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Medium Voltage Drive Evolution

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Evolving Simplicity and Reliability in MV AC Adjustable Speed Drive Systems

Progress in Medium Voltage Drives

In the late 1970s solid-state medium voltage (MV) ac motor adjustable speed drives (ASDs) began to appear in commercial service. These first installations were larger, expensive, less reliable and efficient than their modern counterparts. For the purpose of our discussions, we will consider medium voltage to apply to levels over 1000 Volts, 3- phase.

Three key technology areas have driven improvements in performance and cost:

- Power semiconductor device development
- Power bridge topology arrangement
- Electronic signal processing

General AC Drive Arrangement

Every ac drive includes three major sections between the ac utility supply and the load. These are shown in Figure 1. *Transformation* isolates and changes utility voltages to the levels and configuration of the conversion section. The *Conversion* section changes the transformed utility voltage into adjustable voltage, adjustable frequency ac voltage to match the speed and torque requirements of the connected load. The *Utilization* section consists of the ac motor and mechanical equipment such as gearing and couplings.

The drive conversion section consists of dc *Conversion, Energy Storage, and Switching.* The conversion section of the drive uses a combination of semiconductors to convert the utility voltages into a dc voltage and current. This dc power is stored in inductors or capacitors before being passed to the switching section. The switching section connects the dc voltage or currents stored into the successive phases of the ac motor. The frequency, voltage, and current are regulated to match the needs of the load.

Efficiency

The efficiency of an ac drive is measured by comparing the total output kW of the drive to the total utility input kW. Any energy lost between the power line and the motor input terminals reduces system efficiency. Each element of the drive, including transformers, inductors, storage capacitors, rectifiers, field excitation, output switching devices, firing circuits, snubbers, and cooling equipment are included in efficiency calculations. Considering all these items, the efficiency at maximum output for medium voltage ac drives ranges from 95 to 97 percent.

Transformer losses are usually in the range of 1 to 1 ½ percent of full load rating. Capacitors are typically very low loss devices. Inductors have resistive losses proportional to current-squared (I^2R losses). Semiconductor losses are a bit more complex. Each device has conduction losses proportional to current. For active devices (SCR, GTO, IGCT, etc.) energy is lost both in conducting current and in turning them on and off. These losses vary dramatically between the different devices.

Build It and They Will Use It

Inventors and manufacturers of semiconductors depend on enterprising companies and determined and clever engineers to take their devices into the real world. As each power semiconductor type became available in practical packages and in usable power ranges, the new devices quickly found their way into drive system products.

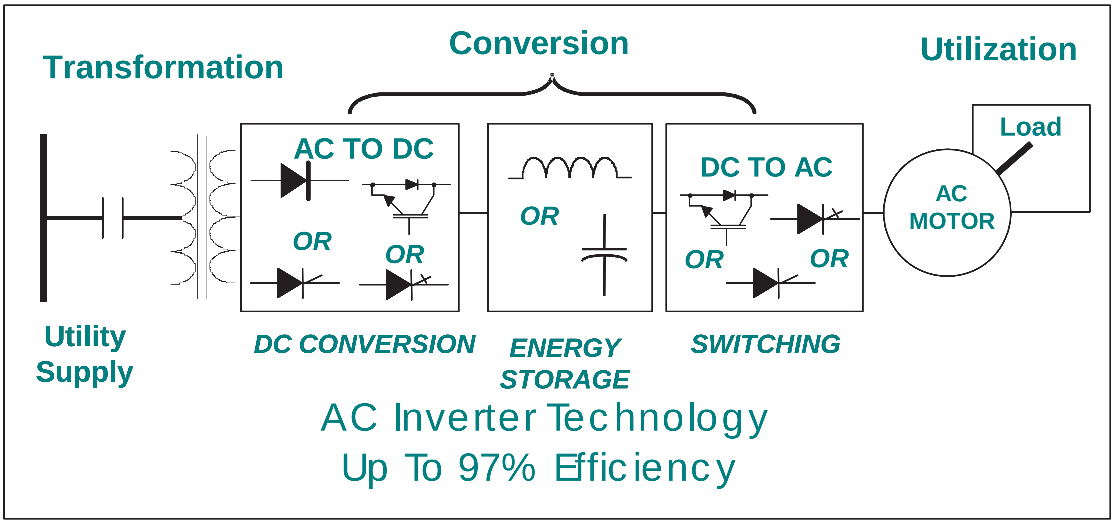


Figure 1. General AC Drive Arrangement

Power Semiconductor History

Adjustable frequency ac drives were first put into service using Thyratron gas rectifiers as early as 1931. But it took the invention and availability of power semiconductor devices to move the technology into wider use. It will be useful to use accepted abbreviated acronym names and device symbols in our further discussions. Table 1 includes the key devices of interest to our discussion.

Figure 2 gives the approximate development timeline for power semiconductors. Each semiconductor type has lent itself best to certain configurations of ac drives. As voltage and current ratings increased, drives moved into the medium voltage (MV) arena.

Power Device Characteristics

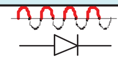
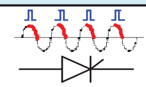
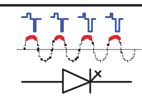
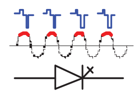
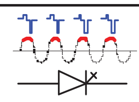
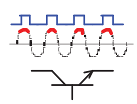
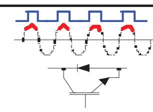
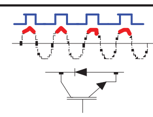
Engineers either work *with* these characteristics or work *around them* to accomplish their goals of efficient drive design. Some of these key device characteristics are listed below. A bit later we will discuss some of the more important characteristics of each device type. We will also review devices that are most relevant to MV drives. Key device characteristics include:

- Continuous current
- Forward blocking voltage
- Reverse blocking voltage
- Switching speed
- Gate power to turn on and turn off
- Switching losses
- On-state losses
- Physical mounting characteristics
- External circuitry required

Power Devices in AC Drives

As power devices have evolved, designers have used their characteristics in the construction of ac drives. The power semiconductors of Table 1 fall into three major Families: diodes, thyristors, and power transistors.

Table 1. Power Device Symbols, Operation, and Description

Device	Operation	Description
Silicon Diode Family of Devices		
Diode		Conducts positive current
Thyristor Family of Devices		
Silicon Controlled Rectifier (SCR)		Gate current triggers the flow of positive current. After loss of gate signal, turns off the positive current at next zero cross over.
Gate Turn Off Thyristor (GTO)		Small positive gate signal turns on positive current, a large reverse gate turns off the positive current.
Integrated Gate Commutated Thyristor (IGCT)		A GTO with electronics for gate control integrated onto a printed circuit wrapped around the device. Blocks voltage in one direction.
Symmetrical Gate Commutated Thyristor (SGCT)		A GTO thyristor similar to the IGCT except that it blocks voltage in both directions.
Transistor Family of Devices		
Bipolar Power Transistor (BPT)		Controls the flow of positive current with current injected into its base.
Integrated Gate Bipolar Transistor (IGBT)		A hybrid device with very a high input resistance gate transistor providing current to turn it on.
Injection Enhanced Gate Transistor (IEGT)		A high-power advanced form of the IGBT with a very low on-state voltage and even lower losses than the thyristor.

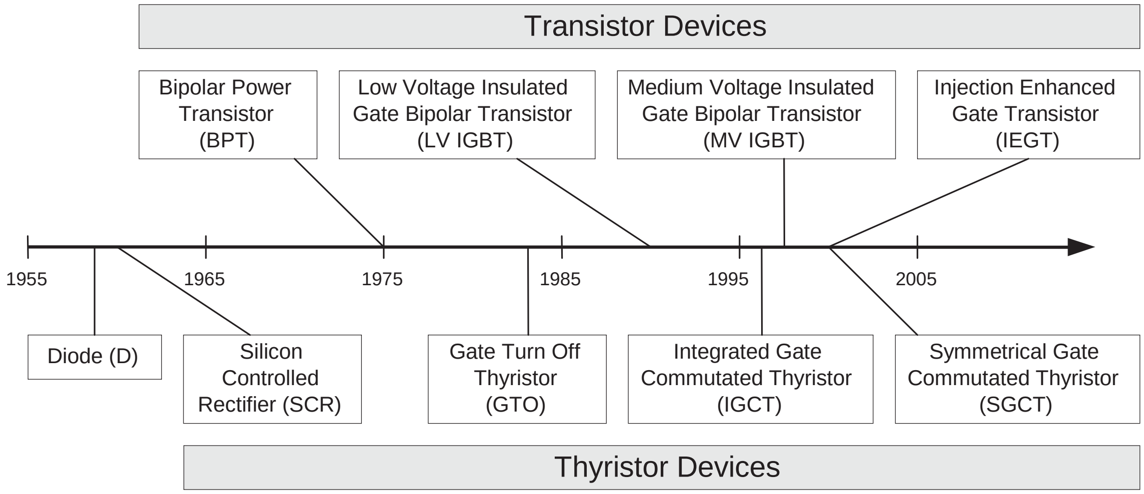


Figure 2. Power Semiconductor Timeline

Trends In Power Devices

In general, power semiconductor devices have moved toward higher voltage, greater continuous current, faster switching speeds, easier switching, and lower losses. Improvements in these important areas have given designers the tools they needed to create today's compact and efficient MV ac drives.

As switches, each of the active devices (thyristors and their device type, transistors and their device type) has advantages and disadvantages. A perfect device would turn on and off with no losses, with little effort, and once on would have no power lost due to voltage drop across its power terminals. Since there are no perfect devices, it will be useful to see which advantages and disadvantages mean the most in practical MV drives. What follows is a factual but non-exhaustive comparison.

Other Trends

Before we get into details of devices and topologies, it would be good to note that device advances have been matched by thermal packaging improvements in MV drives. For example, heat pipe / heat plate cooling is moving into traditional liquid cooling applications in drives up to 5000 HP. Heat plates (sealed, evaporative thermal coolers) provide liquid cooled efficiency, small footprint and more even device cooling, yet with air-cooled simplicity.

General Device Comparisons

Diode Devices

Power Diodes. Power diodes are the successors to the very first semiconductor devices. All diodes are devices that conduct current on only one direction. Whenever the voltage on the anode of the diode is positive with respect to the cathode, the diode will pass current. If the voltage reverses, conduction stops. In practice, diodes have a small forward voltage drop of between 0.5 and 1.5 Volts. Heat is generated in the diode in proportion to the forward current times the forward voltage drop.

Diodes are found in virtually all drives in one form or another. They are used as rectifiers in the ac to dc conversion section. Diodes are also used to steer current, protect devices from reverse voltage, and to clamp voltage to defined levels. Their location and rating depends upon the circuit configuration.

Thyristor Devices

In general, thyristor devices (SCR, GTO, IGCT, SGCT) internally divert some of the device output and feed it back to the gate circuit to cause it to turn on more strongly. For this reason they are sometimes called *regenerative* devices. This positive feedback decreases voltage drop across them, and gives a low forward loss. However, this also makes them relatively slow in switching speed and hard to turn off. So gating circuitry capacity and complexity, and switching losses of thyristor device circuits becomes the focus for disadvantages.

Voltage Withstand. The ability to withstand forward or reverse voltage is another key device parameter. In general, thyristor devices have higher voltage withstand levels (up to 6000 Volts) per device than the transistor device, but this gap is closing with recent IEGT transistors rated at 4500 Volts.

Higher blocking voltage can permit fewer devices to be used in a given MV power circuit. However, if fewer devices are used, the level change at each transition is larger. For all but 2300-volt output drives, this requires some means of filtering the output before being applied to the motor.

SCR. The original thyristor device, the SCR, turns on with a small current injected into its gate. Reducing current in the device to zero through external voltage levels, devices, components, or circuit load characteristics can only turn off the SCR. For example, an SCR conducting in a phase-controlled rectifier circuit turns off when the applied utility ac sine wave voltage across it reverses polarity. At this time, the current through the device is zero and device is reverse biased. Many SCRs are used today in MV drives in the conversion section as phase-controlled dc rectifier front ends (see Figure 1). SCRs are also used in the switching section of MV inverters where the load itself provides the needed switching and reversal of voltage for device turn-off. For example, in the Load-Commutated Inverter (LCI), the connected synchronous motor provides this commutation energy.

GTO. The GTO is a thyristor derivative that can be turned off by signals at its gate. Large reverse current pulses, extracted from the device through the gate of the GTO, can be used to interrupt the forward current. As with the SCR, the level of current required to turn on the device is small, but the turn off pulse must be very high, between 10 to 25% of forward current. The firing and turn-off circuitry is large, and complicated by the difficulty of getting fast pulses into the device through the inductance of the connections and wiring. Large and complex resistor-capacitor snubber networks are needed to prevent damage from excessive voltage to the gate and misfiring from the transient voltages generated by the gate pulses. Needless to say, the GTO had significant application problems. Large size, power losses in gating and snubbers, and cumbersome physical arrangements, characterize GTO inverters and converters. Figures 3 and 14 show this dramatically.

Figure 3. Water-Cooled GTO Module With Snubber, Capacitors, Gate Driver, And Devices

IGCT and SGCT. As we have seen, a chief shortcoming of GTO devices is the external circuit required to fire and turn off the device. In the mid-90s device manufacturers made advances in GTO design that allowed faster switching if a large enough pulse were injected into the gate. To overcome the gate drive problems inherent in previous GTO external gate circuitry, the device makers developed printed circuit assemblies that mounted very close to the new device.

The new arrangement was called the Integrated Gate Controlled Thyristor, (IGCT). The use of a printed circuit board literally wrapped around the device shortened gate signal paths, and minimized inductances. Since current paths were very short, inductances were reduced so much that snubber circuits were eliminated. Gate losses were also reduced. Packaging became easier. Figure 4 shows a typical IGCT device and associated parts.

IGCT & SGCT devices also have much faster switching times than their GTO predecessors. This allows better waveform generation in PWM applications due to higher switching speed. Faster switching times also produce lower switching power losses.

Figure 4. 4.5 KV 4 kV GCT, with power supply, & control power isolation transformer

The original IGCT could block voltage in one direction. The latest thyristor incarnation, the SGCT**,** is similar, but can block voltage symmetrically, that is, in both forward and reverse directions.

Device manufacturers would like you to think of the IGCT or SGCT as a single component. Drive manufacturers who use the SGCT or IGCT have published the failure rate of the device alone as if it were the whole assembly. A simple look at Figure 4, could lead an observer to consider the GCT on its own. However, when you look under the component cover of the assembly, the large number of discrete components required to control the device is obvious. The picture in Figure 5 shows this clearly. Please take note of the scaling object, a hand-held calculator, which we will use again later for another switching device.

Basic Problem. The difficulty comes from the fact that thyristor devices are all current-switched. The pulses needed to turn off an IGCT or SGCT device are shorter than for the GTO, but can reach 4000 amps. Many electrolytic capacitors are included on each integrated firing circuit board to provide this energy. The GCT shown in figure 5 shows 36 such capacitors. Separate power supplies for each GCT are also needed. So, the apparent *simplicity* is really not there at all. In the next section we will show how this affects reliability.

Figure 5. 4000 amp GCT, Integrated Control Box Components Exposed

Transistor Devices

Background. Transistors moved into voltage and power levels sufficient to control motors in the 1970's. These devices required current injection into their base terminals to conduct current. Power Darlington packages, combining two or more transistors into one package to reduce base drive requirements and increase device speed, were the first transistor devices to be used in LV drive applications.

The power Metal Oxide Field Effect Transistor (MOSFET) does not require current to drive conduction in the semiconductor material. Its internal structure is very simple and its gate is insulated. Voltage applied to the gate creates an electric field that permits conduction in the bulk semiconductor material. In the early 1990's the MOSFET was combined in the same package with a traditional bipolar transistor. This resulted in a new hybrid device, the IGBT.

IGBT. The IGBT announces one of its chief advantages by its very name, Insulated Gate Bipolar Transistor. The control signal is voltage, not current. Device control requires very low power. Circuits to control IGBTs are physically small, use very few components, and therefore have an inherently low failure rate.

Low Voltage IGBT Devices. Low voltage (LV) IGBTs are used in large quantities today in LV drives (output levels of <690 Volts). They are quite reliable when properly applied in this service.

Before IGBT devices rated for use on MV appeared, two engineers from Westinghouse, Derek A Paice and Charles Edwards, came up with a novel arrangement of low voltage drives connected in series to construct medium voltage waveforms for motor control. We will discuss this drive in more detail later.

Medium Voltage IGBT Devices. By 1997, IGBT technology had advanced to where a single device could withstand 3300 Volts. Current carrying capacity quickly advanced to 1200 amperes for a single side mounted plastic case device. Switching speeds of less than ½ µsec allowed very low switching losses and accurate control. IGBT circuit design requires no bulky and energy wasting R-C snubber networks.

Output Protection. A native characteristic of the IGBT provides designers with a built-in sensor to prevent damage due to short circuits on the output of the inverter. Above the design current level, the device collector-emitter (C E) on-state voltage climbs rapidly. The gate circuit monitors C E voltage and detects this *de-saturation* condition. Gate drive is shut off instantaneously, without action from the main control. The gate driver signals the microprocessor control of the overcurrent condition. The gate command firing is shut off, and the drive is shut down with an overcurrent trip. In this way, the device is its own protective sensor.

Simplicity. The simplicity of the switching circuitry of the MV IGBT is obvious and clear from a look at typical gate driver hardware. Figure 6 shows a dual 400-amp 3300-volt transistor and its firing circuit. The black potted firing module shown in Figure 6 controls two IGBTs. The whole module is smaller than the reference calculator next to the GCT gate control shown in Figure 5.

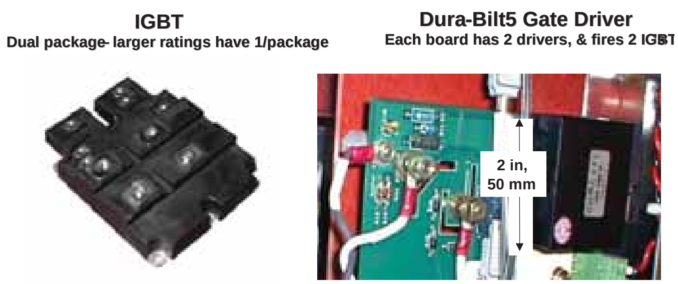


Figure 6. Dual 400 Amp, 3300 Volt IGBT and Firing Circuit

IGBT Forward Voltage Drop. Forward voltage drop of IGBT devices are sometimes higher than for thyristor devices. The reasons behind this are complex. In what may be an over-simplified explanation, this is because traditional construction of IGBT devices and their internal structures inject current carriers into the semiconductor from only one direction. Thyristors are regenerative devices, and once conducting, inject current carriers into the semiconductor from two directions. More carriers can mean lower conduction voltage drop. Low forward voltage drop means lower *on-state* (forward drop x amps) heat losses. This is a good thing. However, IGBT voltage drops are not always greater than those for a comparable IGCT. Refer to Figures 7A and 7B, and compare a 750 amp IGCT from Mitsubishi with a EUPEC 800 amp 3300 volt IGBT. The IGBT for this device comparison has a lower voltage drop than the IGCT.

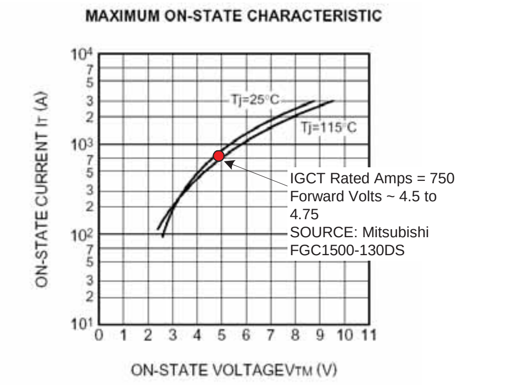


Figure 7A. IGCT On State Voltage vs Current

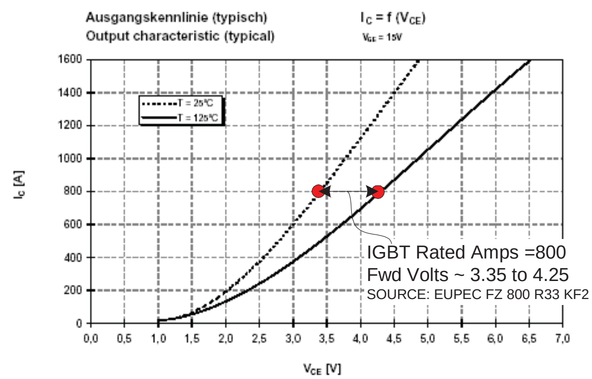


Figure 7B. IGBT On State Voltage vs Current

More importantly, the device forward drop is not the whole story. The MV IGBT switches so fast (300 to 500 nanoseconds, typically) that switching losses are very small. These low losses go a long way to offsetting higher forward conduction losses when compared to the slower GCT switches. Table 2 compares the same IGCT and MV IGBT devices of Figure 7, from a switching loss standpoint. The score? For these comparable devices, the IGCT loses 450% more energy each time it switches.

Table 2. Comparison of Total Switching Loss IGCT vs MV IGBT

DEVICE - >	**IGCT 750 AMP**	**IGBT 800 AMP**
Turn On Joules Lost/pulse	2.15	1.92
Turn-Off Joules Lost/pulse	12.0	1.02
Total Switching Joules lost/pulse	**14.15**	**2.94**

IEGT: More Advanced Yet.

In late 1999, Toshiba announced advances in semiconductor design that combines low forward drop with all of the low gate drive advantages of IGBT technology. The new device was named the IEGT, for Injection Enhanced Gate Transistor. Figure 8 shows an IEGT and its associated firing circuit. Notice the same calculator scaling object. IEGT devices may one day displace traditional MV IGBT devices. Special IEGT gate construction injects current carriers into the semiconductor material from two directions, just like the GCT. IEGT internal structures are simpler than GCT. Combined with the obvious firing circuit advantages, long-term manufacturing economies are possible.

Both press pack and one-side packages are in production. Ratings of 4500 Volts and 4000 amperes are in service.

Figure 8. 4500 volt, 4000 amp IEGT and Firing Circuit

Comparing FIT Data: Current switched GCT vs. Voltage switched IEGT / IGBT. Let's take a final look at the GCT and the IEGT (the most recent IGBT device) from a reliability standpoint. A comparison of calculated device and gating circuit FIT rates is very revealing.

FIT rate is the industry standard failure measurement of statistical failures per billion hours. Note in Figure 9 that the simpler IEGT Gate driver circuitry has a 3115 to 810, almost 4 to 1 FIT advantage over its IGCT counterpart. Base calculations were for a 4000-amp device. Other ratings are similar, but will vary by the total component composition.

When we compare the actual usage of devices in an inverter system in a following section, we will see that this advantage carries over to the assembled inverter as well. Note that IGBT firing circuits are even simpler and have fewer components than their larger IEGT counterpart. This means that IGBT firing circuit FIT rates will be lower and therefore potentially even more reliable than the IEGT example below.

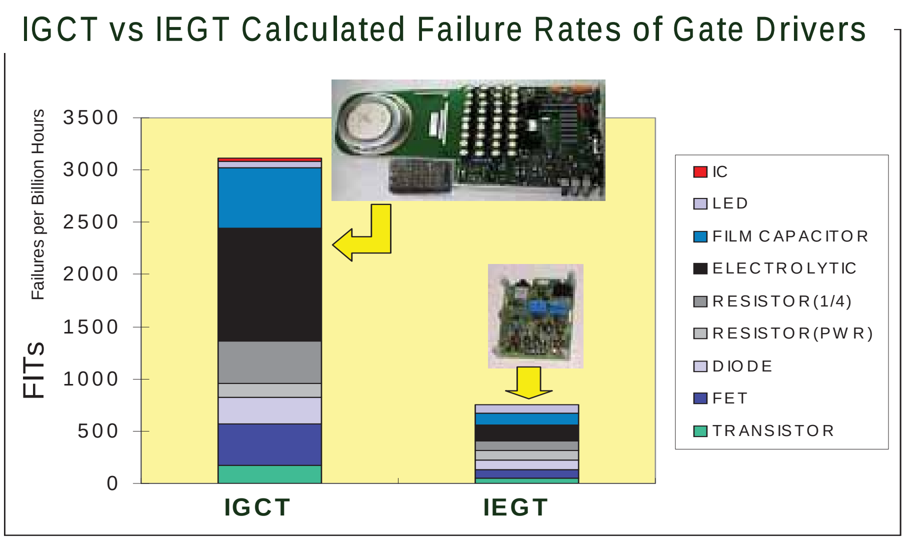


Figure 9. Calculated Comparison of IGCT and IEGT Gating Circuit Reliability FIT Rate, Statistical Failures per Billion Hours

Drive Topologies - A High Level Overview

Because power devices are part of a larger circuit configuration, they cannot be considered on their own. It is only when considered as part of the total circuit that device advantages and disadvantages make sense. The following comparison of MV ac drive topologies will discuss power devices in this context

Major Drive Type Divisions

AC Adjustable Speed Drives (ASD) can be grouped into two major categories: *current source* and *voltage source*. These categories do not refer to the semiconductors in the drive, but to the type of dc link energy storage the drive uses. A reactor tends to keep current constant, and forms the basis of the current source drive. A capacitor tends to keep the voltage constant, and forms the basis for the voltage source drive. Thus the drive type is named for the source of the current and voltage to be fed to the motor by the output converter.

As described earlier in Figure 1 (General AC Drive), the power flows through the conversion section through the semiconductors and a dc voltage or current level is created. This dc level is switched to successive phases of the ac motor.

In the *current source drive* (see Figure 10), the dc voltage level ① is varied to match the average motor terminal voltage ③ with energy stored in an inductor ② in the form of current equal to the average real current in the motor windings, which is proportional to the load torque. The inverter follows motor frequency, and torque is regulated to reach the reference speed.

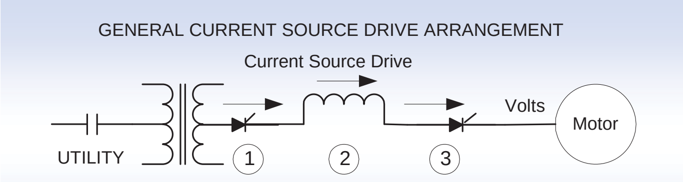


Figure 10. Current Source General Drive Arrangement

In the *Voltage Source Drive*, (see Figure 11) the dc voltage level ② is always the same, set by the utility line level and the transformer windings. The motor voltage is constructed and the current is controlled by the output switches ③ .

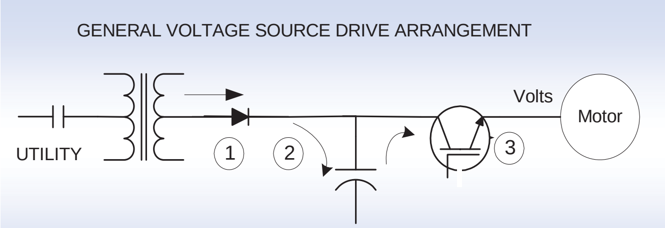


Figure 11. Voltage Source Drive General Arrangement

In both current source and voltage source drives, the motor frequency is set to match the needed motor speed by the output switches and control. Table 3 identifies these and additional characteristics.

Table 3. General Characteristics of AC ASDs
Current Source vs Voltage Source

Task or Area	Current Source Drive	Voltage Source Drive
Rectification	Must be active control	Diode or active control
DC Voltage	Varies to match needed motor volts	Fixed DC bus
Energy Storage	Inductor – some energy lost	Capacitors – no energy lost
Motor Current	Average amps set by input converter	Controlled along with volts by output inverter
Motor Terminal Voltage	Determined by motor excitation, set by input converter	Output switches modulate fixed bus to construct voltage
Utility side power factor	With SCR source, varies with motor RPM	Always high, little variation

MV Drive History

Table 4 summarizes drive history using the example of GE and TMEIC medium voltage drives, both historical and in

Table 4. MV Drive Technology Chart
TMEIC MV Drive Examples

Year	GE or GE Toshiba Model	Input Conversion	Output Inverter	Current Status
1979	LCI	Current Source SCR Rectif	SCR Thyristor 2300 - 4160 V	In Production as Innovation LCI
1985	IMD	Current Source SCR Rectif	GTO 2300-4160 V	Out of Production
1990	Cyclo Converter	Utilty-Fed Voltage Source	SCR Thyristor	Replaced By Tosvert T650
1997	Innovation Type G	Voltage Source Multi-pulse Diode	MV IGBT NPC Multilevel 2300 - 4160 V	Replaced By Dura Bilt5i MV
1999	Innovation Type H	Voltage Source Multi-pulse Diode	LV IGBT Series Connected Cell Multilevel	Replaced By Dura Bilt5i MV
1998	Innovation Type SP IGCT	Voltage Source IGCT Active Source	MV IGCT NPC Multilevel 3300 V	Replaced By Tosvert T650
1998	GE-Toshiba Tosvert T650	Voltage Source MV IEGT Active Source	MV IEGT NPC Multilevel 3300 V	In Production
1998	GE-Toshiba Tosvert T350	Voltage Source IGBT Active Source	IGBT NPC Multilevel 1250 V	In Production
2002	Dura Bilt5i MV	Voltage Source Multi-Pulse Diode	MV IGBT NPC Multilevel 2300 - 4160 V	In Production

current production. Hundreds of these systems continue in successful operation today.

One drive, the *Cyclo Converter*, should be mentioned here for completeness, but it does not fit the general outline in this paper. The cyclo converter is really a series of dc converters, which rectify utility power to sequentially feed the phase windings of very large low speed synchronous motors. Voltage source inverter technology provides superior dynamic and power system performance, and has displaced cycloconverters in new applications.

We began this presentation stating that ac adjustable frequency drive technology grew in response to the availability of power devices. Some of the drives that first appeared are still the best fit today in their area of strength.

Drive System Comparison Points

The following list presents some of the key points for comparing MV drive configurations. Some of the items are self-explanatory. A brief comment may follow any item that could require clarification. Listed first are those related to topology. Other important MV drive comparison criteria are listed separately at the end for completeness.

System ratings

- Power output levels
- Input voltage levels
- Transformer isolation – included?
- Basic output motor voltages available

Packaging & mechanical features

- Size - all components considering inverter, reactors, transformers, switchgear, heat exchangers, etc.

System availability

- Reliability – true FIT rate analysis of all system components down to board level
- Low parts count – including components on sub-assemblies such as gate cards, power supplies, etc
- Simple firing circuitry – down to component level
- N+1 redundancy – ability to keep on running with one or more power components out

Ease of startup, setup, troubleshooting

- Ability to run without a motor connected

Cost of ownership

- Low first cost
- High efficiency
- Life cycle – is this technology in its early, middle, or late stage? Is the quantity of drives and devices in production at present enough to allay fears of obsolescence?

Motor compatibility

- Low motor insulation stress
- Low motor current Total Harmonic Distortion (THD) (Heating)
- Torsional effects, possible induced resonances in load

Performance

- Smooth low speed operation
- Wide motor frequency range
- Fast transient response
- Regeneration

Power line impact

- Harmonic currents produced
- Power factor – measure of lagging power factor or ability to work at unity or leading power factor
- Harmonic currents – are filters required? Meet IEE-519 1992 recommendations?

Other important Points (not directly related to topology)

- Cooling - air or liquid, heat losses into environment, water cooling reliability
- Installation issues, weights, degree of re-assembly at site
- Rear / front access, cable entry locations (top or bottom)
- Easy repair – roll-out or slide out power modules
- True automatic tune-up
- Control, motor, and load simulator
- Warranty – length, terms, parts and labor included?
- Service and parts support
- Rugged packaging

Load Commutated Inverter LCI

In 1979 GE delivered and started its first LCI. In keeping with the semiconductor's development of the time, the LCI used SCR devices. The general circuit arrangement is shown in Figure 12.

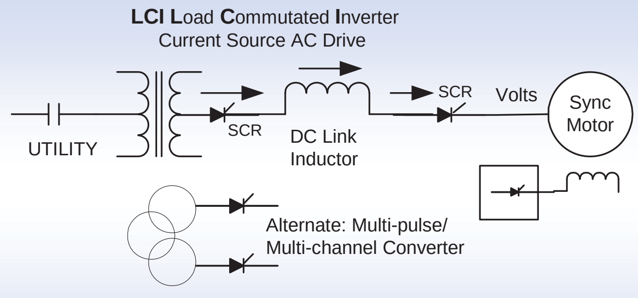


Figure 12. Current Source Load Commutated Inverter

The LCI drive is of the *current source family* of drives as shown in Figure 10. The incoming rectifier converter bridge or bridges create a regulated current in the dc link inductor. The level of current is regulated to match the motor current required to generate the torque needed by load. The output inverter section also uses SCR's to switch the current from phase-to-phase in the connected motor. The input section and inverter are fully regenerative.

LCI drives are always used with synchronous motors. The leading power factor within the synchronous motor is used to provide energy to commutate (turn off) the SCR inverter switches.

LCI drives were the first MV drive topology to be introduced and they are still in current production. Over 300 drives have been built in the last four years.

LCI Comparison Points

The following list defines the key comparison points, strengths and weaknesses of the LCI drive system.

Major LCI Strengths

- Low parts count
- Full Regeneration is inherent
- Rugged & proven reliable
- Economical at high hp
- SCRs can be supplied with N+1 redundancy

Major LCI Limitations

- Requires a controlled front end
- High motor current THD at low speeds
- Slow transient response
- Narrow motor speed / frequency range
- Reduced starting torque
- Limited low speed performance
- Synchronous motors only
- Poor line power factor at low motor speeds
- High ac power line harmonics unless multiple channels are used – may require harmonic filters
- Torsional effects, possible induced resonances in load at low speeds

System Ratings, Other

- Power output levels most practical above 6 megawatts
- Input voltage levels transformer isolated
- Transformer isolation – inherent
- Output voltages - actual inverter channels are usually either 2.3 or 4.16 kV. However, any practical motor voltage can be accommodated through output transformers.
- Ease of startup, setup, troubleshooting: cannot run or test without a motor connected.

Packaging & Mechanical Features

- Most LCIs in production today use liquid cooling, a sealed system with redundant pumps and remote heat exchangers. Early LCIs used forced air cooling.
- Sizes – separate enclosures or assemblies for inverter, reactors, transformers, switchgear, and heat exchangers.

Cost of ownership

- System efficiency benefits from sync motor high efficiency.
- Life cycle – this technology is mature yet modern – designs have been updated and all components are current.

Current Source Inverters (VSI)

Current Source Induction Motor Drive (IMD)

1984 saw the introduction of the first GTO-based IMDs. In keeping with the semiconductor's development of the time, the IMD used SCR devices for input conversion and GTO (Gate Turn Off thyristor) devices for output switching. The general circuit arrangement is shown in Figure 13.

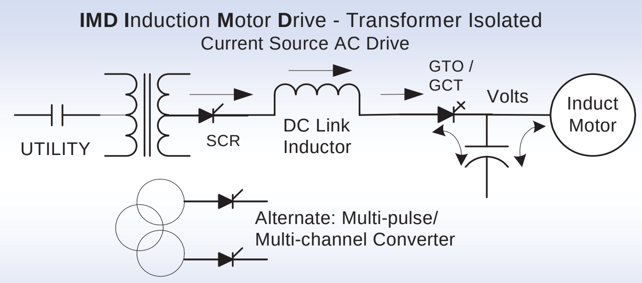


Figure 13. Current Source IMD Induction Motor Drive Transformer Isolated

The IMD is a current source drive. The incoming rectifier converter bridge or bridges create a regulated current in the dc link inductor. The level of current is regulated to match the motor current required to generate the torque needed by load. The output inverter section also uses GTO thyristors or (more recently) SGCTs to switch the current from phase to phase in the connected motor. The converter section and inverter are fully regenerative.

Power system issues

Power Factor. Like the LCI, the IMD requires a current controlled active rectifier to create dc current and voltage. To the power system the current source induction motor drive looks like a dc phase-controlled drive. Power factor is always lagging, and roughly proportional to motor output voltage. Since motor speed, output inverter frequency and motor voltage track each other, this means low speed presents a proportionately low power factor to the incoming utility line. In MV drives the output level is often in the megawatt range, so poor power factor is a serious issue. Capacitor banks, tuned to absorb the power line harmonics of the drive, are often supplied to restore power factor to acceptable levels.

Power Line Harmonics. Hand in hand with poor power factor is an unfavorable harmonic current spectrum. Power system harmonics are currents or voltages having frequencies that are multiples of the utility frequency. The drive produces characteristic odd harmonics in multiples of (n ± 1) where N is the number of pulses in the bridge rectifiers (i.e., 5, 7, 11, 13, 17 and so on). These harmonics can be cancelled by using multiple, phase-displaced windings on the incoming transformer combined with multiple 3-phase rectifiers. A 12-pulse rectifier has harmonics below the 11th cancelled, while an 18-pulse rectifier has harmonics below the 17th cancelled, etc. However, because the input converter must be an active current source, the rectifiers must all be thyristors. Each thyristor rectifier must have its own the gating controls. Additional circuitry is needed for thyristor protection.

Alternatively, tuned MV filters can be added to the utility side of the drive to trap harmonic currents before they propagate to the power grid. Switchgear, capacitors, and inductors are used to construct these filters.

In a recent version of the current source induction motor drive, SGCT switches have been proposed to create the dc current source in place of the traditional SCR rectifiers. This reduces problems with power factor and harmonics, but at significant cost and complexity.

Current Source Induction Motor Drive Performance

The current source induction motor drive relies on forcing current into a storage inductor and switching this current to the motor phases to produce output voltage and current. The rate of change of this current determines the rate of change of current and torque in the output load. This has always limited the application of the IMD to loads like pumps, fans, or conveyors, or loads that do not have a requirement for high performance. Even in the recent SGCT version IMDs, torque performance is published at 50 radians per second, only 10% of the 500-radian rate of modern voltage source drives.

The current source induction motor drive does present clean sine wave voltage to the motor. It does this as a consequence of its output topology. Note the capacitor across the motor terminals in Figure 13**.** This large MV capacitor is needed for successful commutation of the output inverter switches. As a minimum the capacitor can be sized just large enough to supply the excitation requirements of the motor. Because the capacitor is directly across the motor, it tends to smooth the output wave, especially above the mid-point of the speed range. However, another effect of the output capacitor has always been a hindrance: the capacitor will resonate with the motor at some point. This introduces potential for electro-mechanical resonances to occur in the driven load, with potential serious consequences. IMD technology is one reason why consultants still tend to require expensive mechanical resonance studies with MV drive proposals. In GE IMD drives, proprietary software actively modified the drive output to avoid resonance conditions. In contrast, voltage source drives have no inherent resonance issues.

GTO technology IMD drive lineups were very long. Figure 14 shows a photo of a GTO-based current source induction motor drive. Much of the package size came from the snubbers and bulky gate control circuitry shown by example in earlier Figure 3. GCT based drives are more compact.

The GE GTO-IMD enjoyed a long and successful life, with over 130 drives in service. The last IMD drive to be commissioned was in 1998.

Figure 14. 1500 HP 4160-Volt
Water Cooled GTO IMD Induction Motor Drive

Two other points are worth mentioning in recent IMD applications. First, drives are being proposed with no isolation transformers. Instead series reactors are used to provide a form of isolation of the converter from the utility (refer to Figure 15).

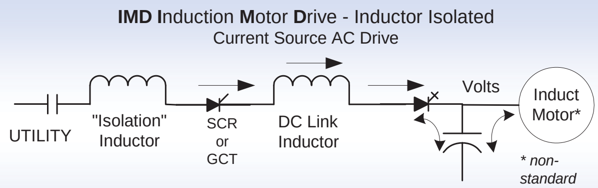


Figure 15. Current Source IMD Induction Motor Drive Inductor Isolated

Transformerless design may cost-reduce the incoming section, but subjects the motor windings to voltage-to-ground levels far in excess of those in a standard motor. As a result, standard design motors cannot be applied. Retrofits to existing motors are not recommended. Of course benefits of harmonic cancellation from phase-shifted transformers or multiple rectifiers are not possible either. One arrangement of active SGCT front end and reactors claims to get around the common mode voltage problem. It seems likely that costs avoided by deleting the isolation transformer would be lost in the additional cost of the GCT equipment.

The second point concerns the dc link reactor. The efficiency of the drive must consider the energy lost in the dc link storage reactor that is the central element of the IMD drive. Sometimes the reactor is mounted remote from the drive. Space requirements, accommodation and labor for remote mounting, and heavy cabling – all present factors that must be considered.

IMD Current Source Drive Comparison Points

Here are some of the key comparison points, strengths and weaknesses of the IMD drive system.

Major IMD Strengths

- Low power device parts count
- Full regeneration is inherent
- Low Motor Current THD at mid to high motor speed
- Low motor insulation stress when isolation transformer is used
- Low dv/dt on motor

Major IMD Limitations

- Requires a controlled front end, with extra parts and complications.
- Slow transient response to fast changing loads.
- Poor PF at low motor speeds.
- High harmonics unless multiple channels or SGCT PWM front end used.
- Torsional effects, possible induced resonances in load due to motor filter / commutating capacitor.

System Ratings, Other

- Power output levels most practical above 1 megawatt.
- Input voltage levels –if it is transformer isolated, only limited by transformer.
- Transformer isolation – recommended, but not always offered.
- Output voltages - originally 2.3 – 4.16 kV now up to 6 kV.
- Packaging & Mechanical Features – recent IGCT based drives are air cooled in smaller sizes. Larger IMD drives use liquid cooling, sealed systems and include redundant pumps.
- Sizes – separate enclosures or assemblies for inverter, transformers, switchgear, and heat exchangers. Reactors can be internal or external to lineup.
- Ease of startup, setup, troubleshooting: cannot run without a motor connected.

Cost of ownership –

- Life cycle – GE GTO IMD is out of production – basic IMD technology is out dated but has been made more current by the use of SGCTs in place of GTOs
- Efficiency – Slow switching GTO devices and circuitry and dc link inductors have negative effect on efficiency. The SGCT version is somewhat better.

Voltage Source Inverters (VSI)

Voltage source inverters (VSI), as shown in Figure 11, use a fixed dc level as the energy source for the inverter. Figure 16 shows how the motor voltage output and currents are constructed from the dc capacitor levels created by rectifiers from the incoming utility power. Pulse width modulation (PWM) is the dominant method for creating these waveforms. The output switches connect the motor phase windings in plus and minus combinations, so that the average voltage across the motor terminals is very close to the average of a sine wave. Figure 17 gives a more detailed trace of this wave construction. The sine wave in the middle of the pulses is drawn in for illustration. The motor current is within 5% of sine wave quality, as illustrated in the trace below the motor in Figure 16.

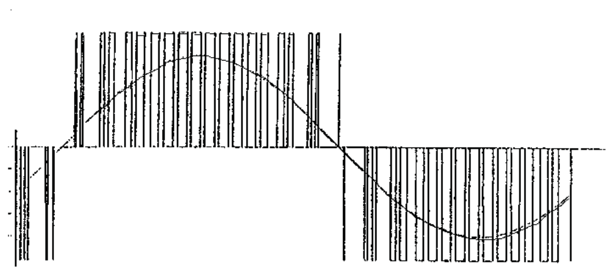
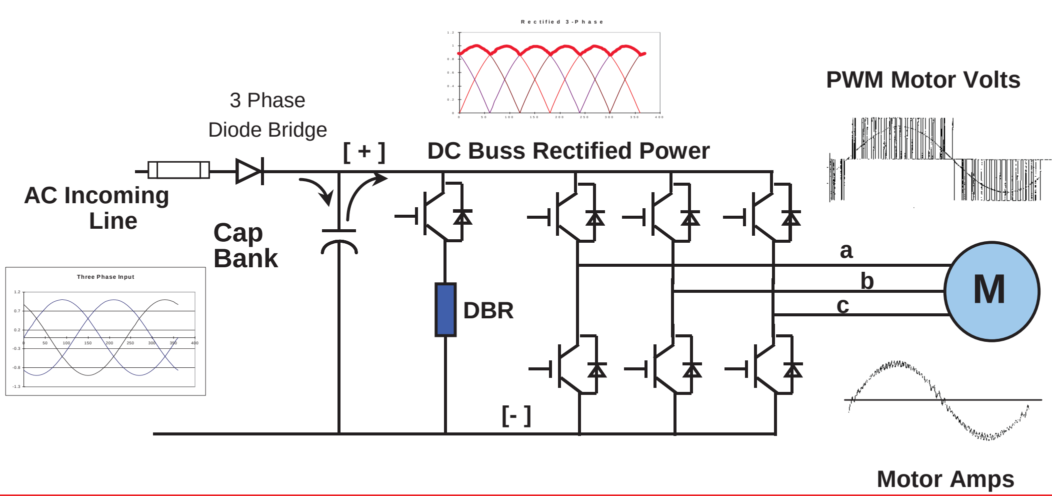


Figure 17. Two Level PWM Inverter Phase Voltage Output



MV Multilevel PWM Inverters.
The two-level modulation scheme is fine for low voltage motors and drives (less than RMS 690 volt output). But medium voltage drives and motors present a different story. The sheer magnitude of the MV voltage is great – a 4160 volt sine wave has a peak value about 1.4 x 4160, or 5820 Volts. Even a thyristor device cannot switch this level of voltage in a single step. Second, a standard motor insulation system would likely fail if subjected to the peak voltages from a two-level voltage wave.

The solution is to create multiple dc levels, and switch between these levels. This can be done by creating several LV buses and constructing the wave using several independent 2-level inverters. This approach has been used with moderate success, and will be described later.

Figure 18 shows a general diagram with multipulse diode conversion and multiple dc levels switched by MV IGBTs.

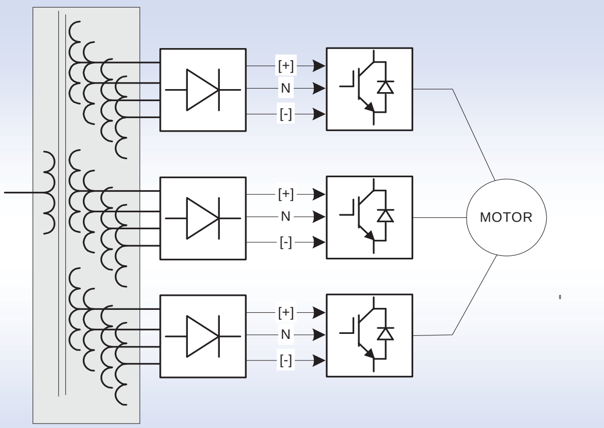


Figure 18. Multilevel Voltage Source MV PWM Inverter

Output Levels
The more dc voltage levels that are created, the more choices are available for the MV switches to form the output wave. From a practical standpoint, three dc bus levels (plus, minus, zero) are fine for motor voltages up to 2400 Volts, and 5 dc bus levels are good for motors of 4160 volt or greater. These happen to fit nicely with the voltage rating of a range of MV switching devices.

Figures 19 and 20 show a 3 / 5 level (2300 volt RMS) and 5 / 9 level (4080 volts rms) voltage waveforms. In figure 19, three available power supply voltages produce 5 possible line-to-line voltages. In figure 20, five available power supply voltages produce 9 possible line-to-line voltages. This is what referring to the output as being 3 / 5 or 5 / 9 level means.

Using more levels allows the voltage wave to more closely approximate a *true* sine wave. Through good PWM algorithms, the current wave can be very close to sinusoidal. In recent testing of a 5 / 9 level inverter, RMS voltage distortion was measured at less than 6%, with current distortion of less than 3%.

Output Distortion
Distortion of the voltage and current feeding a motor load is important because any current whose frequency is anything but equal to the fundamental frequency causes extra motor heating. Harmonic currents do not produce significant torque. Here *fundamental* frequency refers to the instantaneous, synchronous frequency of the motor. For example, a motor with a base nameplate design frequency of 60 Hz, at half nameplate RPM would have a synchronous frequency of 30 Hz (plus or minus slip frequency). Any frequency in the current feed to the motor that is not at 30 Hz will create insignificant torque.

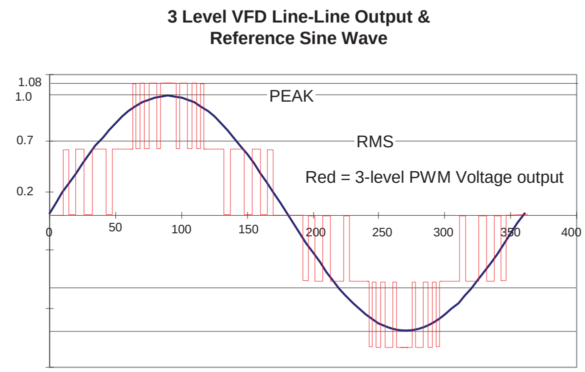


Figure 19. Simulated Inverter Voltage Waveforms
3 / 5 level NPC PWM

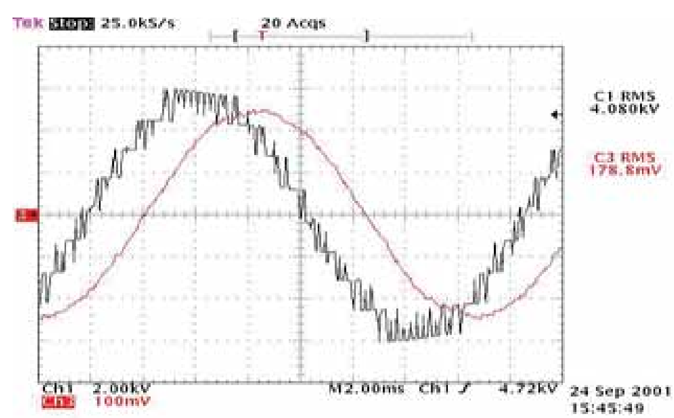


Figure 20. Inverter Voltage & Current Waveforms
5 / 9 level NPC PWM
Voltage RMS = 4080 volts

In practice, current distortions of less than 4% are considered inconsequential from a motor heating standpoint. Most PWM technology based drives can easily achieve this.

One Final Note About Output Levels

Certainly one advantage of power device development is that higher current and voltage rated devices generally means that fewer devices can be used. This is a good thing. Fewer devices and fewer parts mean lower failure rate and potentially higher reliability.

But here is the tradeoff. Many power devices (IGBT or IEGT) have a voltage rating such that two devices are needed in series to achieve 4160-volt output, resulting in a parts-count drawback. But as a consequence of having the devices, a 5 / 9 step voltage wave is produced. Low inherent voltage distortion results in an easier job in producing low current distortion and low motor heating. In contrast, higher voltage-rated switching devices like IGCTs can produce a 4160 volt motor RMS voltage with only 3 levels and will require fewer devices in series. But the 3-level inverter at the 4160-volt output level is too rough, requiring large L-C filters to smooth inverter output to the motor. In practice, all known 4160 volt or greater IGCT PWM drives in production today produce 3 / 5 level output and use such sine wave filters on every drive.

More On Filters

Sometimes output filters on drives are necessary for the operation of the inverter itself. Recall that in the case of the current source IMD drive they are necessary as part of the switching scheme to achieve smooth current transitions. Also we noted in our IMD discussions that having capacitors directly across the motor could result in significant problems with parallel resonance between the motor and the caps.

In the case of the IGCT drive's sine output filter, the main purpose of the capacitors is to smooth out the 3-level sine wave, filling in all the gaps between levels and individual pulses with energy stored in the caps. It is noted that not all IGCT PWM drives use traditional multilevel PWM. However, because there is real power and energy exchange between the motor the inverter and the caps, the capacitors in an IGCT sine filter must be quite large. This raises the same concern over parallel resonance as in the IMD current source drive, with its potential damaging torques in the motor and drive train.

Another reason a filter may be applied is that the leading edge of the voltage pulses of all voltage source PWM inverters rises to the dc level of the fixed bus on every transition. The leading edges of the pulses contain high frequency components. Since a typical motor and its cable present a high impedance to high frequencies, the power cables tend to encourage transient overvoltages at the leading edge of the pulses above the applied dc level. For an example of this overshoot, refer to the trace in Figure 21. The faster the switch, the shorter is the cable length required before the transient voltages build to the theoretical maximum levels. With thyristor devices (IGCT, SGCT) the switching time is about 5 μsec. The transient voltage theoretical maximum appears at a cable length of about 600 feet. However, with inverters that use the fastest switches (IGBT or IEGT) the voltage transitions in about 0.5 μsec and the cable length for theoretical maximum is about 60 feet. While the theoretical level of dc pulse overshoot is 2.0 to 2.2 times the dc level, in practice in larger inverters it is about 1.85.

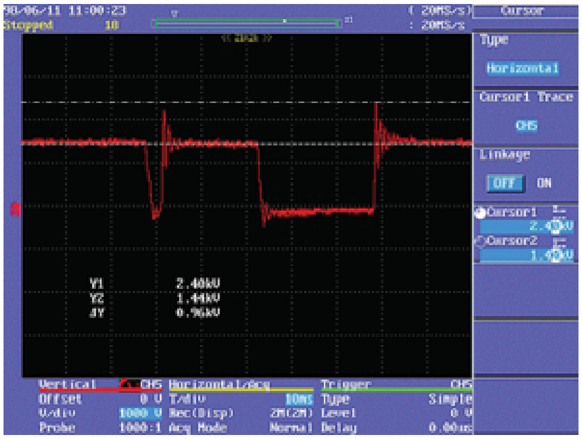


Figure 21. IGBT Inverter Switch Voltage Transition With No Filtering And A Long Connected Cable

DV/DT Filters

The chief concern from high switching speed is that the transient voltages show up at a high rate of rise, or dv/dt. This fast rise means high frequencies are present. High frequency voltage pulses tend to distribute unevenly across the motor winding, appearing across the first few turns on the end turns of the windings. By reducing the rate of rise, the dv/dt filter spreads the voltage increase over much more surface of the winding. Extra stress is no longer placed on winding end-turns so this is no longer a concern. Any remaining voltage stress shows up within the winding slots, where the insulation consists of both winding and ground wall insulation. The total insulation level in the slot, being higher, gives added protection from harmful effects of transient voltages.

Figure 22 shows a simple L-R-C network that can be supplied to reduce the voltage rate-of-rise of an IGBT drive so that the overshoot condition just discussed is minimized. The capacitors are quite small. A practical dv/dt filter typically extends the output pulse rise time from 0.5 µsec to about 4 µsec. This has the effect of allowing a longer cable before peak voltages are experienced (about 450 feet).

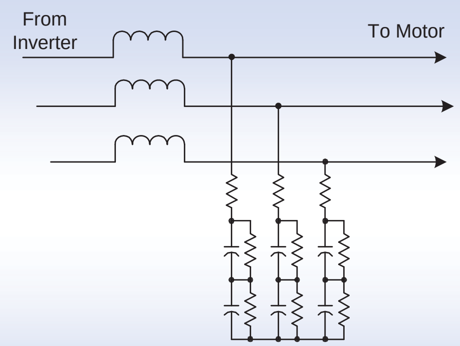


Figure 22. L-R-C DV/DT Filter for MV PWM Drive

So what has experience shown? With over 85 GE and TMEIC MV IGBT PWM drives running, at output levels of both 2300 and 4160 Volts, there has never been a report of any insulation problems. None of the (37) 4160 volt GE drives, whether on new or old motors, has any dv/dt filters included. The 2300-volt drives are 3-level drives, and about 20 of the 50 plus units running had voltage overshoot protection. The rest had no filters, with no reports of trouble in over five years of service.

Neither has any cable on drives at either 2300 or 4160 Volts experienced any insulation problems. This is in keeping with various reports and industry papers, where no reports of cable failures have been attributed to their use on IGBT MV drives.

It is TMEIC's practice not to promote or recommend medium voltage dv/dt filters except for insurance reasons, such as applying the dv/dt filter for feeding older motors, motors with questionable insulation integrity.

Utility Power System Issues: A Multilevel Voltage Source Inverter Advantage

Under our discussions of the IMD (current source induction motor drive), the topic of power system harmonics and power factor were introduced. In the multilevel inverter, line harmonics are controlled and good power factor is maintained in one of two ways:

- With feed transformers having multiple windings that are phase-shifted with respect to each other, diode rectifiers present a high true power factor (kW / kVA), typically 0.95 lagging or better. Additionally, harmonic currents except those of multiples of harmonic number N61 are cancelled, where N is the total number of rectifiers in the 3-phase groups. Example: 4 windings, 6 diodes per bridge = 24 pulse configuration. All harmonics except those numbered as even multiples of (24 ± 1) are attenuated by 90% or more.
- With a single 3-phase winding per voltage level, active switches, connected as an inverter in reverse, can be used as rectifiers. The firing patterns can be arranged to produce less than 5% harmonic distortion in current if enough impedance is included in the line source. Also, an active bridge allows the drive to pass back power to the power line, that is, to regenerate. The active front end has even been used to create leading power factor to offset voltage drop in long utility feed cables.

Usually, the lowest cost approach to optimize power factor and reduce line current harmonics is to use multi-winding transformers and diode rectifiers. Most applications do not require regeneration ability, and the active front end adds expense and requires all the control components associated with a full drive.

Multilevel Voltage Source PWM Inverter with MV IGBTs

The advent of true MV IGBT transistors signaled the beginning of a new generation in MV drives. In 1997 GE introduced the first generation of MV drives built around the MV IGBT. Three other advances made the package complete, including:

- A powerful signal processor electronics package was developed to form the heart of the new system.
- A cooling system was designed around heat-pipe technology that gave the new drive water-cooled thermal efficiency and small size with air-cooled simplicity.
- Designers chose an optimum inverter arrangement called *Neutral Point Clamping* (NPC), originally introduced to the industry in the 1980's. Through clamping diodes in the output bridge and the switches, the output levels are center-point (neutral) referenced. The neutral point is shown by the N designation in Figure 24. By clamping the neutral point, the motor experiences much smaller voltage excursions than inverters without such reference. The NPC design produces small voltage steps on the motor and puts low stress on the motor insulation system.

Examples. Figure 23 displays an overall block diagram of a Multilevel Voltage Source Inverter using MV IGBT switches. Figure 24 gives details of the three phase modules of the 5 / 9 level version shown in Figure 23.

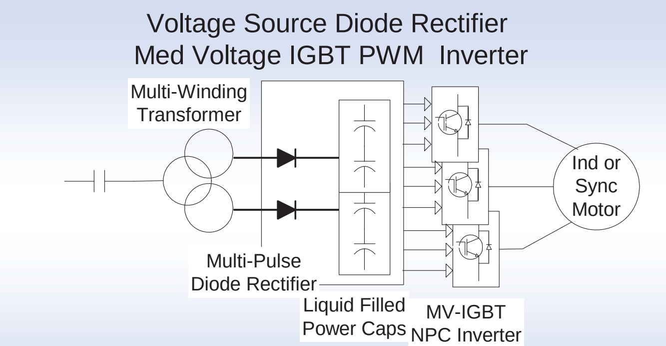


Figure 23. MV Multilevel Voltage Source Inverter With MV IGBTs

The GE version of the voltage source MV multilevel drive was called the Innovation Type G. About 80 of these drives are in service today.

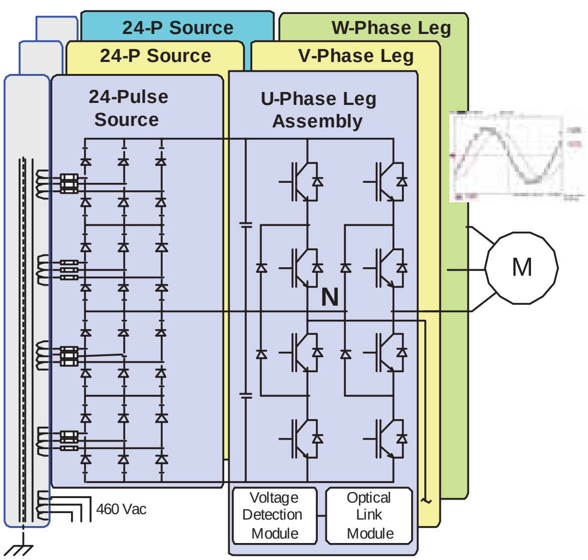


Figure 24. Details of 1 of 3 Phases of a 5 / 9 Level MV IGBT Inverter

In 2002 the first of the next generation MV IGBT heat-pipe cooled drives was installed in a co-operative effort between joint venture partners General Electric Company and Toshiba Corporation of Japan. Manufactured in Houston Texas, the latest drive, called the Dura-Bilt5i MV®, employs the best of GE and Toshiba drive technology. Like its Innovation Series® Type G MV drive predecessor, it uses the NPC inverter bridge arrangement. All models have dc bus rectifiers in a 24-pulse arrangement for less than 2.5% utility current distortion and utility power factor better than 0.95 lagging. Figure 24A shows a complete power module on rollout slides, containing all the elements of the phase-module drawing in Figure 24.

Summary of MV IGBT in MV PWM Drives

Our earlier review of power MV IGBT devices and their advantages will serve as a backdrop to the points below. Consider these items:

- Because of their high 3300-volt rating, few devices are needed to form output bridges for 2300, 3300 or 4160 volt drives.
- Because of their fast switching speed, precise PWM wave shaping can be done, allowing very low output distortion, low torque ripple, and accurate current control.
- Because of their high current ratings, devices usually do not have to be connected in parallel to achieve high output power levels.
- Because of their very low gating power requirements, the very simplest of gate circuitry can be used, increasing reliability.

Figure 24A. Example Inverter Section of MV IGBT PWM Drive Using Heat Pipe Cooling Showing Power Module Rollout Construction

Example MV IGBT NPC Drive TMEIC Dura-Bilt5i MV®

A photo of a current production MV IGBT NPC drive system is shown in Figure 25. On the left of the lineup is a full-voltage bypass and output contactor assembly. The center converter section consists of the incoming line compartment (upper left), and the transformer and rectifier bridges. The right section holds the 3 rollout inverter modules (one per motor output phase), and the microprocessor control. For reference, the drive is 122 inches long, and is rated 2000 hp output at 4160 Volts.

Figure 25A shows the operator keypad of the drive. From the keypad, the operator can start and stop the drive. All of the key operating variables within the control can be monitored in numerical and bar-graph form. Diagnostic fault messages are reported. A dc signal instrumentation output interface is included. An Ethernet™ port allows connection to computers for configuration and monitoring.

Figure 25B (next page) shows an explanatory diagram of the heat plate cooling arrangement of the Dura-Bilt5i MV drive. The cooling plate extracts heat almost as efficiently as a liquid-cooled system, without the complications of pumps, hoses, etc. By keeping the semiconductor device temperatures even over their mounting surfaces, IGBT life is extended.

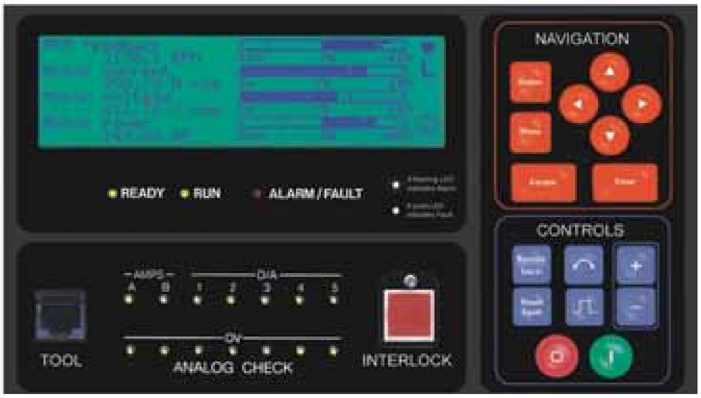


Figure 25A. Example Dura-Bilt5i MV Drive Display

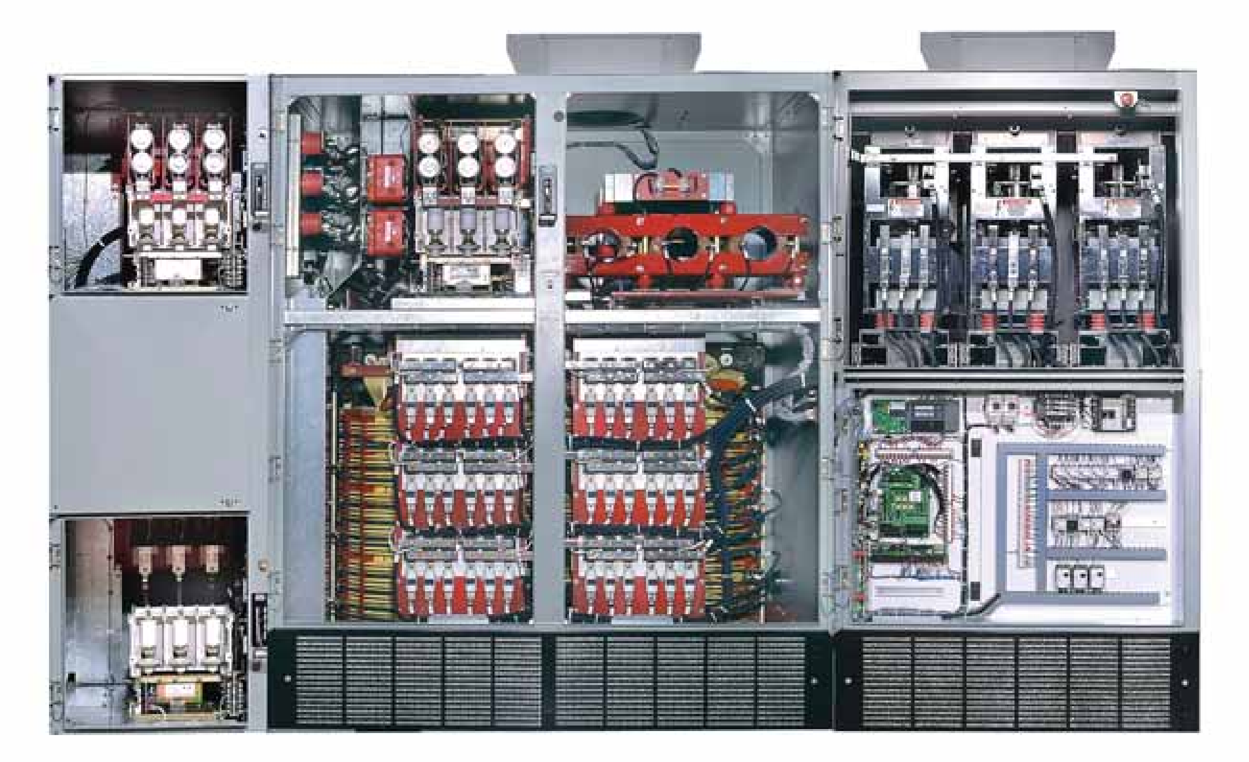
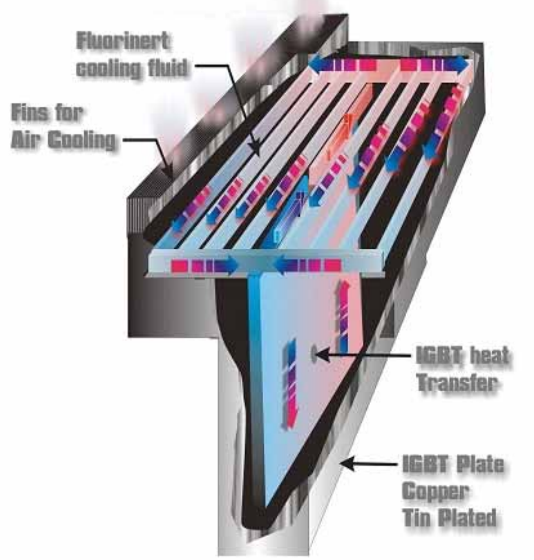


Figure 25. Example TMEIC Dura-Bilt5i MV®
2000 HP MV IGBT Based Voltage Source PWM Drive
Including Transformer, Converter, Switchgear And Inverter Modules

High Efficiency Plate Heat Exchanger for IGBTs



How it works

- Devices are mounted to side of plates
- Current flow generates heat in devices
- With only a few degrees of temperature rise, coolant is vaporized within the plate
- Vapor rises to the top condensing unit passages
- Heat is removed by airflow over fine fins, which liquefies coolant
- Coolant returns to base of chill plate for next cycle

Figure 25B. Example Dura-Bilt5i MV Heat Plate Cooling Arrangement

MV IGBT NPC Drive Comparison Points

Here are some of the key comparison points, strengths and limitations of the MV IGBT NPC drive system

Major Strengths

- Low parts count
- High system Mean Time Between Failures (MTBF)
- DC link energy is stored in liquid filled power capacitors
- Rugged & proven reliable
- Economical 400 – 10,000 HP
- Small footprint
- Fast response
- Wide range of speed and torque control
- High starting torque
- Very low motor current THD
- Low harmonics on power input
- High true power factor over whole speed and load range
- Synchronous or Induction motor compatible
- No significant torque pulsations
- Self-sensing output protection
- Can run in test mode with motor disconnected

Major Limitations

- Regeneration is not possible
- Power device redundancy not practical
- IGBT switching speed can produce motor waveform transient voltages and some installations may require dv/dt filter on drive output,

System Ratings, Other

- Power output levels 200 to 5000 HP at 4160 Volts, 200 – 2500 HP at 2300 Volts.
  Units may be paralleled for double HP
- Input voltage levels -since it is transformer isolated, up to 15 KV.
- Transformer isolation - inherent
- Output voltages - 2.3, 3.3 or 4.16 KV
- Packaging and Mechanical Features - air-cooling to 5000 HP, parallel units are practical.
- Sizes – single integral lineup makes smallest unit. Larger units can separate transformer and converter from Inverter
- Ease of startup, setup, troubleshooting: modern controls contain startup wizards and automatic tune-up routines and built in test mode motor simulator.

Cost of ownership

- System efficiency of > 96.5%, including transformer
- Life cycle – this technology is solid and growing. More and better devices, such as IEGTs will only improve present designs.

Multilevel Voltage Source PWM MV Inverter Using LV IGBTs

As mentioned earlier, low voltage IGBTs are used in large quantities today in low voltage drives (output levels of <690 Volts). They are quite reliable when properly applied in this service.

Before the advent of medium voltage IGBT devices, two engineers from Westinghouse, Derek A Paice and Charles Edwards, came up with a novel arrangement of low voltage drives connected in series to construct medium voltage waveforms for motor control. This arrangement is shown in the diagram in Figure 26**.** We will refer to the design as *Paice technology*, in reference to its early origins.

The voltage waveform output looks very similar to that in Figure 20. The control creates the sine wave by turning on modules successively. The cell types vary by voltage output levels, varying in ac input from a nominal 460 to 690 Volts, and nominal dc link voltage from 620 Volts to 930 Volts. Theoretically, as many modules and steps as desired can be used to create any reasonable MV waveform. Common output motor voltages are from 2300 to 6.9 kV. The module-to-module voltages are far in excess of the typical 1700 max LV IGBT transistor rating.

Module Details

Detail A in Figure 26 shows the typical power components of each of the power modules. A 3-phase rectifier (six diodes) creates a local dc bus. Energy is stored in the electrolytic capacitor. There are four functional IGBT switches, which create dc PWM outputs that add to the PWM outputs of its series-connected companion modules to create the output wave of each motor phase.

The drive can be air-cooled (usually at 3000 HP or below) or water-cooled. Water-cooled drives usually have water-cooling of both transformer and inverter modules.

Output Voltages Over 4160 Volts

In areas such as China, Europe, Japan, and Asia, industrial and infrastructure development seems to be moving toward 6.0 or 6.6 kV system voltage levels. Power device ratings have not progressed to allow the 5 / 9 level NPC design of the previous section to be applied at voltages above 4160 volts economically. NPC inverters would need added devices in series or transformers between the drive and the motor to achieve these motor voltage levels. The Paice design can be extended to higher voltages by adding additional identical power modules in series to build the higher voltage waveform. At the present time, this could provide a reasonable tradeoff of function versus complexity.

Details & Comments

By virtue of using many complete LV inverter modules to do the MV job (typical 4160 volt drive uses a minimum of 12 inverters) there are numerous parts in this drive configuration.

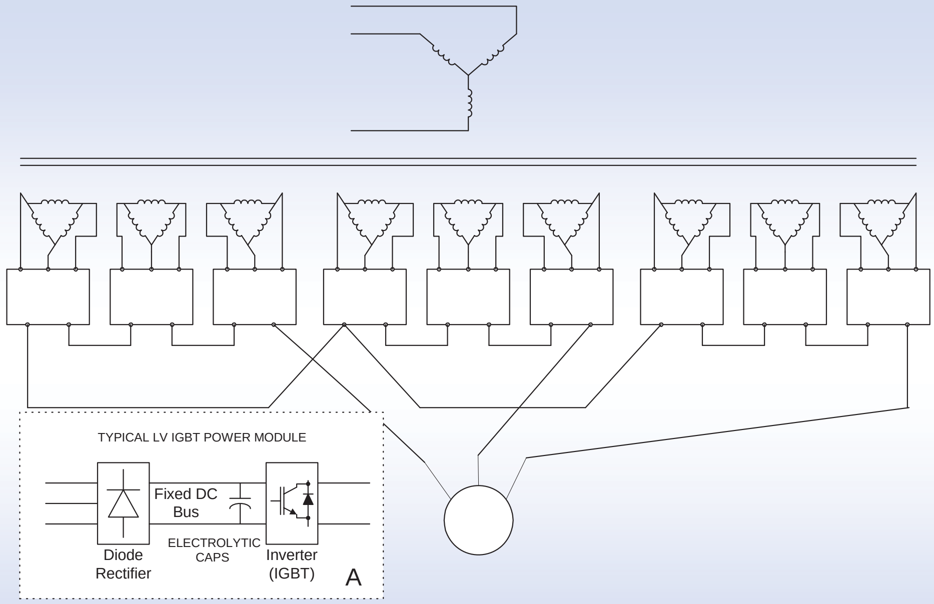


Figure 26. Multilevel MV Voltage Source PWM Inverter Using LV IGBT Drives in Series (Paice Design)

Table 5 compares a typical 1000 HP Paice design 12-module drive using LV IGBTs with its 4160 volt MV IGBT counterpart.

Table 5. MV Drive Power Device Count
MV IGBT Design vs. LV IGBT Paice Design

Drive	IGBTs	Diodes	Caps
MV IGBT	24	72	6
LV IGBT	48	72	168

The parts count above is a dramatic comparison. The capacitor count in particular stands out. The capacitors are electrolytic units, used in series to get voltage rating, and in parallel to get energy storage.

Electrolytic capacitors. Electrolytic capacitors in LV PWM drive service have a published life. Some manufacturers (such as GE Fuji, Model AF300 G11) actually alert the operator of the need to change out the electrolytic capacitors. They could be termed an *electronic consumable* item.

Temperature and even slight overvoltage is the enemy of electrolytic capacitors. For about two years, GE built its Innovation Series® MV drive, Type H using a Paice-topology bridge with a GE Innovation Series® control. Such a drive lineup is shown in Figure 27. In the years these drives have been in service, some sites have seen service extremes of temperature and voltage (wandering plant bus levels, low air flow, high room temperatures). In at least two cases, serious power bridge problems resulted in downtime of critical processes. In these cases capacitor failure led to module damage and subsequent outage time. One thing can certainly be learned from this: users must be very careful to keep any inverter, especially those with electrolytic capacitors, well within published limits of temperature and incoming voltage.

Where Paice technology is used, rigorous component standards must be used to reduce their sensitivity to potential capacitor problems. This includes using selected, high quality capacitors and applying the capacitors with proper margins in temperature, operating voltage, and ripple current.

Power Device Redundancy

When LCI drives were introduced, they were often applied to high-horsepower, energy intensive critical process areas as induced draft fans for boilers. MV drives were then a promising but fledgling technology. Users were nervous about accepting MV ac drives. As engineers considered how to increase the potential reliability of the new systems, they introduced the concept of *power device redundancy*. An additional SCR device, beyond what was needed for conservative design, was inserted into each series device string in the converter and inverter sections of the LCI. In justifying and using this approach the logic of the design team was approximately as follows:

1. The switching devices used were SCR thyristors connected in series as needed to achieve the required voltage rating (this has not changed in LCIs in current production).

2. The normal failure mode of SCR devices is to short out – to remain permanently ON in both directions.

Figure 27. Example GE Innovation Series® Type H Multilevel MV Voltage Source PWM Inverter Using 5 LV IGBT Drives in Series Per Phase, Integral Power Transformer (Paice Design)

3. Since device failure rate is very low anyway (about 80 per billion hours), adding an additional spare device would not decrease the overall normal system reliability significantly.

4. By adding a spare device, operation could continue until maintenance repair could be done. Early controls did not even detect when an SCR had failed – the drive just kept running. No control action was needed. The most modern LCI controls detect a failed device, so the device that failed can be replaced.

The SCR redundancy methodology was pioneered and introduced by GE into LCI and later into the SCR converter section of its GTO-IMD current source drives. It became known as *(N+1) redundancy*, from the thought process that, if quantity **N** SCRs is needed, adding one more redundant device makes the count **N+1**. In practice, most GE LCI drives were shipped with N+1 redundancy. It was offered originally to calm users' fears. The sales premium for N+1 in SCR LCI drives is quite small, so it is not surprising that few purchasers have elected to delete the option.

Where does *N+1* make sense today? The GE *N+1 SCR* concept required no addition of parts except an extra power switch of high reliability. If modern topologies could offer the same (add 1 extra device per group, no other overhead) N+1 could then be used for a potential overall benefit.

Recent Appearances of "N+1" Versions of the Paice-design LV-IGBT have been offered and built with "N+1" redundancy. Here the meaning of N+1 has changed from the inclusion of an extra SCR *device* to mean the inclusion of a complete power cell inverter (see detail A of Figure 26) per motor output phase. Under this scheme, if any power cell fails for any detectable reason, the control tells the bad cell to short itself out with an extra bypass SCR that is optionally added to every cell in the inverter. The added voltage capability of the extra cell is then used to replace the voltage of a failed cell. The control compensates, re-balancing the remaining cells to construct the output waveform.

In actuality, such a bypass scheme primarily protects from a loss of one IGBT, or loss of IGBT firing control for any variety of reasons. If, however, two IGBTs fail shorted, or gate on simultaneously, high currents flow from the local capacitors. These local currents may cause so much damage to the IGBT and its surrounding components that the module no longer has the integrity to be functionally bypassed.

One reason users may elect to purchase any "N+1" offerings would be to reduce fears of drive shutdown from power device failure. Does N+1 implementation in Paice-topology MV drives meet the original simplicity criteria of redundant SCRs outlined above? Can it potentially offer increased availability?

Table 6 below gives a comparison of an LCI drive with N+1 device redundancy with a Paice inverter with an extra power cell per phase.

Table 6 N+1 redundancy comparison
LCI vs Paice MV drive

Comparison Point	LCI SCR Device N+1 Redundancy	Paice Power Cell N+1 Redundancy
Number of power circuit devices added *	12 SCRs	18 diode Rectifiers 12 LV IGBTs 15 bypass SCRs 42 electrolytic Caps
Control action required to execute redundancy	No action - failed device conducts on its own	Control must detect failed power cell and command SCR in cell to bypass it.
Is power device fail-safe? **	Yes	No

* LCI drive with 6-6 pulse configuration

** SCR device normal failure is "On" in both directions

The comparison of Table 6 clearly indicates that the Paice inverter "N+1" concept implemented by power cell redundancy is *not equivalent* to the original N+1 device redundancy that has served the industry in LCI drives. There are more parts, added control complexity, and lack of inherent fail-safe operation. The control itself is not redundant and must be intact to cause any cell bypass. From a FIT (failure analysis) standpoint, the added parts may actually introduce more statistical failures than they overcome. In practice when a power module in a Paice inverter fails, it sometimes does so in such a way that the module is severely damaged. It is then unable to process a bypass command from the control.

Note one final issue. While any module is running "bypassed", transformer ac voltage still energizes the rectifiers and capacitors of the module. Energy can still be fed into failed components within the unit, possibly causing additional damage.

A few last words on reliability and N+1 redundancy in Paice Designs. Recent purchase specifications issued for MV drives have included the requirement for N+1 power device redundancy. As shown, the addition of an extra SCR in each bridge circuit of LCI drives made sense. Also as shown above, in Paice designs, such redundancy may not deliver any user benefit, and may actually harm overall reliability. Including additional redundant power cells to improve availability is the opposite of the traditional approach, which is to *eliminate* parts to improve reliability and then reduce stress levels on remaining components by conservative application. While power cell "N+1" redundancy may be an *allowable* way of approaching reliability, it should not be a requirement.

MV Paice Topology LV IGBT Drive Comparison Points

Here are some of the key comparison points, strengths, and limitations of the MV Paice technology drive system.

Major Strengths

- Fast response, wide range of speed and torque control
- Low motor current THD
- Low harmonics on power input and high true power factor over whole speed range
- Synchronous or induction motor compatible
- No significant torque pulsations
- Extra cell redundancy is possible
- Can run in test mode with motor disconnected

Major Limitations

- N+1 redundancy adds parts with corresponding risks of additional failures
- DC link energy is stored in limited life electrolytic capacitors
- High parts count can mean low MTBF
- Regeneration is not possible
- Large footprint for higher hp

System Ratings, Other

- Power output levels most practical 300 – 2500 HP at 2300 v., 300 to 10,000 HP 4160 – 7200 v
- Input voltage levels –integral transformer isolated, up to 15 KV, possibly higher
- Transformer isolation - inherent
- Output voltages - 2.3 to 7.2 KV, higher voltages possible with more power cells
- Packaging and mechanical features – air-cooling to 3000 HP, liquid cooling above, including liquid-cooled transformer
- Sizes – single integral lineup. Separate / remote transformer not practical

Cost of ownership

- System efficiency of > 96%, including transformer
- Life cycle – this technology is presently widely used.

Multilevel Voltage Source MV IGCT PWM Inverter

The Integrated Gate Controlled Thyristor (IGCT) appeared about the same time as the MV IGBT (refer to Figure 2). Not long after, MV PWM IGCT inverters with the NPC (Neutral Point Clamped) topology appeared. Refer to the NPC topology discussions under the MV IGBT PWM drive section above.

Because the IGCT itself can be made in a voltage rating of 6.0 kV or more per device, NPC inverter bridges can be built in 4160 volt configurations with only two devices in series, as shown in Figure 28. To take advantage of the higher device rating and use fewer devices, inverters built around IGCTs are usually 3-level inverters. Although control algorithms other than PWM are used, the waveform in Figure 19 is still illustrative of the 3-level topology output. For output voltages higher than 3300 a full sine wave output filter (discussed earlier) is usually included in the system. Figure 28 illustrates this.

Converter Options The harmonic current limit recommendations in IEEE 519 1992 are often required to be met at the terminals of MV drives. Figure 28 shows an input rectifier of 12-pulse configuration. This configuration has a current THD typically near 12%. The IEEE 519 limits for most power systems are usually lower than 12%, and many purchase specifications require 5% distortion.

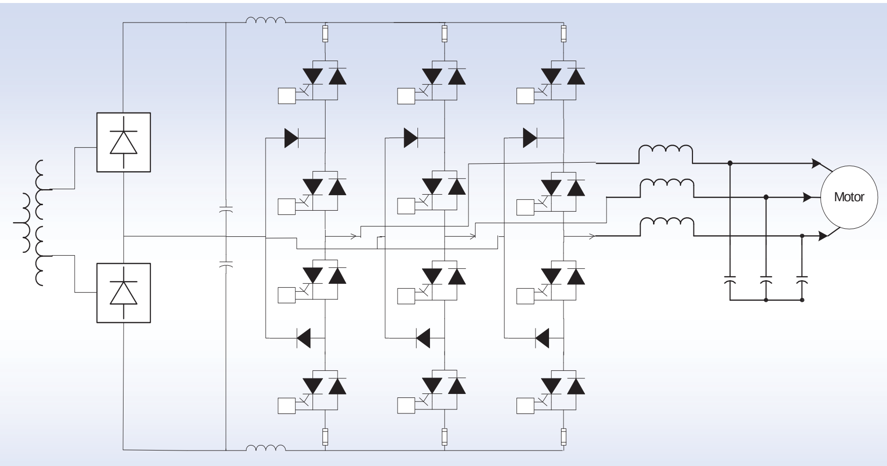


Figure 28. MV 3-level IGCT NPC Voltage Source Inverter With MV IGCTs

In order to meet harmonic distortion limits, the alternate converter configurations shown in Figure 29 can be used to develop the two bus levels needed for the IGCT inverter.

Detail A illustrates an active IGCT converter. With sufficient input source reactance isolation and proper firing algorithms, it is possible to achieve low current THD with a single winding transformer feeding the converter. Detail B shows a 24 pulse diode-fed converter. Its inherent current THD is 3% or less.

Two additional advantages are provided with the active converter front end. First, the converter is now fully regenerative, allowing braking control of overhauling loads. Second, with proper algorithms, the active front end can actually be switched in a pattern that presents a leading power factor to the power system. This is useful in maintaining voltage at the end of a long ac utility feeder.

In the late 90s, GE produced the Innovation Series® MV IGCT PWM drives with active front-ends. Figure 30 shows one such equipment lineup. They were applied in high-performance synchronous motor steel mill applications.

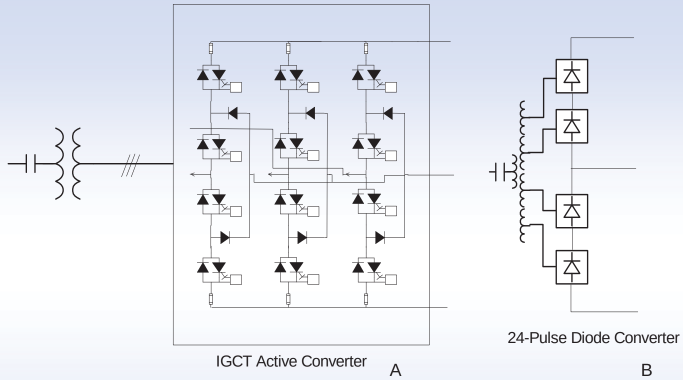


Figure 29. Converter Options for MV IGCT 3-level Voltage Source Inverter (A) Active IGCT Converter & (B) 24 pulse Diode Converter

Figure 30. Example GE Innovation Series® MV IGCT Based 3300 Volt VSI PWM Drive Including Active Converter & Inverter Modules

MV IGCT Drive Comparison Points

Here are some of the key comparison points, strengths and limitations of the MV IGCT NPC drive system.

Major Strengths

- Low power switch count
- High power levels with largest IGCT devices
- Fast response & wide range of speed and torque control
- No significant torque pulsations
- Regeneration is possible with active front end

Major Limitations

- 3-level inverter requires output sine filter
- Very high parts count within complex IGCT firing circuitry
- May not be able to run in test mode with motor disconnected and output filter in place.
- Power device redundancy not practical.
- Possible resonance between motor and output sine filter, if included.

System Ratings, Other

- Power output levels 1.0 to 16+ MW
- Input voltage levels - transformer isolated, limited by transformer
- Transformer isolation - inherent
- Potential for low harmonics on power input (with active IGCT or 18 + more pulse diode converter)
- Output voltages - 2.3 to 6.9 KV
- Packaging and mechanical features – remote transformer

Cost of ownership

- System efficiency of > 96%, including transformer
- Life cycle – this technology is current, but being challenged by IEGT technology

IEGT Voltage Source PWM Inverter

In our discussions of power devices, we mentioned the growth in the transistor devices into new forms such as the IEGT. How would these devices be applied to greatest advantage? Figure 31 shows a power one-line of one implementation, with an active IEGT converter.

The high switching speed and low losses of the IEGT lend themselves to some very high power output levels at motor voltages up to 3300 Volts.

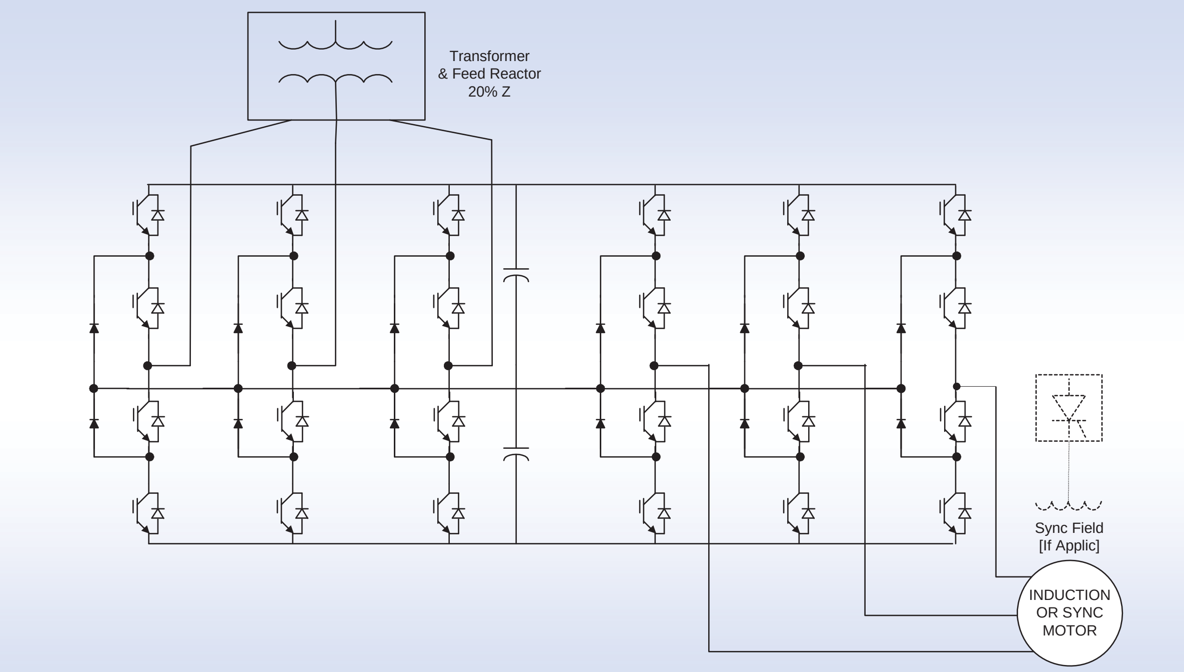


Figure 31. IEGT 3300 volt Voltage Source Inverter and IEGT Active Regenerative Source

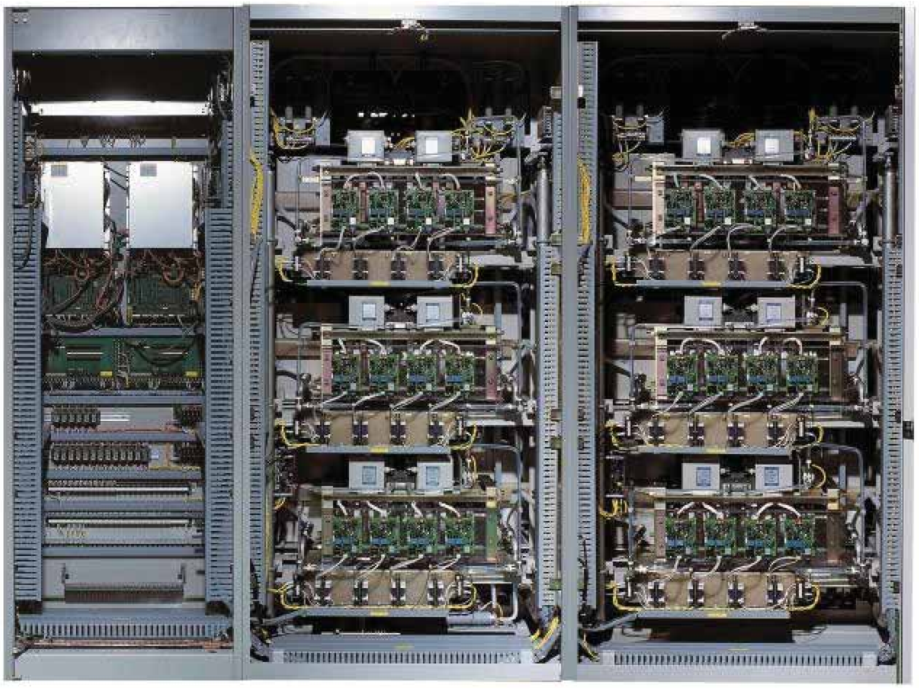


Figure 32. Example TMEIC T650 IEGT 3300 volt 8 MW Regenerative Inverter

Figure 32 shows a complete regenerative eight MW inverter including all the devices shown in Figure 31.

Figure 33 shows a photo of one complete liquid-cooled phase leg of the IEGT inverter.

IEGT VSI PWM Comparison Points

The comparison points of the IEGT drive system configuration of Figures 31, 32 and 33 are nearly identical to the MV IGBT VSI inverter previously described.

Major Strengths

- Low power device count – only 24 for complete 8 MW inverter-converter systems.
- Very high system MTBF
- DC link energy is stored in liquid filled power capacitors with 20+ year life
- Low power system harmonics
- Unity or leading power factor
- 3-level output and less than 5% motor current THD
- Simple voltage-controlled gate circuit almost 4:1 more reliable than IGCT gate control.
- Rugged and proven reliable
- Fast response
- Wide range of speed and torque control
- High starting torque
- Synchronous or induction motor compatible
- Can run in test mode with motor disconnected

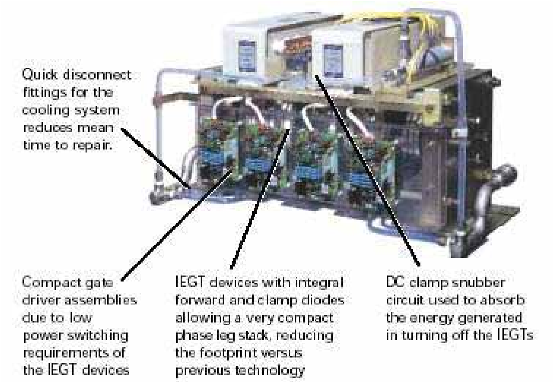


Figure 33. Example IEGT Water Cooled Phase Leg
One of six in an 8 MW Regenerative Inverter System

Major Limitations

- Power device redundancy not practical
- IEGT switching speed can produce motor waveform transient voltages and some installations may require dv/dt filter on drive output

System Ratings, Other

- Very high power levels – up to 8 MW per single bridge, 32 MW with parallel bridges
- Input voltage levels – transformer isolated
- Transformer isolation - inherent
- Output voltage: 3.3 KV
- Packaging & Mechanical Features - liquid cooling, with closed loop redundant system

Cost of ownership

- System efficiency of > 96.5%, including transformers
- Life cycle – this technology solid and growing
- Very small footprint using water-cooling

Signal Processing over the Years

Early MV inverter systems were based on a fair amount of electronic "real estate". Rows of printed circuit boards were typical of every drive. Additionally, as knowledge of ac drives advanced, the algorithms and methods for creating ac output waveforms also grew over the years. Table 7 presents a summary chart of some of the key hardware, software and support changes from "then" to "now".

Table 7. Comparison of 1970's Vintage MV AC Drive Controls with Current State of the Art

Comparison Area	AC Drive Control Vintage	
	Then	**Now**
Hardware Packaging	Multiple printed circuit assemblies, custom wire-wrapped backplanes	Single Board processors in VME form factor or flat mount
Micro Processor	16-bit processors	32 bit main processors with additional special purpose auxiliary processors
Control Basis	Hardware dependent control with limited sequencer capability, fixed block diagram regulators.	Software based control with flexible sequencing logic and Windows based control system toolbox, animated graphic displays, trending.
Control and Data Interface	Local control push buttons, printers, meters, single serial interface.	Complete Knowledge Management, including multiple data ports, Ethernet drive set up, multiple software drivers, HMI screens.
Speed Feedback	Most drives required speed feedback sensors.	Most applications can use tachless algorithms to determine speed with good precision.
Drive Set up	A lengthy and manual process with multiple meters, strip chart recorders, etc.	A brief process using true automatic drive tuning, with motor parameters and load characteristics automatically determined by microprocessor controlled measurements
Diagnostic Process & Tools	Some diagnostic Aids, including printed troubleshooting guides, diagnostic indicator lights, printed fault logs.	Extensive online help files, data capture buffers, built-in trend recorders, failed power switch identification, animated block diagrams or signal flow tracing.
Support	Telephone and local field engineer site support, with average time to solve problems 8 - 24 hours including travel time.	24 x 7 remote diagnostic and monitoring service, with average time to restore service < 90 minutes.

Examples. Some illustrative photos may tell the story best. Figure 35 shows an early LCI drive control rack of printed cards. Figure 36 is the same control for a modern LCI drive, including advanced diagnostics. Finally, Figure 37 shows the single 10-inch by 10-inch 32-bit microprocessor card for a modern PWM MV drive. The number of printed circuit cards and overall visual reduction in complexity is quite a contrast. This is particularly obvious when one considers that the new control has a much higher level of diagnostic and communication capability within the simplified package.

There has certainly been an interesting interplay between the appearance of power devices, the growth of signal and data processing power and the creation of the many inverter topologies. An all-digital implementation has made possible the high reliability both needed and expected of modern MV drives.

Conclusion

Over the course of this paper we have covered a fairly broad range of MV drive topics. We have attempted to show where MV drive technology has been, what drove it forward, and some present and future trends. Hopefully we have accomplished at least some of those goals.

One thing seems certain: there have been many enhancements in MV technology. And yet much has remained the same. Users will continue to expect high reliability and maintainability of their MV drives. Energy conservation and the economic benefits of process optimization will move MV drives into expanded markets and application areas.

Newer and more efficient power devices will continue to appear, and will be even easier to control. Engineers will continue to create novel and reliable systems from the emerging technology. The winner will be the ever-widening group of MV drives systems users.

Figure 35. 1970's Vintage LCI MV Drive Control

Figure 36. Modern LCI MV Drive Control

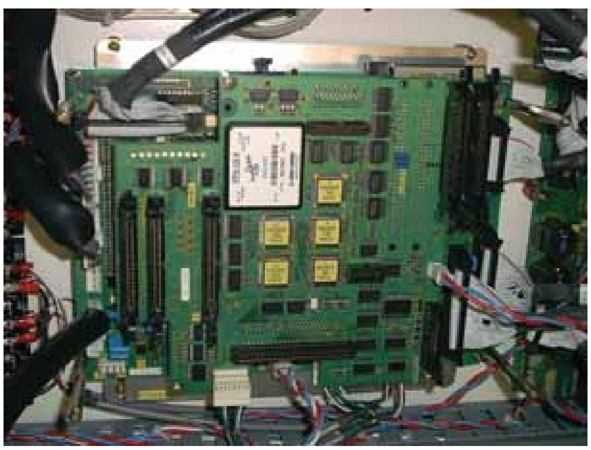
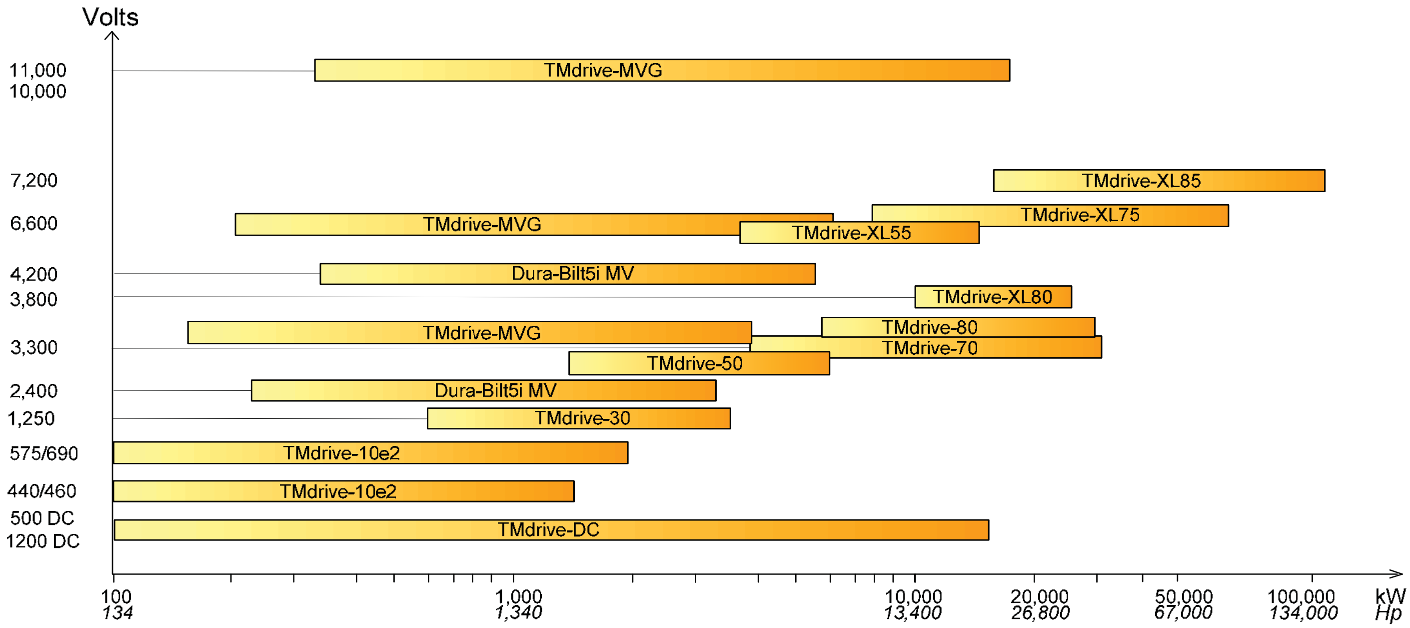


Figure 37. Modern MV PWM Single-board Control Processor

TMdrive System Drives Offer Complete Coverage



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