Large PWM Inverters for Rolling Mills

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INTRODUCTION

DC drives and cycloconverters have been used in rolling mill applications for many years. The appearance of the IEGT (Injection Enhanced insulated Gate bipolar Transistor) or IGCT/GCT made the large PWM drive system practical. The newer 3kV IEGT device has been used to develop 3-level voltage source inverters in configurations up to 40MVA. The IEGT Inverter has excellent performance characteristics that make it suitable for rolling mill main drives and many other high performance applications. We will introduce the features of the IEGT Inverter and recent applications in hot strip mills.

DC DRIVE

DC drives have been used successfully in rolling mill applications for many years. They have an excellent performance record meeting rolling mill drive requirements including; speed control accuracy, rapid speed control response, fast load recovery, and more.

Speed Accuracy

Many drives in a rolling mill run in a coordinated fashion using a reference from a PLC or earlier analog forms of master control. High quality products require speed control accuracy to the master control reference from all drives in order to maintain the proper forces and tensions.

Speed Response

Drive speeds change during the rolling process for a variety of reasons. The command may come from the operator, an automation function adjusting gauge, or the need to thread the mill at a low speed and then accelerate to a higher rolling speed. Regardless of the cause, rapid speed control response means a smaller offset from the desired speed during the speed change and therefore a higher quality product.

Load Response

When metal impacts the roll face, a very large load is rapidly applied to the motor. The result is that speed drops until the motor output torque can adjust to the required rolling torque. Then the motor speed slowdown is stopped and accelerated to the speed reference. Rapid response to load change reduces the speed drop and improves quality.

Figure 1 shows the control system of a dc drive. The dc motor has armature and field windings. Each winding is separately controlled. The armature current is provided by a thyristor converter and controlled by the armature current regulator. The field current is controlled by the field current regulator and supplied by the field thyristor converter or exciter. The current control consists of a current reference and current feedback. In either case, when the reference is bigger than the feedback the voltage is increased and more current flows. This control is very simple, proven, and in use for a long time using increasing sophisticated control components.

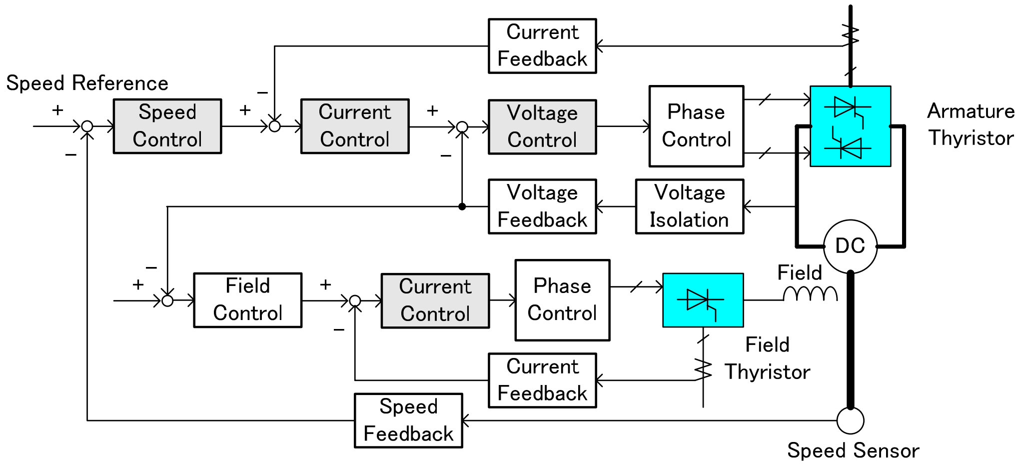

Figure 1 Configuration of a dc drive system

Figure 2 shows a large dc drive system utilizing a 12-pulse configuration. This approach improved the current motor ripple and power system harmonics over that of the 6-pulse configuration of Figure 1.

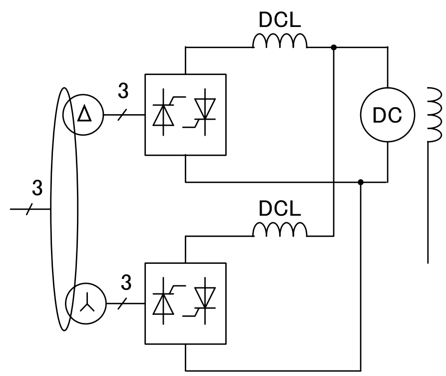

Figure 2 Large dc drive system

DC Motor Restrictions

DC motors have a manufacturing limitation which can be expressed by the M-value as follows:

$$M = P \times (N_{top})^2 / N_{base}$$

Where

P is DCM output kW (rated)
N_{Top} : Base speed of DCM (rpm)
N_{base} : Top speed of DCM (rpm)

The M-value shows the commutation issues related to speed and density of electron and magnetic flux. In the past, many DC motors have been manufactured and used for metal rolling main drives. The maximum value of the M constant is 2×10^6 to 3×10^6 for reversing rolling mills and 3×10^6 to 5×10^6 for non-reversing rolling mills. Figure 3 shows the technical selection criteria for single versus multiple dc motors for non-reversing rolling mills. The value of M is a function of commutation. In non-reversing applications the armature brushes can be shifted for optimum commutation for the direction of rotation. In reversing applications the brush position must commutate well in both directions of rotation so the range of M values is lower.

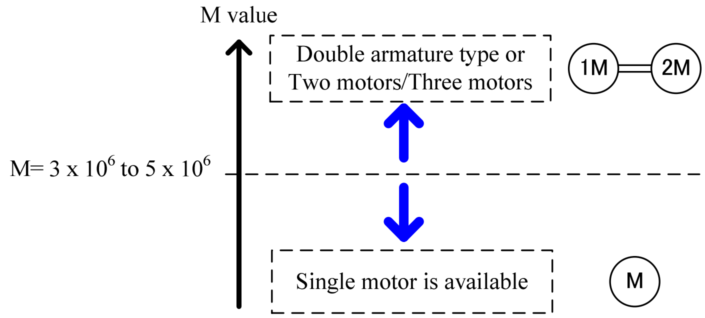

Figure 3 Selection of the dc motor for non-reversing rolling mills

The following examples use two motors with the same kW rating but different speeds to illustrate the point.

Example 1

Roughing Mill Motor rated 8,000 kW, Base speed; 50 rpm, Top Speed; 100 rpm

M value = $8000 \times (100)^2 / 50 = 1.6 \times 10^6$

Therefore a single motor can be applied

Example 2

Finishing Mill Motor rated 8,000 kW, Base speed; 200 rpm, Top Speed; 500 rpm

M value = $8000 \times (500)^2 / 200 = 10 \times 10^6$

The M value is greater than the criteria so either a double armature dc motor or two motors are required.

CYCLOCONVERTER

The development of the microprocessor made high performance vector control of ac motors practical. The high performance speed and torque characteristics of the dc drive systems could now be implemented without the dc motor commutation limitations.

Figure 4 shows the configuration of a cycloconverter system as applied on a main drive. It consists of three thyristor bridges, each phase bridge controlled by an algorithm to output a sinusoidal voltage instead of a dc voltage. Each phase voltage is shifted 120 degrees to make the 3-phase voltage applied to the motor.

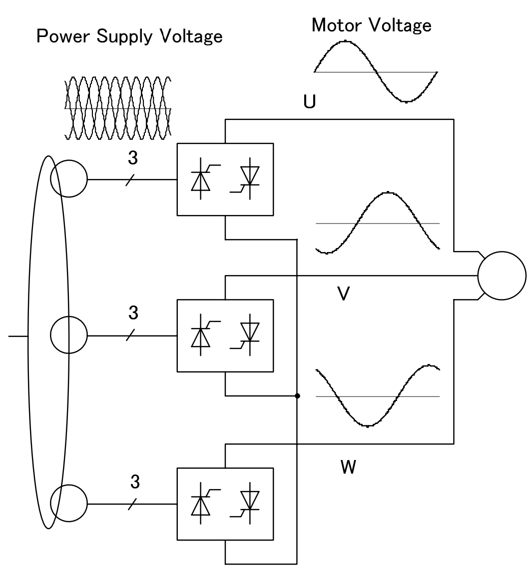

Figure 4 Configuration of a cycloconverter system

The cycloconverter was applied in main drive applications, but its output frequency was limited to approximately 20 Hz or less. Phase control in the cycloconverter's ac-ac conversion is limited to a percentage of the incoming line, making it difficult to realize higher frequencies.

The main motor requirements of rolling mills can be very large. This large capacity pushed the technology to higher voltages to minimize conductor size and installation costs. Figure 5 shows one solution using two cascade-connected cycloconverters.

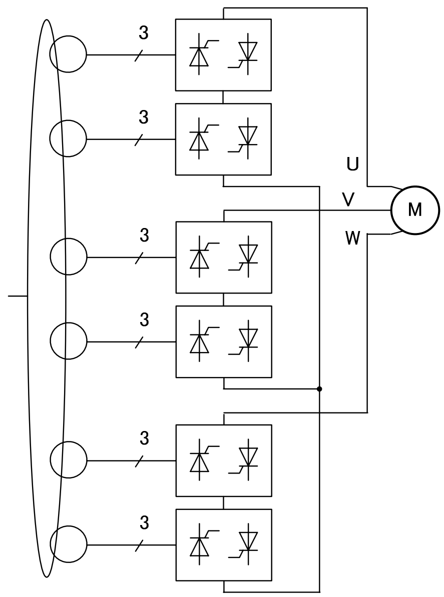

Figure 5 Two cascade-connected cycloconverters

Figure 6 shows the circulating current type cycloconverter which can have higher outputs frequency of up to 50Hz. The price for the higher output frequency is increased circuit complexity and component count.

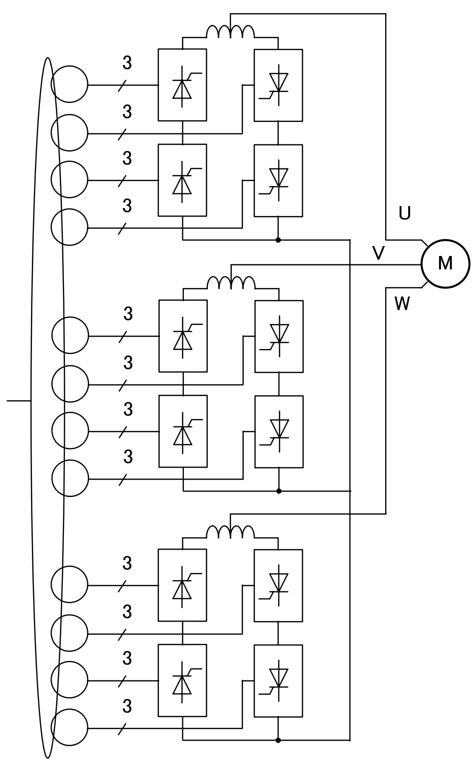

Figure 6 Circulating current cycloconverter

The power factor of the cycloconverter, which is a variation of the dc drive, often required correction in mill applications. In addition, the cycloconverter interjects non-integer order harmonics into power system which are difficult to filter. The voltage source inverter greatly improves the power factor and harmonics over that of the cycloconverter.

HIGHER VOLTAGE MOTORS

Motor kW capacity is proportional to the voltage and current. As motor kW increases there are certain break points where higher voltages become practical and desirable from the motor and drive point of view. Also, in general lower current improves the motor efficiency and construction cost.

The dc motor commutator voltage was limited to approximately 1200 V. The ac motor, which has no commutator limitations, is available at 3300 V, 6600 V and higher levels. Switchgear is also available in these voltage classes.

Most of the wiring cost depends on the motor current, although voltage class is also a factor. In general, wiring cost is reduced with large higher voltage motors up to about 10 kV. The most economical voltage for installation depends upon the cable cost, the number of cables applied per phase, and the number of phases (compare Figures 4, 5 and 6 above).

2-LEVEL VOLTAGE SOURCE INVERTER CIRCUIT

Figure 7 shows the 2-level PWM inverter. Typically, a 1200 V rated IGBT is used for 460 V output inverters. It is necessary to apply higher voltage rated devices for higher output voltages. At present higher power devices are limited to 4500 V or 6000 V. Extrapolating on the 460 V applications, a 4500 V device would have an output voltage of about 1750 Vac (460/1200x4500).

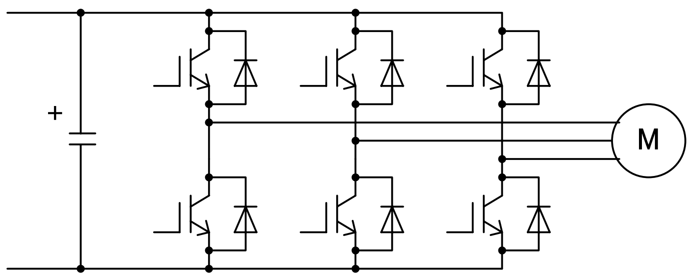

Figure 7 2-level PWM inverter

3-LEVEL VOLTAGE SOURCE INVERTER CIRCUIT

Figure 8 shows the 3 level PWM circuit. Each phase of the 3 level circuit consists of 4 switching devices and two clamping diodes. The Q1 and Q2 devices are connected in series. Thanks to the clamping diode DP, the emitter voltage of Q1 will never be at a lower potential than the Neutral Point. In this case, the Q1 collector-emitter voltage is limited to the P to Neutral Point voltage.

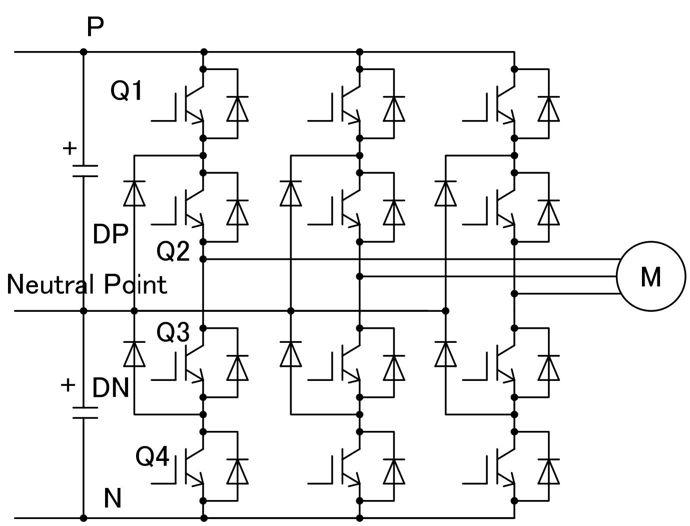

Figure 8 3-level PWM inverter

The 3-level circuit can output twice the voltage of 2-level circuit. So using the 4500 V device in the above example, 3300 V class output voltages are available.

Inverters based on GTO (Gate Turn-Off Thyristor) devices were used in late 1990`s. They featured the voltage source inverter advantages of very good power factor applied to the power system and sinusoidal motor waveforms. Then the improved GCT/IGCT (Gate Controlled Thyristor) power devices became available and were used for the main drive inverters. They featured better switching characteristics, lower losses and improved performance.

POWER FACTOR ADVANTAGE OF THE VOLTAGE SOURCE INVERTER

In the case of a conventional cycloconverter applied to a large rolling mill stand you could expect the average power factor over 15 or 30 minutes of rolling to be 0.7 lagging at best. The voltage source PWM inverter would be closer to 1.0 PF and require no additional correction by fixed banks of capacitors. The following figure illustrates the case of a 10 MW motor powered by cycloconverter and PWM drives for the case where 0.90 PF is required by the utility contract. The cycloconverter drive requires a large amount of capacitors, most likely in some sort of controlled arrangement such as a static var compensator (SVC), to meet voltage flicker and power company requirements for power factor. The PWM drive on the other hand is capable of supplying leading vars to other loads.

10 MW drive type..	Cycloconverter	PWM
Contract MVAR allowance	4.8	4.8
Drive MVAR requirements	10.0	0.0
MVAR from capacitors or SVC	5.2	0.0
Leading MVAR available for other loads.......	0.0	4.8

Figure 9 Drive MVAR comparisons

The 1.0 PF case has no MVAR and therefore is also the minimum ampere case. While minimum amperes may be the most attractive case when considering the power distribution system and cable size, it does not provide the minimum voltage fluctuation. Regulation of voltage at the drive level requires a leading PF to offset resistive voltage drop.

VOLTAGE STABILIZATION

Considering the utility voltage fixed, the voltage available to the drive will vary as a function of power drawn and the associated line drop. In the case of a reversing drive, MW are both supplied to and regenerated by the connected motor load. While motoring the IR voltage drop reduces the voltage available at the converter terminals. However, during regeneration power is supplied from the drive to the utility and the IR voltage rise increases the converter terminal voltage. Therefore both leading and lagging MVAR are required to offset the voltage drop/rise effects of the MW effects.

As shown below, the Fixed Pulse Pattern solution can operate at a leading PF to assist in stabilizing voltage over that of conventional PWM operation of the voltage source inverter. The Fixed Pulse Pattern (FPP) mode of PWM operation allows operation of the drive converter in both leading and lagging modes as a function of its incoming line voltage. When the line voltage drops for any reason leading vars are produced by the drive; and, if the line voltage should increase the drive draws lagging vars. This feature enhances the possibility of operating very large inverters on power systems without the need for external voltage assistance.

Figure 10 graphs the results of operating conventional and FPP PWM converters on a sample power system. Voltage drop at points between the Utility Infinite Bus and the Converter Terminals are proportional to impedance. Rated motor power delivered at 0.98 PF leading in this sample system produces virtually no voltage drop between the utility infinite bus and the converter terminals.

An additional benefit of the FPP mode is reduced harmonics as noted in the referenced papers.

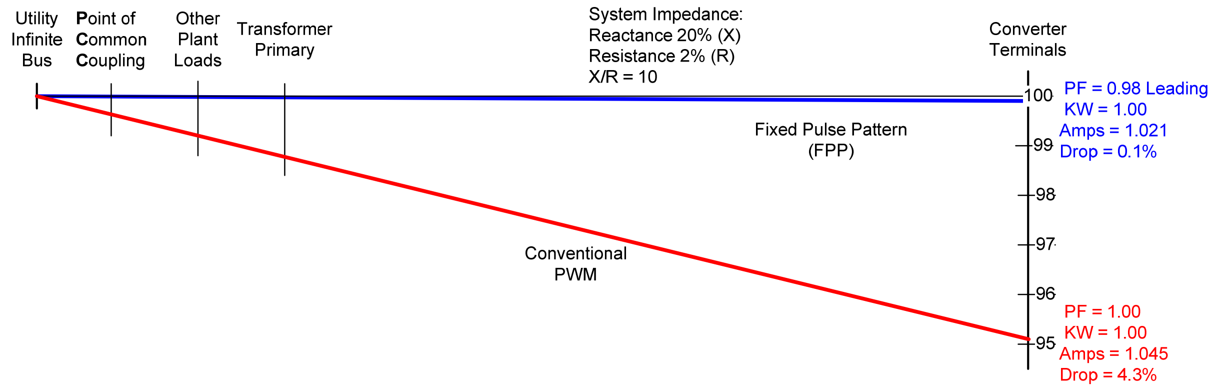

Figure 10 Line voltage comparison of conventional and FPP modes of PWM operation

In practice the impedance ratios as measured at each of the indicated points would vary, but the general result would be a smaller voltage drop contribution by the drive load at the point of connection to other plant loads and the Point of Common Coupling (PCC). A comprehensive load flow power study considering the entire plant is required to estimate the actual voltage fluctuations that can be expected.

IEGT - INJECTION ENHANCED GATE TRANSISTOR

The next step in large power device development was the press pack type IEGT. This device is based on transistor technology rather than the GTO and GCT/IGCT thyristor technology. The rating of the standard IEGT device is 4.5 kV, 2100 A in a diameter of 125 mm. Figure 11 shows the inside view of this device with 42 pieces of individual IEGT chips installed inside the press pack. The press pack packaging has been used for many years on thyristor based devices. It is designed to make good contact for all the IEGT chips and therefore maximize the package rating. One advantage of the IEGT is that the gate driver is a voltage signal with a simple circuit with relatively low power requirements.

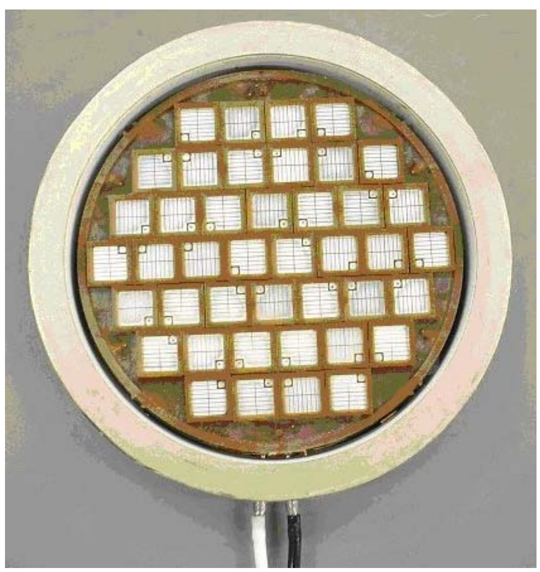

Figure 11 Internal view of an IEGT

More recently 4.5 kV, 2600A IEGT device was developed using the same number of the chips as the 2100 A package. This was made possible by improving the individual chip characteristics to include a lower on state voltage and faster switching.

HIGHER POWER IEGT DEVICE INVERTER CONSIDERATIONS

The 2100 A IEGT has been used since 1999 in an 8 MVA 3-level inverter and applied to large metals drives such as mill stands. Availability of the 2600 A IEGT device allowed the 25% larger 10 MVA inverter to be put into service. Figure 12 shows one phase leg of the 3-level circuit of Figure 8 and the physical packaging of the 10 MVA IEGT phase leg unit.

Each IEGT unit consists of a front side stack and back side stack. The front side stack consists of 4 IEGTs and the 2 clamping diodes mounted in water cooled heat sinks. The back side stack consists of the 4 IEGT bypass diodes mounted in water cooled heat sinks. The top of the IEGT unit contains the dc clamp snubber circuit. This snubber circuit is designed with minimum inductance, allowing for maximum suppression of the turn off surge voltage initiated by high speed device switching.

The use of de-ionized water ensures minimal corrosion and long life. Water cooling of power bridges has been used for many years to maximize power density (floor space) and minimized noise.

The gate boards (green cards) are mounted on the front of the IEGT stack. The gate turn-on/turn-off signal is calculated by the automatic control board (mounted remotely to the power bridge) and transmitted to the gate board as a optical signal. The gate boards convert the optical signal to the voltage pulse which is applied to the IEGT device. There is a gate ON/OFF monitoring circuit in the gate board whose status is returned to the automatic control board as a optical signal. These gate signals are recorded every micro-second and used for failure analysis.

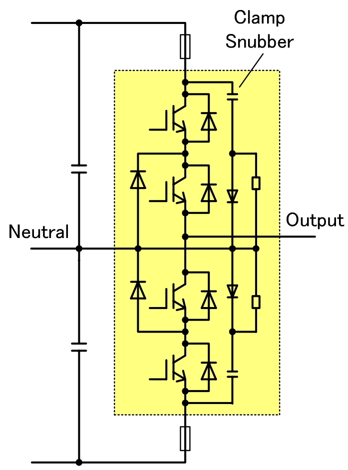

Figure 12 One phase leg of the 10 MVA IEGT inverter

The heat loss of the IEGT device is simply the voltage drop across the device times the current. There are two heat loss modes. One is the on state loss which consists of the on state saturated collector-emitter voltage times current. Therefore, when the current is increased the on state loss is increased. The on state voltage of the 10 MVA IEGT is 20 % less than that of the 8 MVA IEGT. This allows the on state loss to be the same wattage even with 25% more current (4/5 volts x 5/4 amps).

The other loss comes from device switching and the resulting surge voltage. The 10 MVA IEGT inverter was re-designed with a 30% reduced inductance. The result was the same surge voltage in both inverter ratings at their maximum current. This re-designed snubber circuit kept switching losses the same in both the 8 and 10 MVA inverters.

Overall the IEGT junction temperature is kept same for both the 8 and 10 MVA ratings at their rated currents and a 25% power improvement achieved. Figure 13 shows the outline of the 10MVA IEGT inverter which of course is the same cubicle size for both ratings.

Pictured from left to right are (3) cubicles in one lineup. Note that in the voltage source inverter application the ac-dc converter and dc-ac inverter are identical circuits.

Control:	800 mm
Converter:	1200 mm
Inverter:	1200 mm
Total:	3200 mm
Depth:	1650 mm
Height:	2300 mm

Figure 13 Outline of the 8 and 10 MVA IEGT drive lineup

Device technology has consistently increased power density over the years; that is, more drive MW in less floor space. The previous discussion of the higher power IEGT is one such example. Device efficiency and packaging is an example of how technology has improved operating efficiency. Our tests have indicated a significant efficiency improvement in the IEGT inverter over the GTO inverter with its higher gate turn off requirements.

10000 kW GTO inverter at 96% efficiency	400 kW losses
10000 kW IEGT inverter at 99% efficiency	100 kW losses
Difference	300 kW
300 kW x 24 Hr x 340 Days	2,448,000 KWH

Figure 14 Example energy efficiency calculations

Every user needs to do their own energy savings calculations as “results may vary”. However, it is clear that device and packaging technology plus the use of ac motors has greatly improved operating efficiency over that of the dc drive. Decreased energy use translates directly into reduced utility fuel consumption, CO_2 emissions and generally a better sustainable environment.

10 MVA IEGT INVERTER APPLICATION CONSIDERATIONS

Inverters can be configured in several arrangements to increase total power capability. Figure 15 shows several configurations using the two frame sizes discussed that provide inverter ratings from 8 to 40 MVA. The effective capacity of large main motors is determined by the process overload requirements which may be 150%, 175%, 225% or more. In this case the rated motor MVA/kW must be adjusted accordingly.

Count the number of inverter boxes for each configuration and multiply by 8 or 10 MVA to get the corresponding rating. A synchronous motor is shown since these are usually applied above 10 MVA effective capacity.

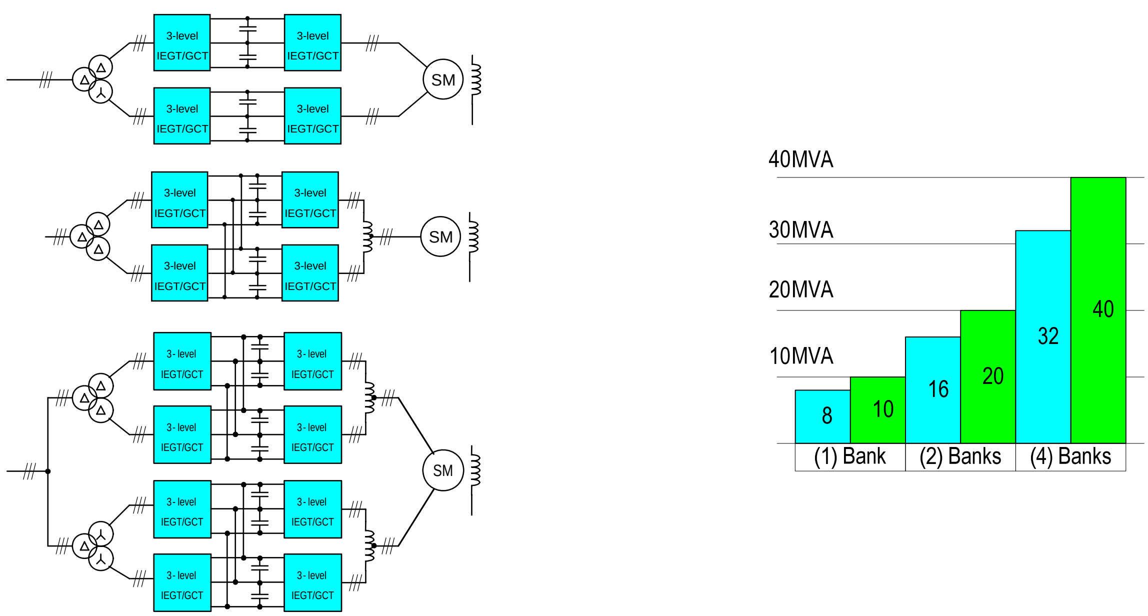

Figure 15 Various inverter configurations and ratings

Figure 16 shows the main circuit configuration of the 16 MVA (2 x 8) dual winding motor and the 10 MVA motor application. Transformer and motor wire count alone indicate a potential savings in both installation space and cost when the single inverter can be applied.

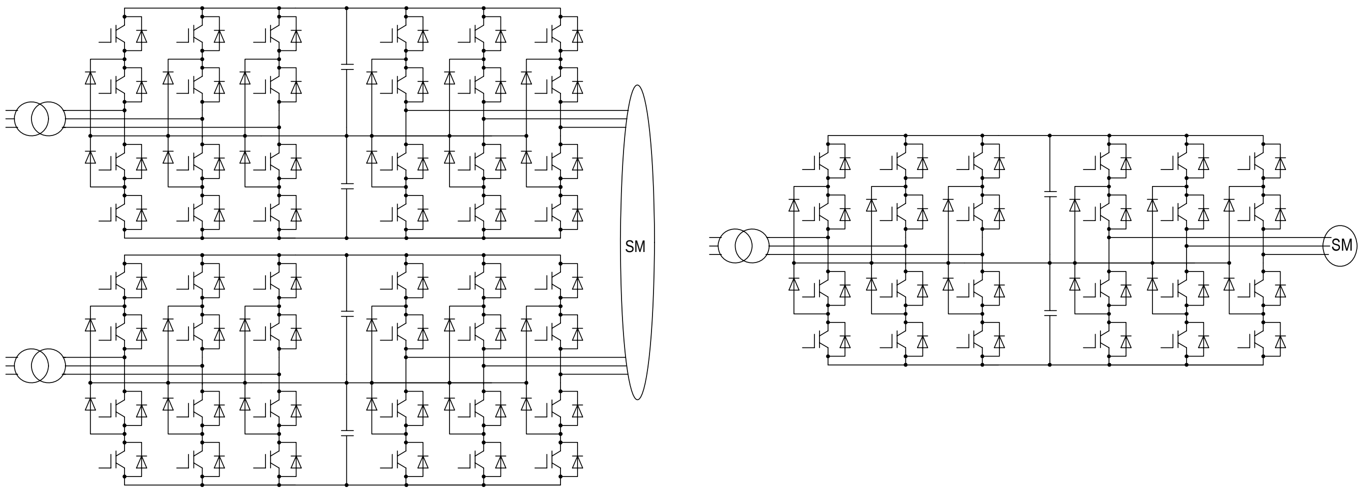

Figure 16 Two inverter and single inverter system details

Also, any time the 20 MVA (2 x 10) inverter can replace the 32 MVA (4x8) inverter there will be savings. In the case of a 5-stand Cold Mill or a 7-stand Hot Strip Mill the savings can be considerable since the main stands tend to fall in similar effective ratings.

TRENDS IN HOT STRIP MILL DRIVE TYPES

The number of installations using a particular drive type depends upon many factors, including the world economy effect on the number of new plants and major upgrades. Figure 17 plots the number of our new installations over a twenty year span including commitments for the next several years. Not included are upgrades of existing dc main drives or the experience of other suppliers. Note that the number of drives is not shown, but rather the number of installations to indicate trends in drive type.

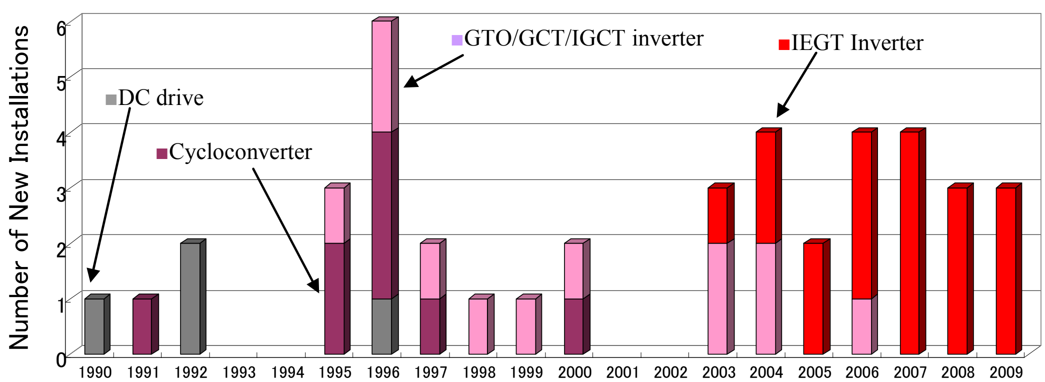

Figure 17 Hot strip mill lines installed by year by drive type

DC Drive

The dc drive has very good performance and was used extensively prior to 1990. For new installations and re-powering, the DC drive has been replaced by ac drives. DC drives continue to be applied for revamps where the existing dc motor is retained.

Cycloconverter

Cycloconverters were used in the 1990's because of its excellent performance, ability eliminate gear boxes in some applications and lower ac motor maintenance. Power factor correction and harmonics were major issues holding back their wider application.

GTO and GCT Inverter

The voltage source GTO inverters overcame the cycloconverter power factor and harmonic issues but have their own device related issues. These problems were overcome by the GCT inverter which was successfully applied in hot strip mill and other large drive applications,

IEGT Inverter

Since about 2000 the IEGT has been applied in high power voltage source inverters. They presently are the highest efficiency inverters and converters available. Figure 17 also shows the IEGT inverter, in our experience, to be the clear volume leader.

CONCLUSIONS

AC drive systems have been greatly improved in the last 10 years with new power devices and control technologies. The emergence of the high power 3-level voltage source inverter changed rolling mill main drives from dc to ac. The new ac drives have excellent performance characteristics and high efficiency. The ac drive system will continue to be improved in the future. One recent example is the higher power IEGT device which can often result in overall savings.

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