidify and to stick to the mill shell. This is called frozen charge and could happen even within minutes.

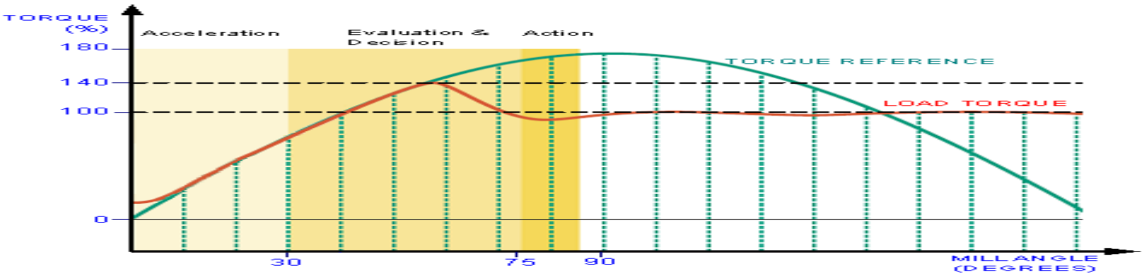


Fig. 4 Frozen Charge Detection [17]

Control system detect torque from 30°-75° by current measurement. If the load torque drops within 140 % , the system known to be behaving as per requirement otherwise a frozen charge is detected and fast shutdown is initiated as shown in Fig, 4.

7) Inching, Creeping and Positioning is often used to avoid the occurrence of frozen charges and also used to position the mill for maintenance work.

8) Ensuring power sharing between drives and gears in case of pinion drives is essential for trouble free operation in case of geared mill.

9) Taking care of Network Voltage Problems is important and accordingly drive system is used. It must actively support network in case of voltage dips by reducing the power drawn. The drive behavior must enable the network to fast recovery.

10) Mechanical system design requirements.

In case of short circuit fault, circulation of very large currents through the stator winding of the machine originates huge forces. The structure of the stator, its winding design, fittings and foundation must be designed to resist the forces.

Isolation failure of stator windings due to wet moisture could be one of the issues. By wet grinding, water splashing may contaminate the windings if seals are imperfect. Intelligent isolation surveillance may be considered to solve this issue.

Vibrations and deflections due to asymmetrical air gap between the motor stator and the rotor to be monitored. Electromagnetic linear and non-linear excitation forces may be produced under failure conditions. Deformation modes and force distribution along the poles of the rotor should be carefully analyzed during design stage, in order to ensure global system compatibility without dangerous air gap fluctuations.

DRIVE SYSTEM FOR GEARED MILLS.

Because of limitations on power upto 9MW, AC induction motor a high speed solution, or a brushless synchronous motor for low speed solution fed by VSI drive is commonly used.The mills are typically single quadrant operation but some are designed for running in both directions.

THE HIGH SPEED MOTOR SOLUTION FOR GEARED MILLS

Squirrel cage induction motors:

These are the most common motors used in the industry due to their versatility, reliability and simplicity and also minimum maintenance. Typically 6- 8 pole induction machine driven by 50 Hz is used to turn the mill. The motors are generally forced cooled which allows running the motor at very low speed (approx. 5-10% of nominal speed) for service mode. Automatic positioning for liner changes and creeping for visual inspection can be performed with the main drive without the need of additional equipment.

Depending on the environment, air cooled motors or water cooled motors which are totally enclosed are used for powers up to 9MW. The advantage of a totally enclosed motor is that the cooling air inside the motor is not affected by the external dusty environment. These motors are equipped with flange mounted bearings installed on the end shields of the motors. To prevent bearing damage from circulating currents, both bearings and case are electrically insulated. The shaft is grounded to avoid static charges of the stator.

Slip Ring Motors

Slip ring motors are high speed fixed speed drives (typically 6 or 8 pole motors) that are usually used for smaller mills. They offer a low capital expenditure solution compared with other drive systems. These motors are started with a starting resistor (oil starters with stepping resistors or liquid starters). Based on the resistor characteristics a relatively smooth start is possible. This drive system is rather robust against voltage dips. However, the power factor is typically not very high and gets worse at part load conditions. Thus, often power factor compensation is installed individually for each slip ring motor. Furthermore, a separate device is required for inching and creeping.

Dual high speed slip ring motors can be used to drive through gearboxes to dual pinions. Load sharing is inherently possible but not very accurate. This can lead to load swings between the two motors and result in accelerated gear wear. To overcome these conditions, a permanent slip resistor may be installed between the two rotors. This will improve the load share capability, but at the expense of the drive efficiency (up to 1.5 % reduction).

LOW SPEED MOTOR SOLUTION FOR GEARED MILLS

Due to the high torque required by the mill, low speed motors are generally synchronous machines. The mill is a low dynamic system therefore a brushless synchronous machine is best suited for this application. Brushless synchronous motors have no wearing parts, and the AC/ AC excitation power is kept small. The drive provides the supply and the excitation control as well as the necessary protection. The brushless exciter is a separate AC generator mounted on the motor shaft. For these high torque low speed motors, efficient cooling is required. The choice is between water cooled totally enclosed motors or open machines weather protected type II enclosure and filter air inlet. In addition to their high torque capability, synchronous motors offer a wide field weakening range. This allows the design of motors with nominal frequency below the network frequency. The low speed solution motor used with the drive has a nominal frequency varying from 10 – 20 Hz. This means a machine with 8- 12 poles can be used instead of the big 30- 40 pole machine required by a fixed speed solution having the same torque output.

The main benefits of the low speed motor solution with only 8- 12 poles, beside the lower capital cost compared to the traditional low speed motors with 30 to 40 poles, is the compactness. Less weight, smaller dimensions and therefore easier installation create less demand in the foundation design and less issue for the transportation of the equipment on site. Depending on the power, flange mounted sleeve bearings mounted on the end shields of the motor, or pedestal mounted sleeve bearings, are provided. The motors with integral pedestal bearings are as easy to mount and align as motors with flange mounted bearings; no further assembly is required on site. Also for the low speed solution the bearings are both electrically insulated and the shaft is grounded.

Slip Energy Recovery Drives.

These drive systems use slip ring motors and are started similarly using starting resistors, thereby limiting the inrush current. To adjust the speed, the slip resistance needs to be changed accordingly. This can be achieved by inserting resistance in the rotor circuit and dissipating this energy into the starting resistors. This solution is very inefficient, so rather than using the starting resistor, the slip energy is converted to direct current, inverted to the frequency of the power system feeding the motor, and then fed back into the power system through a step-up transformer. The switch over to the slip energy recovery system can be done between 50 and 100 % of nominal speed.

Here the speed range is smaller than of frequency converter drives, frozen charge protection is not possible and a separate inching drive is required. In reducing the speed of the slip ring motor, the slip energy recovery equipment will generate frequencies at multiples of 6 times the slip frequency, depending on the number of pulses built into the equipment. Because of these excitation frequencies there is a high probability that certain speeds in the operating range of the mill (possible resonance frequencies) will need to be blocked and it is not possible to operate within this particular speed range.

The main reason in the past for using slip energy recovery drives was capital expenditure. However, the use of these drive systems has very much decreased during the last decade because frequency converters have become more and more cost effective. Operational limitations and significant higher maintenance compared with frequency converter drives also made them unattractive.

DRIVE SYSTEM FOR GEARLESS MILLS (GMD)

Because of great throughput requirements, nowdays GMD are preffered. It has ring motor shown in Fig. 3, which is wrapped to the outside body of mill cylinder. The cylinder being large diameter (42 feet), motor has to be designed and manufactured for assembly in sections and assembled at site. Large diameter motors have advantage of very large torque as it is proportional to square of diameter. Because of huge power requirements (> 32 MW) motor needs to be very efficient in order to minimise power loss and cooling requirements. Keeping this in mind motor should have good power factor and good efficiency. Since motor is a part of rotating mill cylinder which works at low speed (0-10 RPM) it is of direct drive type without any gear working at very low speed. So the desired torque is required at low speed and at the time of starting also. In the category of fulfilling requirements, qualified candidates are Induction motor, Synchronous motor and PM motor which are under development at various places.

INDUCTION MOTORS VS SYNCHRONOUS MOTORS

Induction motors have higher currents for the same power levels due to lower efficiency and lower power factor (PF) than Synchronous Motors (SMs). This gap becomes wider with increased pole-pair construction and lower base speeds. SMs operate with higher efficiency, lower currents due to high PF, and have usable low-speed torque characteristics with a VFD. When operated direct on line, the leading PFs provided by SMs offer reactive power that compensates for the reactive power used in other parts of a plant.

The induction motor PF depends largely on the base speed or the number of poles in the motor design. For example, in a 5,000-hp, 20-pole SM design, the current can be 585 A while an induction motor at the same base speed and power requires 820 A, a 40% increase due to extra reactive power used with a lower PF in the induction motor. This reduces the efficiency of Induction motor and increases the cooling requirements as copper losses gets increased significantly.

In induction motors the stator constantly supplies a certain amount of magnetizing current to maintain the magnetic flux, resulting in a lagging motor power factor (PF) at all operating conditions. On the other side, synchronous motor offers an extra freedom of motor field current control and hence its operating PF can be adjusted by the drive to leading, unity or lagging as the system operation prefers.

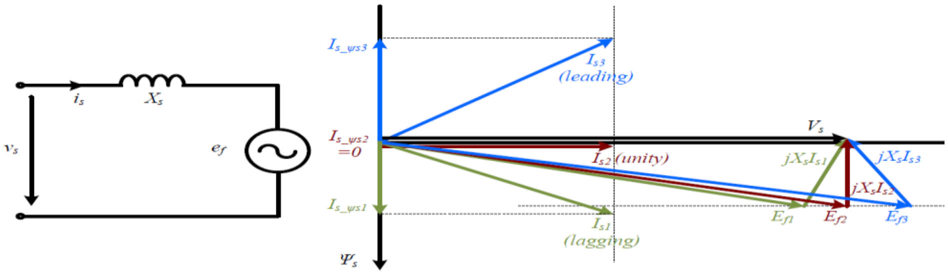
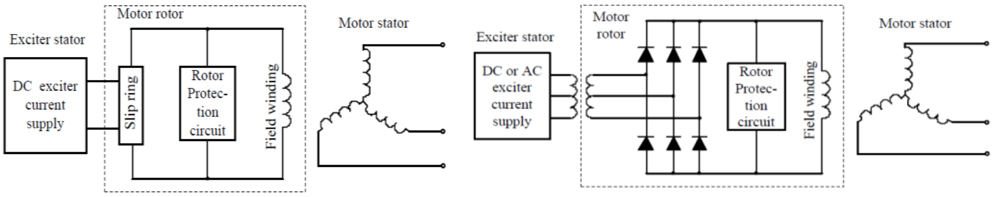


Fig. 5 Power factor in case of Synchronous Motor [16]

Fig.5 shows the motor PF control through variation of field excitation current and magnetizing current while keeping the torque producing current constant for the same load condition. Note that the stator resistance and rotor saliency are neglected in Fig. 5 for the simplicity of comparison. Unity PF is achieved when the flux is fully supported by the field current and stator magnetizing current averages around zero (Is_ψs2=0) in steady state. Under-excited motor field winding demands positive stator magnetizing current (Is_ψs1 in the same direction of stator flux Ψs) and thus lagging PF. Similarly, over-excited motor field winding requires negative stator magnetizing current to maintain the same flux level and lead to leading PF. Unity PF is often seen in VFD control because it minimizes the motor current under the same load condition.

Exciter types in Synchronous Motor.

Synchronous motors (SMs) require an external DC supply to power the rotor field winding, and can be classified into brush-type or brushless-type based on the exciter structure. Both circuits are shown in fig. 6.



(a) Brush-type exciter (b) DC or AC brushless exciter

Fig. 6 Synchronous motor with brush or brushless exciter [5]

A brush-type synchronous motor is fitted with a static exciter where the current is provided to the rotor through slip rings and brushes. A brushless-type synchronous motor is supplied by a rotating exciter. The exciter stator current, either in AC or DC form, is transferred to the rotor through the rotating transformer. The AC current induced in the rotor is then rectified to a DC current to supply the field winding. In a DC-brushless synchronous motor, the induced voltage in the rotor is proportional to the rotor speed, assuming a constant DC supply in the exciter stator. When the rotor is at standstill, there is no field current supplied to the rotor and therefore, the starting torque capability is limited as compared to brush-type or AC-brushless-type of synchronous motor where constant torque load can be supported with position sensor feedback. As the motor speeds up, the voltage induced in the exciter rotor winding increases and thus the DC-brushless motor can support high load torque in the medium to high speed range.

The ring-motor is a low speed synchronous motor fed by a cyclo-converter. Depending upon the mill speed, the number of rotor poles will be selected. In general, the bigger the mill diameter is, the lower are the mill operating and critical speeds and the higher are the number of rotor poles. It has to be noted that the number of pole units will impact, like with any motor, the motor efficiency. Since the gearless mill drive is typically by far the largest power consumer in a concentrator plant, the number of pole units should be kept to the minimum. The pole number varies typically from 48 for very small ball mills to 76 poles for the largest GMD motors. Broad comparison of Induction and Synchronous motors is given in Table 1.

Table 1

S.N.	**Characteristics**	**Induction Motors**	**Synchronous Motors**
1	Complexity	Simple design	Complex
2	Self-starting	Generally yes	Generally no
3	Power-Density	Average	High
4	Efficiency	Average	High
5	Power-Factor control	No (always lagging)	Yes (can lead and lag)
6	Cost	Low	High

PM MOTORS

PM motors are the latest and popular synchronous motors and are considered best because of good power density. It has very good power factor and various control strategy could be applied so as to track torque requirements. It has got magnets embedded on rotor eliminating slip-rings and brush for field. Good amount of work is reported in PM motors and also strong magnets like NdFeB and SmCO are available with reasonable cost. However it has practical difficulties in terms of manufacturing and assembly. This is because for such a huge torque requirements of 100s of KNm, and requirements of motor manufactured in segments, assembling at site, is a difficult task. It needs huge fixtures and extremely skilled approach for safe assembly. Also with variation of air gap while assembly, may introduce huge unbalance forces on the bearings, which may reduce life of bearings and increase maintenance. Considering advantages like compact, efficient and ease of control for Mill operation, PM motors are still being considered and research is being carried out worldwide for overcoming various difficulties for implementation of these machines.

POWER CONVERTERS TECHNOLOGIES FOR MILLS [17,24]

In early 90, eighty percent of the variable speed solutions were accomplished with DC drives and the rest were based on the slip energy recovery system with a wound rotor motor or AC drives. Developments in the power electronic components, availability of efficient DSP controllers and the extensive reductions in costs and dimensions of the hardware has revolutionized the way of drives. Nowadays, the efficient and reliable technology of AC drives has overtaken the DC solutions. This evolution from fixed speed through DC to AC variable speed brought additional benefits from the electrical, mechanical and operational point of view. Due to the high power requirement, medium voltage (MV) drives are the best solution on mill drives.

BASIC REQUIREMENTS FOR POWER CONVERTER DRIVES FOR GMD MILLS ARE AS FOLLOWS

1) Very good efficiency >98 %
2) Line Harmonics control to comply with IEEE-519-2014.
3) Modular design with minimum component count to ensure reliability.
4) Fine speed control capability to take care of optimisation of Mill operation.
5) Low speed operation for creeping, inching operation for start-up and maintenance.
6) High dynamic performance, regenerative braking and four quadrant operation.

Mill drives require high power and very low speed about 0-10 RPM. Presently cyclo-converter is being used as an effective and acceptable drive solution.

CYCLO-CONVERTER [24]

The cyclo-converter is a frequency changer which converts a three phase voltage with the frequency f_1 into a poly-phase voltage with a lower frequency f_2. In the case of mill drives the operational output frequency is from 0.3 Hz to 10 Hz. The cyclo-converter is classified in the group of line-commutated converters. The output current of a converter is controlled to obtain a sinusoidal shape with a given frequency, as shown on Fig. 7.

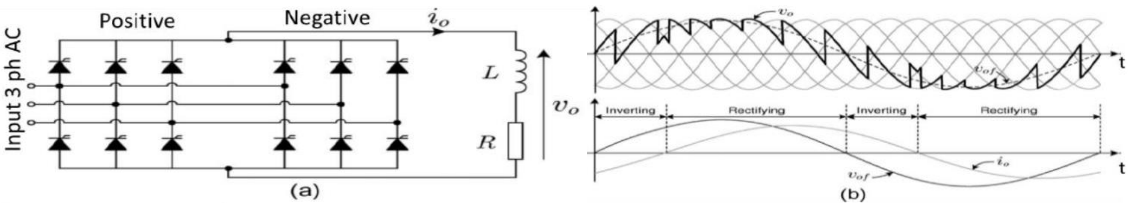


Fig. 7 Six-pulse Cycloconverter (a) power circuit (b) output waveforms

The basic unit is generally a three-phase bridge where a three-phase voltage is converted into a direct voltage, positive side by positive bridge and negative side by negative bridge as shown. By means of phase-angle control this voltage can be continuously varied from zero to roughly the maximum. The reactive power of commutation required for the transfer of current between the individual legs of each bridge is obtained from the power system. A complete 3-phase cyclo-converter circuit for SM with excitation control is shown in Fig. 8.

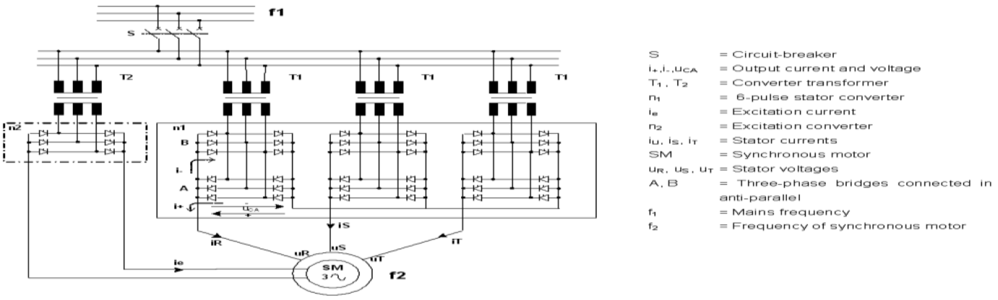


Fig. 8. Six-pulse cyclo-converter circuit [17]

ADVANTAGES OF CYCLO-CONVERTERS

1) The drive has an inherent 4-quadrant operation capability which allows reversible rotation and the controlled roll back by feeding energy back to the network.
2) The high efficiency of a direct drive since no intermediate conversion stage.
3) The flexibility of selecting the optimal motor voltage
4) Very Compact construction.
5) Good performance at low speeds, like overloading capability during starting.

DIS-ADVANTAGES OF CYCLO-CONVERTERS

1) The power factor is relative low and not constant over the entire speed range. The reactive power is supplied by Supply Network and may affect other loads.
2) The drive generates harmonics and inter-harmonics. The total harmonic distortion depends also on the number of pulses of the cyclo-converter.

ISSUES WITH CYCLO-CONVERTERS

RELIABILITY ASPECTS

Cyclo-converters are built with twelve 6-pulse bridges in dual converter connection using thyristors without circulating current operation. To switch off the thyristors during normal operation, the network voltage is needed for reference. When a power disturbance occurs and the cyclo-converter is operating in the inverter mode, a short circuit may happen because thyristors cannot commutate. Under this circumstances, pulsating torque produced can reach upto 700% of rated value. Proper mechanical design needs to ensure that the thyristors, machine and foundation can withstand such situation. The control and protection system should recognize the abnormal conditions in order to switch off the thyristors at the right time before such a short circuit is produced.

POWER QUALITY ISSUES

Power quality directly affects the reliability of operation because electrical equipment may be damaged or tripped under abnormal power conditions. Harmonic currents and voltages are frequency components superimposed to the fundamental component of currents and voltages, respectively, which produces additional losses in equipment and can trip electrical protection systems. Voltage regulation and energy efficiency is affected by reactive power and also by starting of a big machinery. Operation of equipment with or without load also gives rise to transients as shown in fig.9.

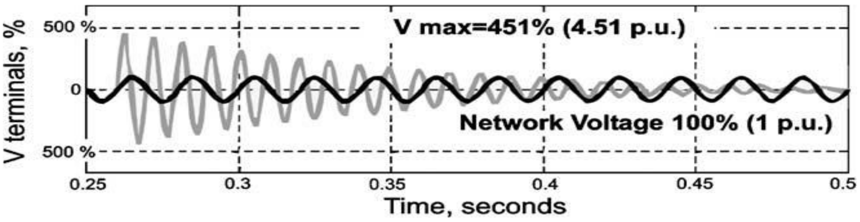


Fig. 9 Overvoltage by off switching of a transformer under no-load condition [11]

Power quality is a major concern in the application of mill drives, mainly due to the following reasons:

1) A failure in this equipment originates a large loss of production and
2) The high power of this equipment (MW) has an important impact on the operation of the power distribution system. The power factor and the current harmonics generated by the converter, has detrimental effect on other loads on the network.

HARMONICS AND INTERHARMONICS

Cyclo-converter has no DC-Link with energy storage components like inductors or capacitors between the network and load. That is why it injects not only harmonics but also inter-harmonics into the network. Inter-harmonics are components like lateral bands with non-integer frequencies. The frequency of theses inter-harmonics is not constant but depends on the output frequency. Cyclo-converters inject a distortion current I_D into the network with superposition of harmonic and inter-harmonics currents components. For a 6- pulse configuration the harmonic components are given by [1]:

$$I_D = \sum\{f_1 \pm 6kf_0\} + \{11f_1 \pm 6kf_0\} + \{13f_1 \pm 6kf_0\} + \{f_2\} + \{f_3\} + \{f_4\} \quad , \qquad (2)$$

where $\{f_h +/- 6kf_0\}$ is a term comprising the characteristic frequency component f_h and its lateral sidebands, f_1 is the fundamental current component of the network side (50 Hz), f_0 is the output frequency of the cyclo-converter, and k is an integer value k = 0, 1, 2, 3, . In addition, non-characteristics harmonics components f_2, f_3, f_4 should also be considered, especially when parallel resonances may happen, (Fig.10).

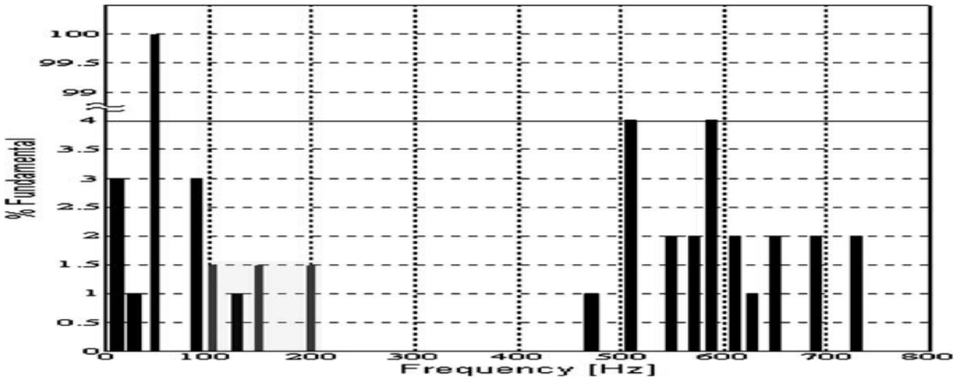


Fig. 10 Harmonics and inter-harmonics injected by a cyclo-converter for a given speed

FILTER DESIGN CONSIDERATIONS

Harmonic filters are employed to improve power factor and reduce harmonic distortion to comply with IEEE-519 guidelines. The total compensation power must be calculated using the expected active and reactive power demand of the plant under different operating conditions. Compensation power is distributed into different filter modules. To reduce harmonic voltage distortion produced by cyclo-converter, the tuning of filter branches should be carefully calculated for attenuating the characteristic harmonics and inter-harmonics.
Proper design and placing of the parallel resonances at convenient frequencies is not an easy task, requiring many trade-offs between system configuration and modularity of filters with more flexibility. Variable speed operation of GMDs injects inter-harmonics with changing frequency over a broad range, increasing the chance for exciting resonances. That is why, high-pass filters with damping resistors are applied. In order to reduce the losses in the resistors, a C-Filter structure is used, especially for branches with tuning to lower frequency values. The mitigation of the lower parallel frequencies is complex and a trade-off must be designed among the reduction of voltage distortion, installation cost losses, together with maintenance and operation.

VOLTAGE & CURRENT SOURCE INVERTER (VSI&CSI) [17, 24]

The Voltage Source Inverters (VSI) are the most common topology today and is being used with induction and synchronous motors. As shown in fig. 11, it consist mainly of a phase shifting transformer with input filter, rectifier followed by L-C filter for smoothening the DC voltage and an inverter which converts DC to AC with a variable frequency and voltage and again filter at the output to achieve desired THD to reduce heating and reduction of dv/dt at motor terminals. The capacitor bank located in the DC link smoothens the voltage and supplies reactive power to the motor while uncoupling at the same time the motor from the supply network and protecting it from network transients and faults.

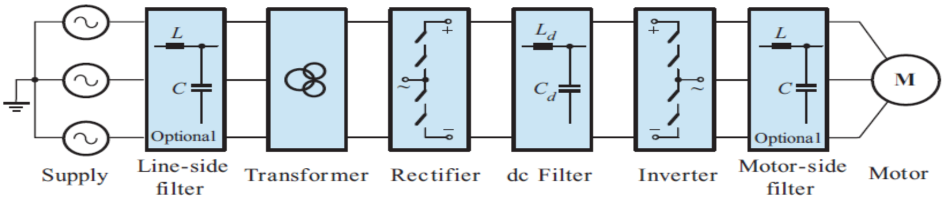


Fig. 11 General block diagram of the VSI drive [23].

Technical Requirements and Challenges

The technical requirements and challenges for the VSI & CSI are generally divided into four groups: the requirements related to the power quality of line-side converters, the challenges associated with the design of motor-side converters, the constraints of the switching devices, and the drive system requirements.

LINE-SIDE CHALLENGES

LINE CURRENT DISTORTION

The rectifier normally draws distorted line current from the utility supply, and it also causes notches in voltage waveforms. This can cause numerous problems such as nuisance tripping of computer-controlled industrial processes, overheating of transformers, equipment failure, computer data loss, and malfunction of communications equipment. The drive should comply with the guidelines specified by standards such as IEEE 519-2014 for harmonic regulation [4].

INPUT POWER FACTOR

High input power factor is a general requirement for all electric equipment. Most of the electric utility companies require their customers to have a power factor of 0.9 or above to avoid penalties.

LC RESONANCE SUPPRESSION

For the MV drives using line-side capacitors for current THD reduction or power factor compensation, the capacitors form LC resonant circuits and resonates with the line inductance of the system. The LC resonant modes may be excited by the harmonic voltages in the utility supply or harmonic currents produced by the rectifier. Since the utility supply at the medium voltage level normally has very low line resistance, the lightly damped LC resonances may cause severe oscillations or over voltages that may destroy the switching devices and other components in the rectifier circuits.

MOTOR-SIDE CHALLENGES

Dv/dt and Wave Reflections. Fast switching speed of the semiconductor devices results in high dv/dt at the rising and falling edges of the inverter output voltage waveform. Depending on the magnitude of the inverter dc bus voltage and speed of the switching device, the dv/dt can well exceed 10,000 V/μs. The high dv/dt in the inverter output voltage can cause premature failure of the motor winding insulation due to partial discharges. It induces rotor shaft voltages through stray capacitances between the stator and rotor producing current through shaft bearing, leading to early bearing failure.

The high dv/dt may cause a voltage doubling effect at the rising and falling edges of the motor voltage waveform due to wave reflections in long cables. The reflections are caused by the mismatch between the wave impedance of the cable and the impedances at its inverter and motor ends, and they can double the voltage on the motor terminals at each switching transient if the cable length exceeds a certain limit. The critical cable length for 500 V/μs is in the 100-m range, for 1000 V/μs in the 50-m range, and for 10,000 V/μs in the 5-m range.

COMMON-MODE VOLTAGE STRESS.

The switching action of the rectifier and inverter normally generates common-mode voltages. The common-mode voltages are essentially zero-sequence voltages superimposed with switching noise. If not mitigated, they will appear on the neutral of the stator winding with respect to ground, which should be zero when the motor is powered by a three-phase balanced utility supply. Furthermore, the motor line-to-ground voltage, which should be equal to the motor line-to-neutral (phase) voltage, can be substantially increased. Due to the common-mode voltages, the premature failure of the motor winding insulation system may occur shortening life expectancy of the motor.

MOTOR DE-RATING.

High-power inverters may generate a large amount of current and voltage harmonics. These harmonics cause additional power losses in the motor winding and magnetic core. As a consequence, the motor is de-rated and cannot operate at its full capacity.

LC RESONANCES.

For the VSI/CSI drives with a motor-side filter capacitor, the capacitor forms an LC resonant circuit with the motor inductances. The resonant mode of the LC circuit may be excited by the harmonic voltages or currents produced by the inverter. Although the motor winding resistances may provide some damping, the problem should be addressed at the design stage of the drive.

SWITCHING DEVICE CONSTRAINTS

DEVICE SWITCHING FREQUENCY.

The device switching loss accounts for a significant amount of the total power loss in the VSI/CSI drive. The switching loss minimization can lead to a reduction in the operating cost and cooling requirements. In practice, the device switching frequency is normally around 200 Hz for GTOs and 500 Hz for IGBTs and GCTs. The reduction of switching frequency generally causes an increase in harmonic distortion of the line and motor side waveforms of the drive.

SERIES CONNECTION.

Switching devices in the VSI/CSI drive are often connected in series for medium-voltage operation. Since the series connected devices and their gate drivers may not have identical static and dynamic characteristics, they may not equally share the total voltage in the blocking mode or during switching transients. A reliable voltage equalization scheme should be implemented to protect the switching devices and enhance the system reliability.

RECTIFIERS [23]

In an effort to comply with the stringent harmonic requirements set by guidelines such as IEEE standard 519-2014, major high-power drive use multipulse diode rectifiers lke 12,18,24 pulse rectifier with phase shifting transformer with a number of secondary windings. The dc output of the six-pulse rectifiers is connected to a voltage source inverter.

The main feature of the multipulse rectifier lies in its ability to reduce the line current harmonic distortion. This is achieved by the phase shifting transformer, through which some of the low-order harmonic currents generated by the six-pulse rectifiers are canceled. In general, the higher the number of rectifier pulses, the lower the line current distortion is.

The multipulse rectifier has a number of other features. It normally does not require any LC filters or power factor compensators, which leads to the elimination of possible LC resonances. The use of the phase-shifting transformer provides an effective means to block common-mode voltages generated by the rectifier and inverter in medium voltage drives, which would otherwise appear on motor terminals, leading to a premature failure of winding insulation.

PULSE DIODE RECTIFIER

There are two identical six-pulse diode rectifiers powered by a phase-shifting transformer with two secondary windings [1,23]. The dc outputs of the six-pulse rectifiers are connected in series. It can be seen in fig.13, that this circuit reduces THD below 10% for 50% load and power factor better than 0.95. this is without any additional filters.

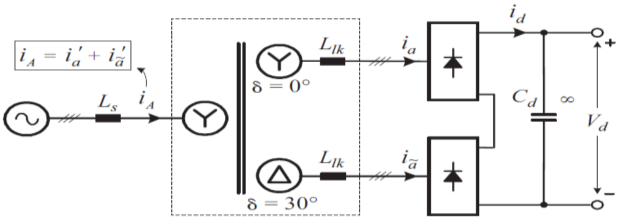


Fig.12 **The** 12-pulse series-type rectifier

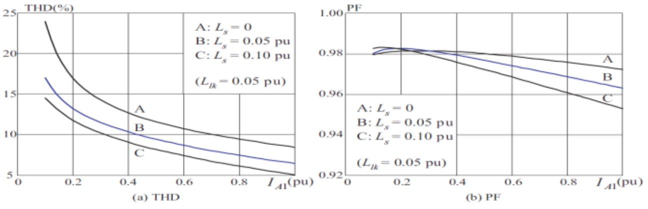
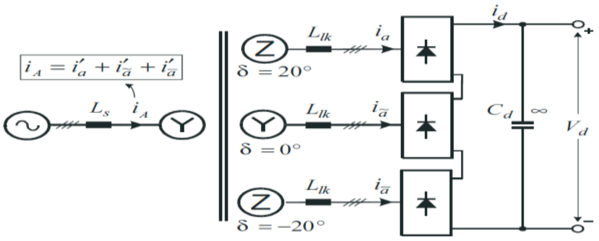


Fig.13 Line current THD and PF of the 12-pulse Series-type rectifier...

PULSE DIODE RECTIFIER

The block diagram of an 18-pulse series-type diode rectifier is shown in Fig.14. The rectifier has three units of identical six pulse diode rectifiers fed by a phase shifting transformer. The sign “Z” enclosed by a circle represents a three-phase zigzag connected winding, which provides a required phase displacement δ between the primary and secondary line-to-line voltages. The 18-pulse rectifier is able to eliminate four dominant harmonics (the 5th, 7th, 11th, and 13th). This can be achieved by employing a phase-shifting transformer with a 20° phase displacement between any two adjacent secondary windings. This circuit reduces THD below 4% for 50% load and power factor better than 0.96 shown in fig. 15.



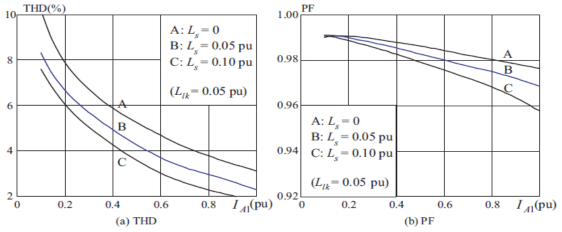


Fig. 14 The 18-pulse rectifier

Fig. 15 THD and PF of the 18-pulse rectifier.

PULSE DIODE RECTIFIER

The configuration of a 24-pulse series-type diode rectifier is shown in Figure 16, where a phase-shifting transformer is used to power four sets of six-pulse diode rectifiers. To eliminate six dominant current harmonics (the 5th, 7th, 11th, 13th, 17th, and 19th), the transformer should be arranged such that there is a 15° phase displacement between the voltages of any two adjacent secondary windings. This circuit reduces THD below 2% and power factor better than 0.96 without filters as shown in Fig. 17.

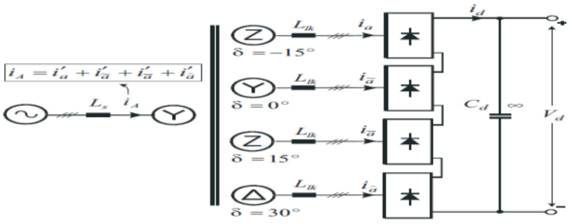


Fig. 16 The 18-pulse rectifier.

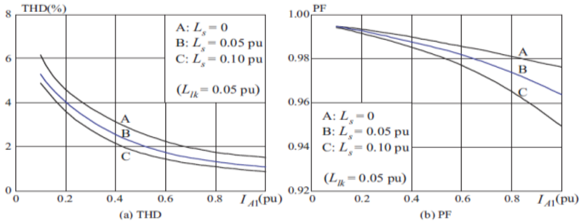


Fig. 17 THD and PF of the 24-pulse rectifier.

VOLTAGE SOURCE INVERTERS (VSI)

The self-commutated inverter use High Voltage Insulated Gate Bipolar Transistor (IGBTs) or Integrated Gate Commutated Thyristor (IGCTs), with higher level topologies are suitable for MV drives.

H-BRIDGE INVERTERS [25]

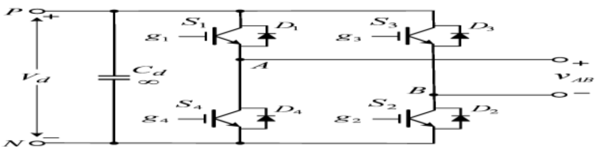


Fig. 18 Single-phase H-bridge inverter.

H-bridge is a power cell consisting of single phase bridge Inverter structure as shown in Fig.18. It has Input as DC terminals and Output as AC terminals. This bridge is considered as independent module and no. of them are used to construct single leg of three phase Inverter. This topology is called as Cascaded H-bridge (CHB) multilevel inverter and it is one of the popular converter topologies used in high-power medium-voltage (MV) drives [14, 23, 25]. It is composed of a multiple units of single-phase H-bridge power cells. The H-bridge cells are normally connected in cascade on their ac side to achieve medium-voltage operation and low harmonic distortion.

In practice, the number of power cells in a CHB inverter is mainly determined by its operating voltage and manufacturing cost. For instance, in the MV drives with a rated line-to-line voltage of 3300 V, a nine-level inverter can be used, where the CHB inverter has a total of 12 power cells using 600 V class components. The use of identical power cells leads to a modular structure, which is an effective means for cost reduction. The CHB multilevel inverter requires a number of isolated dc supplies, each of which feeds an H-bridge power cell.

CASCADED H-BRIDGE INVERTER WITH EQUAL DC VOLTAGE

The cascaded H-bridge multilevel inverter uses multiple units of H-bridge power cells connected in a series chain to produce high ac voltages. A typical configuration of a five-level CHB inverter is shown in Fig.19, where each phase leg consists of two H-bridge cells powered by two isolated dc supplies of equal voltage E.

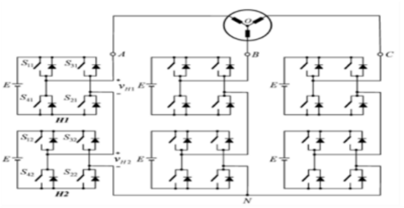
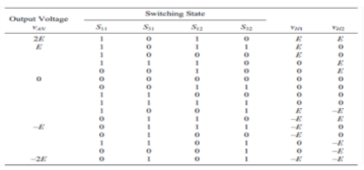


Fig 19. Five level Cascaded H-Bridge Inverter

Table 2, Voltage Level & Switching State of 5-Level CHB Inverter



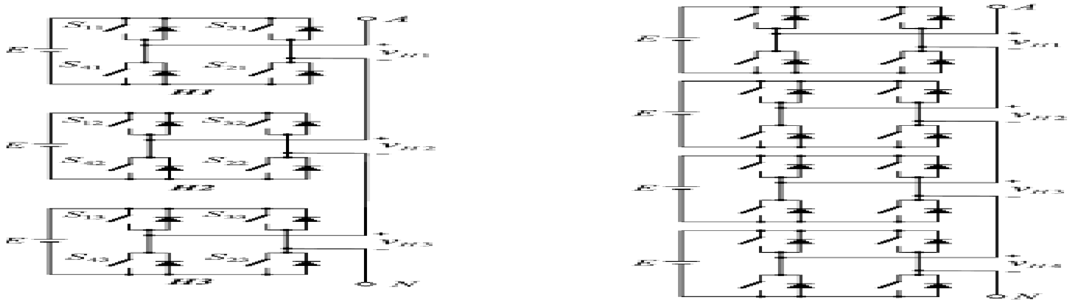
Output Voltage	Switching State					
v_{AN}	S_{11}	S_{31}	S_{12}	S_{32}	v_{H1}	v_{H2}
2E	1	0	1	0	E	E
E	1	0	1	1	E	0
	1	0	0	0	E	0
	1	1	1	0	0	E
	0	0	1	0	0	E
0	0	0	0	0	0	0
	0	0	1	1	0	0
	1	1	0	0	0	0
	1	1	1	1	0	0
	1	0	0	1	E	−E
	0	1	1	0	−E	E
−E	0	1	1	1	−E	0
	0	1	0	0	−E	0
	1	1	0	1	0	−E
	0	0	0	1	0	−E
−2E	0	1	0	1	−E	−E

The CHB inverter in Fig 19 can produce a phase voltage with five voltage levels. When switches S_{11}, S_{21}, S_{12}, and S_{22} conduct, the output voltage of the H bridge cells H1 and H2 is $v_{H1} = v_{H2} = E$, and the resultant inverter phase voltage is $v_{AN} = v_{H1} + v_{H2} = 2E$, which is the voltage at the inverter terminal A with respect to the inverter neutral N. Similarly, with S_{31}, S_{41}, S_{32}, and S_{42} switched on, $v_{AN} = –2E$. The other three voltage levels are E, 0, and –E, which correspond to various switching states summarized in Table 2. It can be observed from Table 2, that some voltage levels can be obtained by more than one switching state. The voltage level E, for instance, can be produced by four sets of different (redundant) switching states. The switching state redundancy is a common phenomenon in multilevel converters & provides a great flexibility for switching pattern design, especially for space vector modulation schemes. The number of voltage levels in a CHB inverter is given as:

$$m = (2H + 1), \qquad (3)$$

Where H is the number of H-bridge cells per phase leg. The voltage level m is always an odd number for the CHB inverter while in other multilevel topologies such as diode-clamped inverters, it can be either an even or odd number. The CHB inverter introduced above can be extended to any number of voltage levels. The per-phase diagram of seven and nine level inverter is shown in Fig. 20, where the seven level inverter has three H-bridge cells in cascade while the nine level has four cells in series. The total number of active switches (IGBTs) used in the CHB inverters can be calculated by

$$N_{sw} = 6(m – 1), \qquad (4)$$



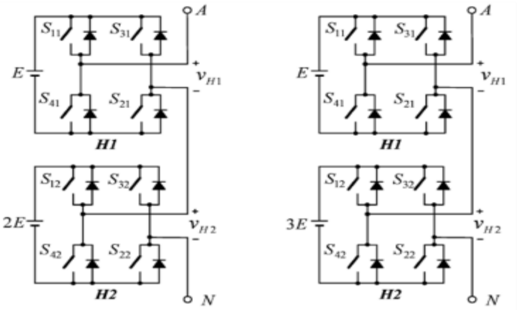
(a) Seven-level inverter (b) Nine-level inverter

Fig. 20 Per-phase diagram of seven- and nine-level CHB inverters.

The dc supply voltages of the H-bridge power cells chosen above is E and same for all the cells. Alternatively, different dc voltages may be selected for the power cells. With unequal dc voltages, the number of voltage levels can be increased without adding H-bridge cells in cascade.

Fig. 21 shows two inverter topologies, where the dc voltages for the H bridge cells are not equal. In the seven-level topology, the dc voltages for H1 and H2 are E and 2E, respectively. The two-cell inverter leg is able to produce seven voltage levels: 3E, 2E, E, 0, –E, –2E, and –3E. The relationship between the voltage levels and their corresponding switching states is summarized in Table 3.

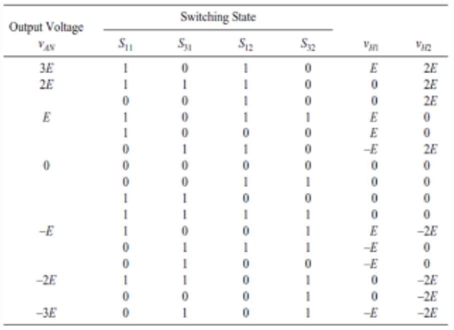
In the nine-level topology, the dc voltage of H2 is three times that of H1. All the nine voltage levels can be obtained by replacing the H2 output voltage of vH2 = ±2E in Table 3 with vH2 = ±3E and then calculating the inverter phase voltage vAN.



(a) Two-cell seven-level topology (b) Two-cell nine-level topology

Fig 21 CHB Inverter with unequal Voltages

Table 3 Voltage Level and Switching States



Output Voltage	Switching State					
v_{AN}	S_{11}	S_{31}	S_{12}	S_{32}	v_{H1}	v_{H2}
3E	1	0	1	0	E	2E
2E	1	1	1	0	0	2E
	0	0	1	0	0	2E
E	1	0	1	1	E	0
	1	0	0	0	E	0
	0	1	1	0	–E	2E
0	0	0	0	0	0	0
	0	0	1	1	0	0
	1	1	0	0	0	0
	1	1	1	1	0	0
–E	1	0	0	1	E	–2E
	0	1	1	1	–E	0
	0	1	0	0	–E	0
–2E	1	1	0	1	0	–2E
	0	0	0	1	0	–2E
–3E	0	1	0	1	–E	–2E

ADVANTAGES OF CHB

Multilevel inverter: Modular structure**.** The multilevel inverter is composed of multiple units of identical H-bridge power cells, which leads to a reduction in manufacturing cost.

1) Lower voltage THD and dv/dt**.** The inverter output voltage waveform is formed by several voltage levels with small voltage steps. Compared with a two-level inverter, the CHB multilevel inverter can produce an output voltage with much lower THD and dv/dt;
2) High-voltage operation without switching devices in series**.** The H-bridge power cells are connected in cascade to produce high ac voltages. The problems of equal voltage sharing for series-connected devices are eliminated;

DISADVANTAGES

1) Large number of isolated dc supplies**.** The dc supplies for the CHB inverter are usually obtained from a multi-pulse diode rectifier employing an expensive phase shifting transformer;
2) High component count**.** The CHB inverter uses a large number of IGBT modules. A nine-level CHB inverter requires 64 IGBTs with the same number of gate drivers.

DIODE CLAMPED MULTILEVEL INVERTERS

The diode-clamped multilevel inverter employs clamping diodes and cascaded dc capacitors to produce ac waveforms with multiple levels. The inverter can be generally configured as a three, four, or five level topology, but only the three-level inverter, often known as neutral-point clamped (NPC) inverter, has found wide application in high-power medium voltage (MV) drives.

The main features of the NPC inverter include reduced dv/dt and THD in its ac output voltages in comparison to the two-level inverter discussed earlier. More importantly, the inverter can be used in the MV drive to reach a certain voltage level without switching devices in series. For instance, the NPC inverter using 6000 V devices is suitable for the drives rated at 4160 V.

DIODE CLAMPED THREE-LEVEL INVERTER:

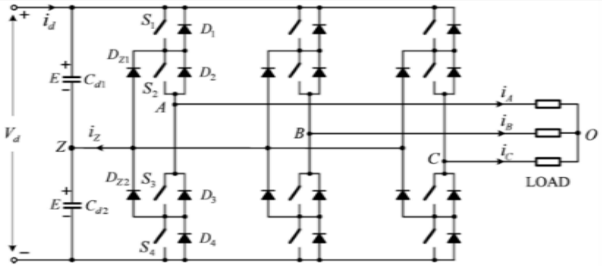
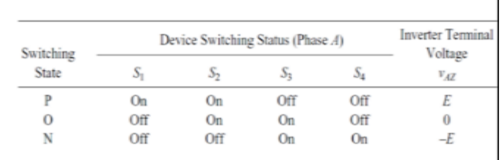


Fig 22, Three Level NPC Inverter

Table 4 Definition of Switching States



Switching State	Device Switching Status (Phase A)				Inverter Terminal Voltage v_{AZ}
	S_1	S_2	S_3	S_4	
P	On	On	Off	Off	E
O	Off	On	On	Off	0
N	Off	Off	On	On	$-E$

As shown in fig.22, the dc bus capacitor is split into two, providing a neutral point Z. The diodes connected to the neutral point, D_{Z1} and D_{Z2}, are the clamping diodes. When switches S_2 and S_3 are turned on, the inverter output terminal A is connected to the neutral point through one of the clamping diodes. The voltage across each of the dc capacitors is E, which is normally equal to half of the total dc voltage V_d. With a finite value for C_{d1} and C_{d2}, the capacitors can be charged or discharged by neutral current i_Z, causing neutral-point voltage deviation.

SWITCHING STATES

The operating status of the switches in the NPC inverter can be represented by switching states shown in Table 4. Switching state ‘P’ denotes that the upper two switches in leg A are on and the inverter terminal voltage v_{AZ}, which is the voltage at terminal A with respect to the neutral point Z, is +E, whereas ‘N’ indicates that the lower two switches conduct, leading to $v_{AZ} = –E$.

Switching state ‘O’ signifies that the inner two switches S_2 and S_3 are ON and v_{AZ} is clamped to zero through the clamping diodes. Depending on the direction of load current i_A, one of the two clamping diodes is turned on. For instance, a positive load current ($i_A > 0$) forces D_{Z1} to turn on, and the terminal A is connected to the neutral point Z through the conduction of D_{Z1} and S_2. It can be observed from Table 4, that switches S_1 and S_3 operate in a complementary manner.

Fig 23 and 24 shows how the line-to-line voltage waveform is obtained. The inverter terminal voltages v_{AZ}, v_{BZ}, and v_{CZ} are three-phase balanced with a phase shift of 120 degree between each other. The line-to-line voltage v_{AB} can be found from $v_{AB} = v_{AZ} - v_{BZ}$, which contains five voltage levels (+2E, +E, 0, –E, and –2E).

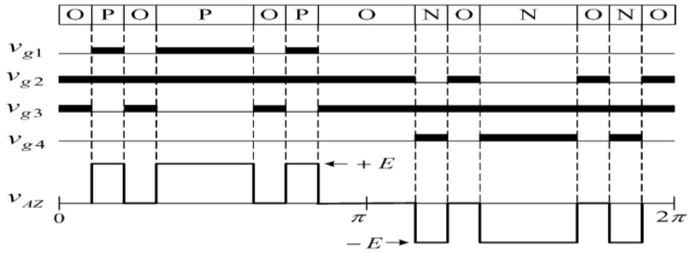


Fig.23 Switching states, gate signals & v_{AZ}

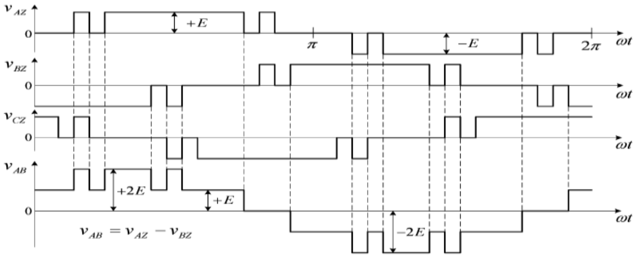


Fig.24 Inverter terminal and line voltage waveforms

ADVANTAGES

1) No dynamic voltage sharing problem in devices. Each of the switches in the NPC inverter withstands only half of the total dc voltage during commutation.
2) Static voltage equalization without using additional components**.** The static voltage equalization can be achieved when the leakage current of the top and bottom switches in an inverter leg is selected, lower than that of the inner switches.
3) Low THD and dv/dt. The line-to-line voltages is composed of five voltage levels, which leads to lower THD and dv/dt in comparison to the two-level inverter operating at the same voltage rating and device switching frequency.

DISADVANTAGES

1) Needs additional clamping diodes
2) Complicated PWM switching pattern design is required
3) Possibility of deviation of neutral point voltage.

NEUTRAL-POINT VOLTAGE CONTROL

The neutral-point voltage v_Z varies with the operating condition of the NPC inverter. If the neutral-point voltage deviates too far, an uneven voltage distribution takes place, which may lead to premature failure of the switching devices and cause an increase in the THD of the output voltage.

Causes of Neutral-Point Voltage Deviation

In addition to the influence of switching voltage, the neutral-point voltage may also be affected by a number of following factors,

1) Unbalanced dc capacitors due to manufacturing tolerances
2) Inconsistency in switching device characteristics
3) Unbalanced three-phase operation

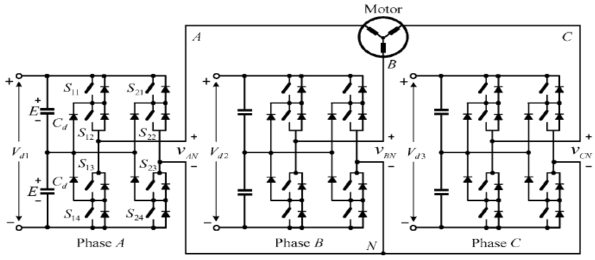
To minimize the neutral-point voltage shift, a feedback control scheme can be implemented, where the neutral-point voltage is detected and then controlled.

NPC / H-Bridge Inverter

The NPC/H-bridge inverter is developed from the three-level NPC inverter topology and shown in Fig.25. This inverter has some unique features that have promoted its application in the MV drive applications.

The output voltage and power of a three-level NPC inverter can be doubled by using 24 active switches, every two of which are connected in series. The NPC/H-bridge inverter also uses 24 active switches to achieve the same voltage and power ratings as the 24-switch NPC inverter. Each of the inverter phases is composed of two NPC legs in an H-bridge form. The NPC/H-bridge inverter has some advantages over the three-level NPC inverter. The distinct advantage is the inverter phase voltages, v_{AN}, v_{BN} and v_{CN}, contain five voltage levels instead of three levels for the NPC inverter, leading to a lower dv/dt and THD.

The inverter does not have any switching devices in series, which eliminates the device dynamic and static voltage sharing problems. However, the inverter requires three isolated dc supplies, which increases the complexity and cost of the dc supply system.



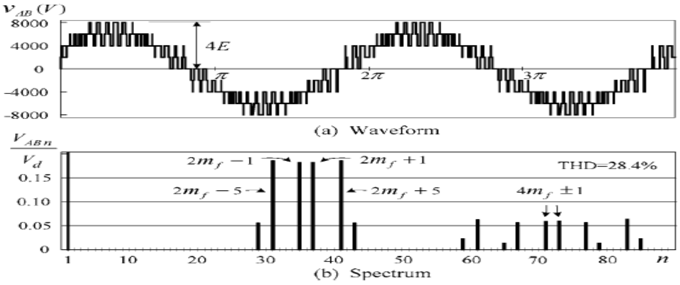


Fig 25 Five-level NPC/H-bridge inverter. Fig. 26 **S**pectrum of the inverter line voltage

Waveforms and Harmonics of NPC/H-bridge Inverter

The waveform for the inverter line-to-line voltage v_{AB} is illustrated in Fig. 26. It contains nine voltage levels. The triplen harmonics in v_{AN} do not appear in v_{AB} due to the three-phase balanced system, resulting in a reduction of THD from 33.1% to 28.4%.

MULTILEVEL FLYING-CAPACITOR INVERTERS [7, 22]

Fig. 27, shows a typical configuration of a five-level flying-capacitor inverter. It is evolved from the two-level inverter by adding dc capacitors to the cascaded switches. There are four complementary switch pairs in each of the inverter legs. For example, the switch pairs in leg A are (S_1,S'_1), (S_2,S'_2), (S_3, S'_3), and (S_4,S'_4). Therefore, only four independent gate signals are required for each inverter phase.

The flying-capacitor inverter can produce an inverter phase voltage with five voltage levels. When switches S_1, S_2, S_3, and S_4 conduct, the inverter phase voltage v_{AN} is 4E, which is the voltage at the inverter terminal A with respect to the negative dc bus N. Similarly, with S_1, S_2, and S_3 switched on, v_{AN} = 3E. Table 5 lists all the voltage levels and switching states.

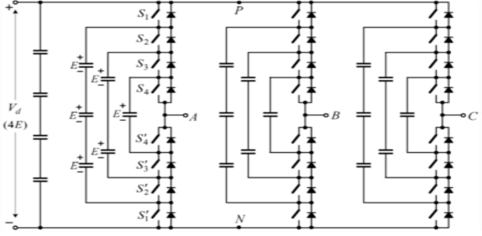


Fig 27, Five level flying capacitor Inverter

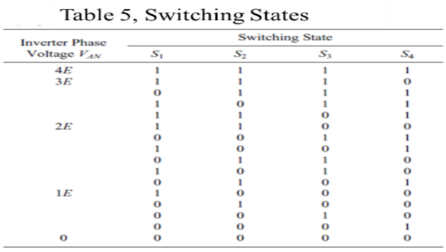


Table 5, Switching States

Inverter Phase Voltage V_{AN}	Switching State			
	S_1	S_2	S_3	S_4
4E	1	1	1	1
3E	1	1	1	0
	0	1	1	1
	1	0	1	1
	1	1	0	1
2E	1	1	0	0
	0	0	1	1
	1	0	0	1
	0	1	1	0
	1	0	1	0
	0	1	0	1
1E	1	0	0	0
	0	1	0	0
	0	0	1	0
	0	0	0	1
0	0	0	0	0

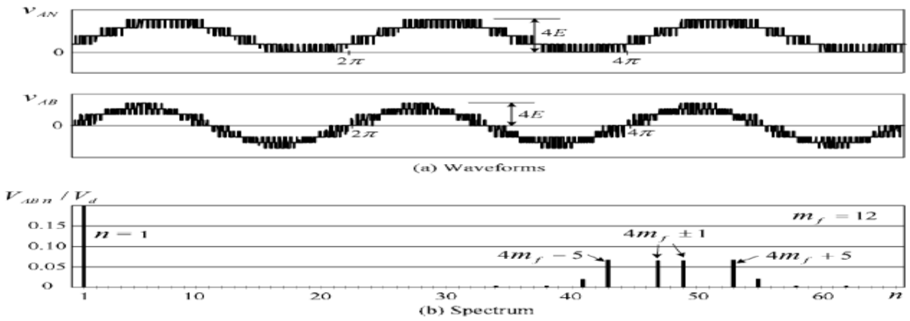


Fig. 28 **S**pectrum of the five-level flying-capacitor inverter.

Flying-capacitor inverter topology is derived from the two-level inverter hence it carries the same features as the two-level inverter such as modular structure for the switching devices. It is also a multilevel inverter, producing the voltage waveforms with reduced dv/dt and THD. However, the flying-capacitor inverter has following limitations:

1) The inverter requires several banks of bulky dc capacitors, each needs a separate pre-charge circuit.
2) The dc capacitor voltages in the inverter normally vary with the inverter operating conditions. To avoid the problems caused by the dc voltage deviation, the voltages on the dc flying capacitors should be tightly controlled, which increases the complexity of the control scheme.

Due to the above-mentioned drawbacks, the use of the flying-capacitor inverter in the drive system is limited.

CURRENT SOURCE INVERTER (CSI) [24]

CSI is similar to VSI but here current regulating choke is used in DC link unlike capacitors in VSI. It utilizes active switching devices on the motor side, and thus can adopt suitable PWM together with advanced control strategies to improve motor dynamic performance and reduce torque ripples. Motor PF is controllable with these drives. At the line side, LCI and CSI drives have inherent regenerating capability. In contrast, a large percentage of the industrial VSI drives employ single or multi-pulse diode rectifier at the line side that prevents power to be regenerated back to the line.

CSI or VSI drives with an active front end are also capable of line PF correction. For high-power medium-voltage applications, traditional two-level VSI supplies the motor with chopped voltage waveforms and thus generates high dv/dt at the motor terminals. Multi-level VSIs are therefore used to reduce the voltage steps and stress in the motor. CSIs, on the other side, provide the motor load with sinusoidal output voltage and current waveforms with low harmonics because of the filter capacitor at the output. Devices can be connected in series to achieve higher voltage rating, making the structure relative simple and robust for high voltage and power ratings.

LOAD COMMUTATED INVERTER (LCI) [16]

LCI drives employ thyristors as switching devices. Thyristors do not have self-turn-off capability but can be naturally commutated by the load voltage with a leading PF. The LCI features low cost and high efficiency and the lack of pulse width modulation. It is a popular solution for very large drives where the initial investment and operating efficiency are important. However, the LCI itself is not a grid and motor friendly topology. It normally generates low-frequency current harmonics, and the grid-side PF is not controllable. Active filters of high power ratings are employed for the LCI to improve the grid performance.

Other concerns include the difficulty of device commutation at low speed due to the low motor back EMF to commutate the inverter. A method named dc-link pulsing is commonly used to assist device commutation through intentionally created zero-current intervals. A side effect of the method is increased torque pulsation. Often these pulsations are not acceptable and a separate inching device is needed. The dynamic performance of the LCI drive is the poorest among all three due to its naturally commutated operation.

COMPARISON OF MULTILEVEL TOPOLOGIES

The two-level inverter has the lowest cost and weight in comparison with the other topologies. But this inverter has a very high THD and high dv/dt because of level switching between positive and negative DC link voltage. It needs series connection of devices because they are available with low voltage ratings.

The cost and the weight of the 5-level multilevel inverters seem better than the 9-level multilevel inverters. By increasing the number of levels, the cost and weight of the multilevel inverter will be increased. The advantage that the 9-level multilevel inverters have over the 5-level multilevel inverters is their THD without filters. Using the 5-level inverter and a filter is a better design in terms of component count, power loss and reliability.

The Flying capacitor clamped inverter has the lowest power losses among all the topologies. Because of bulky capacitors it is heavier than the other topologies. Practically it is not used in applications that are going to be used has restriction on space.

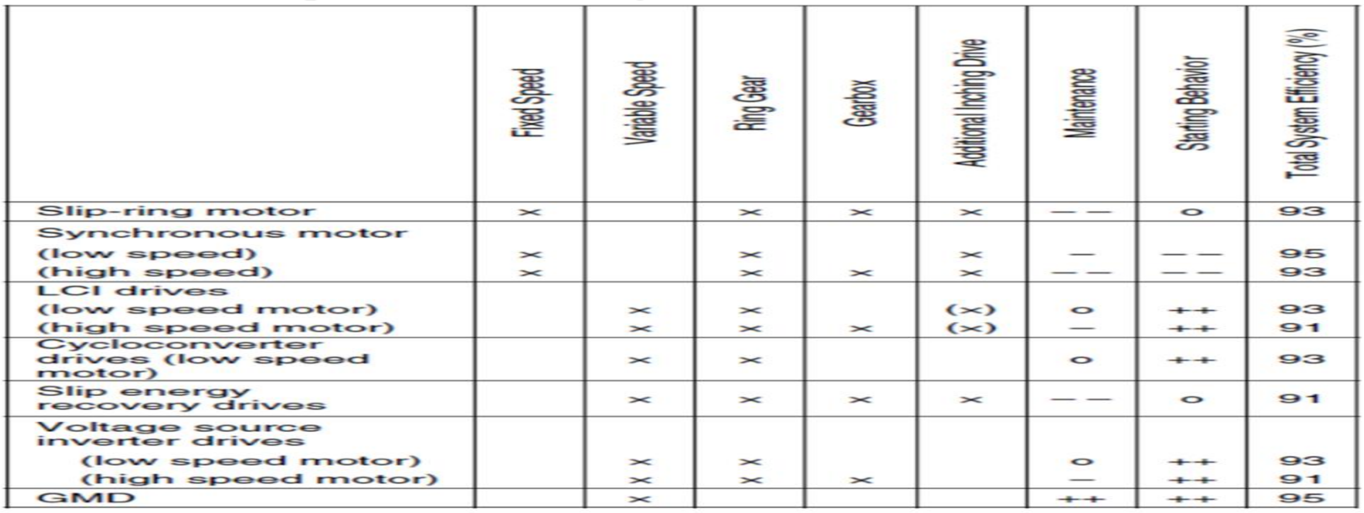
The cascaded H-bridge has the lowest weight and cost between the multilevel inverters, but its power losses are marginally higher than all other topologies because of more number of devices conducting at a time. But this topology scores over all because of modular power cells built with low voltage switching devices. Modular structure gives easy maintenance possibility hence low downtime. This topology is most suited for high power applications like GMD mills.

The diode clamped multilevel inverter power losses are lower than cascaded H-bridge. Diode clamped inverter topology have THD, cost and power losses between other types of inverters. Only problem is increased number of components as number of levels go up.

DRIVE COMPARISON FOR MILLS. [2]

In the Table 6, the main criteria for selecting drive systems are given. For specific projects process requirements, equipment cost, system efficiency and the related energy savings and maintenance aspects and the related costs need to be evaluated. The efficiency of the ring gear and the gearbox depends also on other factors, e.g. alignment, and can be significantly lower than the assumed values used for the comparison.

Table 6



	Fixed Speed	Variable Speed	Ring Gear	Gearbox	Additional Inching Drive	Maintenance	Starting Behavior	Total System Efficiency (%)
Slip-ring motor	×		×	×	×	— —	o	93
Synchronous motor								
(low speed)	×		×		×	—	— —	95
(high speed)	×		×	×	×	— —	— —	93
LCI drives								
(low speed motor)		×	×		(×)	o	++	93
(high speed motor)		×	×	×	(×)	—	++	91
Cycloconverter drives (low speed motor)		×	×			o	++	93
Slip energy recovery drives		×	×	×	×	— —	o	91
Voltage source inverter drives								
(low speed motor)		×	×			o	++	93
(high speed motor)		×	×	×		—	++	91
GMD		×				++	++	95

ENERGY AND COST SAVINGS

Process optimization can lead to a much more efficient use of grinding power and thus to significant energy savings. Furthermore, significant energy savings can be achieved with drive systems that have high efficiency.

EFFICIENCY COMPARISON

The evaluation of the overall system efficiency is an important factor during the selection of the most appropriate drive system when considering the life cycle costs. Table 7, shows the typical efficiencies for a 16 MW ball mill with different drive configurations. It compares dual pinion variable speed ring-geared alternatives and GMD solution. The efficiency of the ring-gear and the gear reducer are affected by other factors, e.g. alignment, and can be significantly lower than the sprecified values used. Motor and transformer efficiencies can be improved by modifying their design (impact on costs) and can slightly vary depending on the application.

The main observation is that, the lower are the components present on the system, the higher is the overall efficiency. Variable speed grinding mill drives equipped with high speed squirrel cage induction motors, require a gear reducer and a ring-gear. If a two stage gear reducer is used, efficiency drops to about 97%. On the other hand, the variable speed alternative using low speed synchronous motor eliminates the gear reducer, improving the overall efficiency. The GMD is able to provide unmatched efficiency.

Table 7

-	VSD High speed	VSD Low speed	VSD GMD
Transformer	99.1%	99.1 %	99.1 %
Converter	98.6%	98.6%	99.2%
Motor	97.2%	97.2%	96.8%
Gear reducer	98.5%	n/a	n/a
Ring-gear	98.0%	98.0%	n/a
Overall efficiency	**91.7%**	**93.1%**	**95.2%**

COST COMPARISON

Several factors and cost considerations must be taken into account in the drive system evaluation. A proper evaluation and the right selection of the drive system impacts the total cost of ownership (TCO) of the mill. The TCO analysis must include direct and indirect costs. As an example of indirect costs can be cited the loss of production related to the non-availability of the system. The GMD, by having fewer components, has the highest availability. It is followed by the low speed VSD solution and by the high speed VSD.

Also as direct costs, the efficiency and the use (including disposal costs) of lubricants on the ring-geared mills shall be considered. Plant layout is a factor for evaluation when comparing geared and gearless drives. Obviously, the footprint for gearless, single pinion and dual pinion drives is different. Single pinion drives require the smallest amount of space, but only marginally less than gearless drives. Dual pinion drives have the maximum space requirement.

The capital expenditure for gearless mill drives is typically higher than for other drive systems. However, energy savings due to higher efficiency and reduced maintenance costs usually leads to smaller lifecycle cost compared with other drive system solutions. The lowest capital expenditure is given by the high speed (VSD) solution, where the electrical equipment cost less and the mechanical part more, as a result of the inclusion of the ring-gear and gear reducer.

MAINTENANCE AND REDUCED SHUT DOWNS

Beside the cost savings related to energy savings additional cost savings can be achieved with reduced maintenance. GMD systems show excellent low speed characteristics without the need for any speed encoder. Cycloconverters are ideally suited for low speed applications and deliver precise and strong torque control during start up and during cascading of the material. The drive control has modes for inching and creeping. This allows fast, easy and accurate positioning of the mill and thus reduces the maintenance time needed for changing liners.

Service and maintenance for a drive system is mainly needed because there are parts that have wear such as gearboxes, bearings and carbon brushes or may get dirty or clogged such as heat exchanger tubes or air filters. These components need to be checked and replaced before the functionality cannot be guaranteed anymore, the behavior is degraded too much or the replacement would require an unplanned shutdown. It is clear that the maintenance work increases with the number of wearing components.

In case of component failures spare parts are needed on site to reduce downtime of the plant. However, proper design, operation of the equipment within safe limits and the use of supervision systems eliminate the risk of severe failures as far as possible.

Often routine maintenance of drive systems can be done during normal planned mill outages. However, the maintenance work that needs to be done for bearings, ring gears, gearboxes and other wearing parts leads to higher maintenance costs, tends to increase shutdown times and thus reduces system availability.GMD systems have only very few wearing parts, i.e. the brushes and the greaseless motor dust sealing, and therefore need relative little service and maintenance. This ultimately results in very high availability of GMD systems and lower maintenance costs compared with other drive systems.

CONCLUSIONS

Grinding of ores in mine demands advanced technologies that improve overall efficiency and reliability. Grinding has now been driven by large diameter mills for increased throughput for cost competitive processing of ores. Sizes of mills have gone upto 42 feet diameters and power about 38 MW. At such power levels the geared mills has got limitations and only solution is Gearless mills (GMD).

The technology for GMD calls for low speed (0-10 RPM) ring motor wrapped around mill cylinder and manufactured in multiple segments for ease of assembly at site. The motor options are Induction motor, synchronous motor and PM motor. Presently synchronous motors are being used because it can be operated with unity or leading power factor, reduced motor current and hence reduced loss. It also offers good starting torque without affecting power system. Induction motors have operating power factor always lagging drawing more current compared to synchronous motors but it has simple and rugged construction which can improve availability. PM motors are most promising because of its very high power density, unity power factor and ease of operation but has issues in assembly, unbalance forces on bearings etc. which need to be addressed.

Presently for driving GMD, cyclo-converters are used because of compact construction, direct drive and regenerating capability. But it has disadvantage of harmonics and inter-harmonics injected into supply network. Moreover GMD needs variable speed operation for process optimisation which is tricky in case of cyclo-converter to generate very fine frequency steps. Also filter requirement is huge at line side to take care of weak power supply network.

With development of IGBT and IGCT devices and upcoming SiC, voltage source and current source Inverter offer good alternative to cyclo-converters. The multilevel and H-bridge Inverters with multi pulse 12, 18, 24 rectifiers with phase shifting transformer at input presents good input THD performance without filters. Also Inverter stage is built with modular construction for low dv/dt and better maintenance. This configuration can be built with both VSI and CSI as per design requirements. Comparison with cyclo-converter shows that modern VSI/CSI Inverter are promising alternative to cyclo-converters. With use of various function in GMD like stop sequences to protect the mechanical system from dangerous torque kicks and reduce the wearing of mechanical elements, operation and maintenance requirement like inching can be implemented easily. Variable speed operation which offers important benefits in process operation is possible with VSI/CSI drive with very precision speed control without compromising THD limits. It can be concluded that the modern VSI/CSI drives shows a great potential for GMD application.

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