TOSHIBA GE

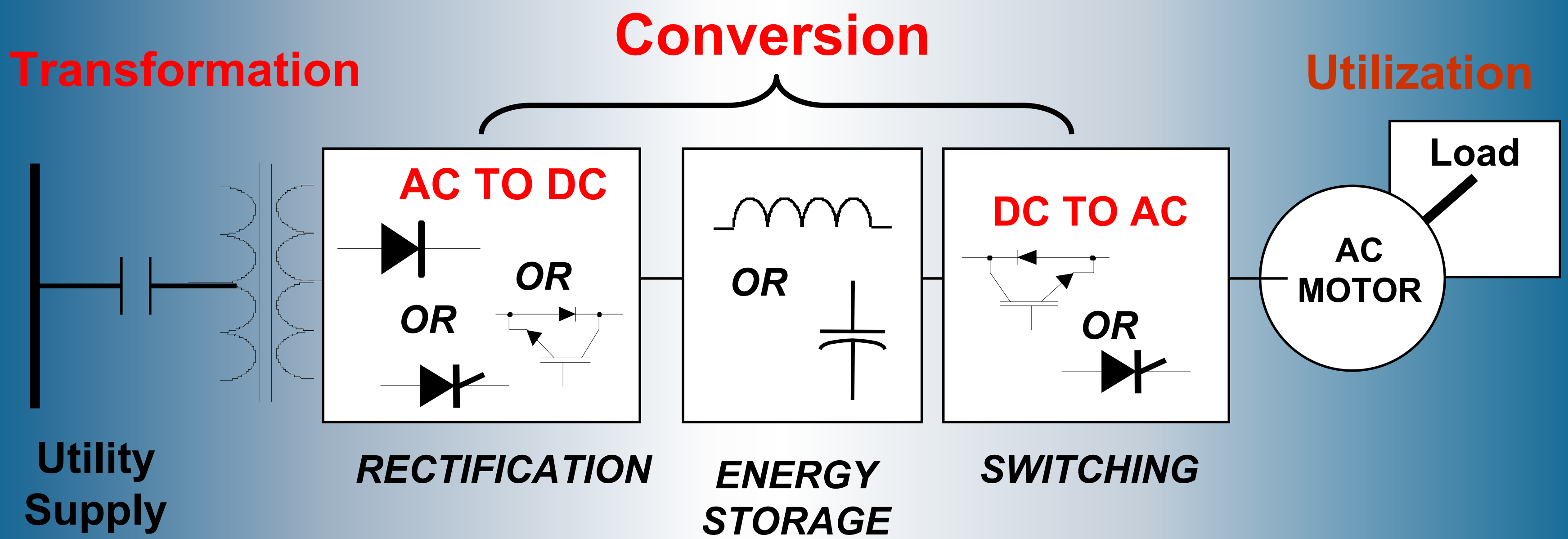
GE TOSHIBA AUTOMATION SYSTEMS

DURA-BILT 5i MV

Medium Voltage AC Drive Topology

Comparisons & Feature-Benefits

Typical AC Inverter System



AC Inverter Technology

Up To 97% Efficiency, including transformers

AC Drive Topology:

A map-like diagram showing the elements of an AC drive and the relationships between them.

Two Basic AC Drive Topologies

- Current source drive: ENERGY STORAGE section between converter and inverter consists of an inductor.
- Voltage Source Drive: ENERGY STORAGE section between converter and inverter consists of capacitors.

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DURA-BILT5i MV

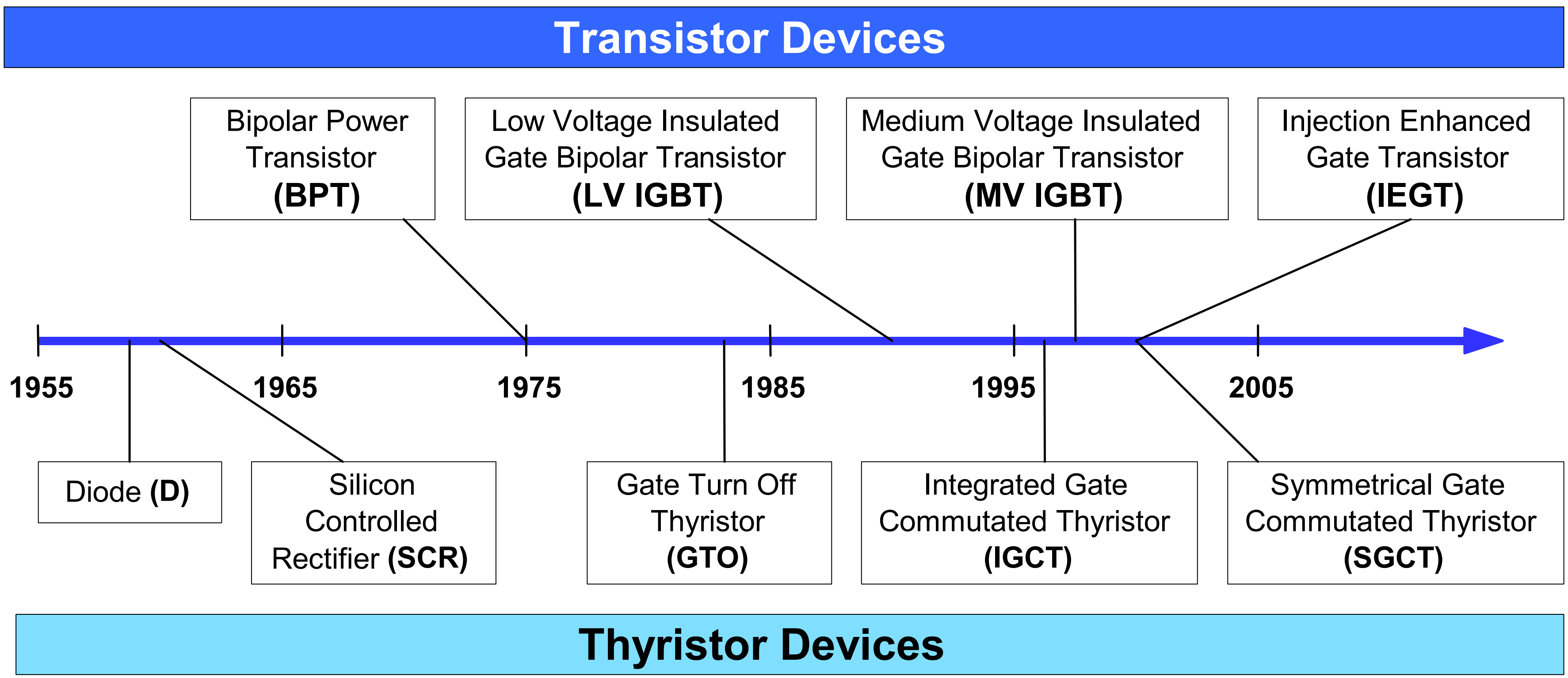
Evolution of Power Devices

Leads the pace of AC drive development

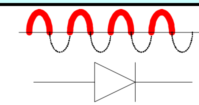
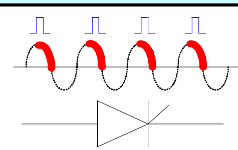
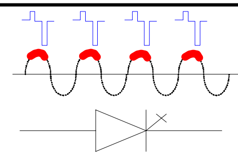
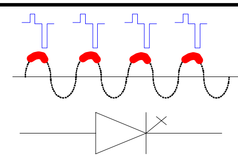
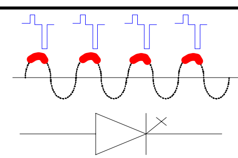
Advances in Power Semiconductor Technology Lead the Way in MV Drive Development

- The Common Threads:
  - ✓ All AC Drives rectify AC to DC
  - ✓ All AC Drives use switches to create AC from DC
- Drive topologies were created as power rectifiers and switches grew in ratings and capabilities.
- Each new or uprated device opens up new applications
- A quick look at the device development timeline is useful

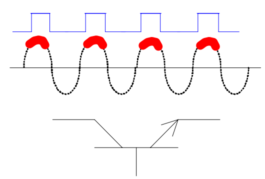
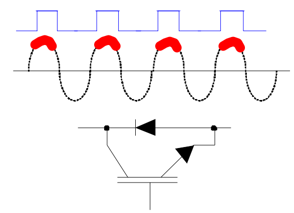
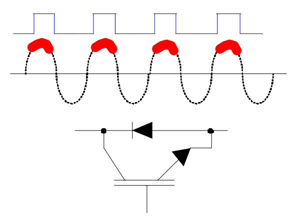
Development Time Line of Power Semiconductors



Diode and Thyristor Families of Devices

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

Device	Operation	Description
Transistor Family of Devices		
Bipolar Power Transistor (BPT)		Controls the flow of positive current with current injected into its base.
Insulated 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.

Power Device Comparison

Detailed Overview

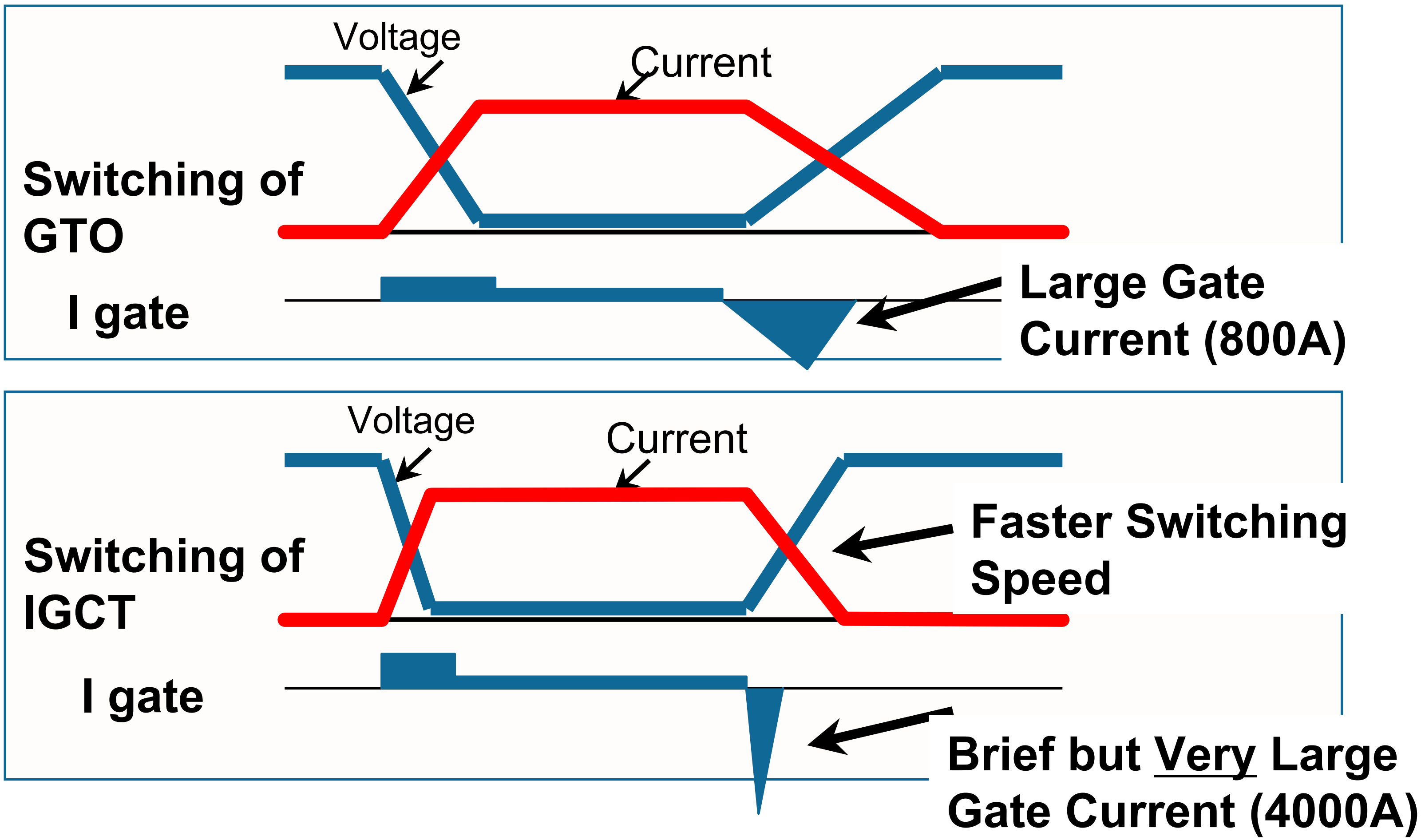
Drive Power Device Application Comparison

Device → / Comparison Area ↓		Silicon Diode Rectifier	Thyristor [SCR] Silicon Controlled Rectifier	GTO Gate Turn Off Thyristor	Bipolar Transistor Power Darlington Type	IGBT LV Insulated Gate Bipolar Transistor	IGBT MV Insulated Gate Bipolar Transistor	IGCT Integrated Gate Controlled Thyristor	SGCT Symmetrical Gate Controlled Thyristor	IEGT Injection Enhanced Gate Transistor
Inverter Switch				X	X	X	X	X	X	X
AC - DC Conversion		X	X	X		X	X	X	X	X
Inverter Circuit		X								
Inverter types	Current Source		X	X					X	
	Voltage Source	X		X	X	X	X	X		X
Efficiency		High	High	Low	Low	High	High	Medium-High	Medium-High	High
Gate Control Signal		NA	Current	Current	Current	Voltage	Voltage	Current	Current	Voltage
Gate Current		NA	< 2 amps	400-1000 amps	up to 10 amps	0.1 amps	< 1 amp	4000 amps	4000 Amps	< 1.5 A
Gate control component Count		NA	Medium	High	Low	Low	Low	High	High	Low
Voltage Rating		High	High	High	Low	to 1200 v	to 4500 volts	to 6000 volts	to 6000 volts	to 4500 volts
Current Rating		6000 amps	5500 amps	1000 amps	500 amps	1000 amps	to 1200 amps	4000 amps	5000 amps	to 4000 amps
Switching Losses		NA	Medium	High	Medium	Low	Low	Medium	Medium	low
Snubber Parts		NA	Few	Many	NA	Low	None	None	None	Low
Switching Speed		NA	Low	Low	Low	Very High	High	Medium	Medium	High
Life Cycle Point		Mature but current	Mature but current	Phasing out	Rarely used	Current & Growing	Current & Growing	Current	Current	Current & Growing
Mounting		Press-Pack & Single Side	Press-Pack	Press-Pack	Single side	Single side	Single side	Press-Pack	Press-Pack	Press-Pack & Single Side

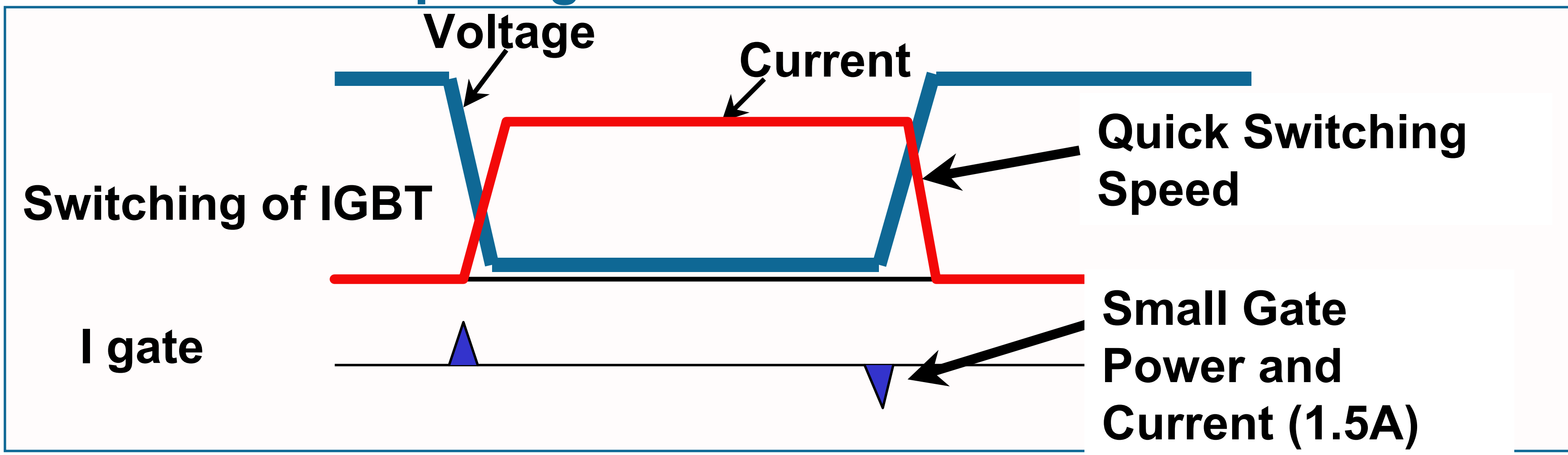
Comparison Areas for Drive Power Devices

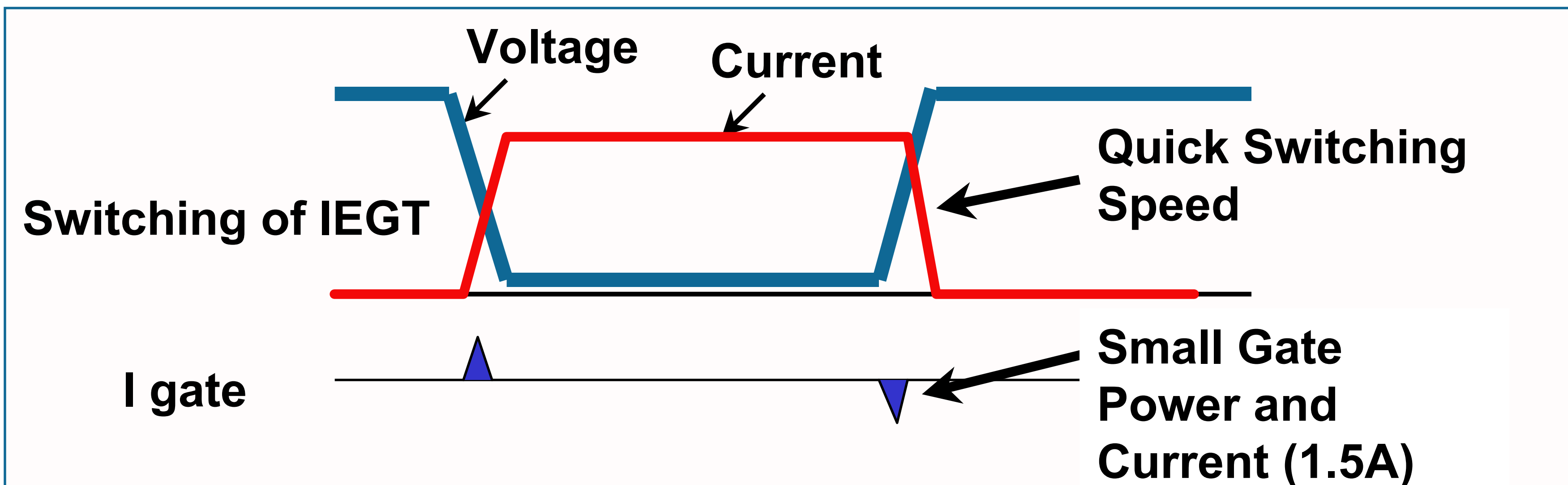
Comparison Areas	Impact
Gate power to turn device on & off External circuitry [firing & protection]	Number of control devices & system reliability
Switching speed, switching losses On-state forward drop and losses	System efficiency & cooling
Continuous current ratings Forward & reverse blocking voltage	Number of power devices, & system reliability
Physical mounting & thermal characteristics	Packaging & system Size

Comparing Gate Power of Devices - 1



Comparing Gate Power of Devices - 2





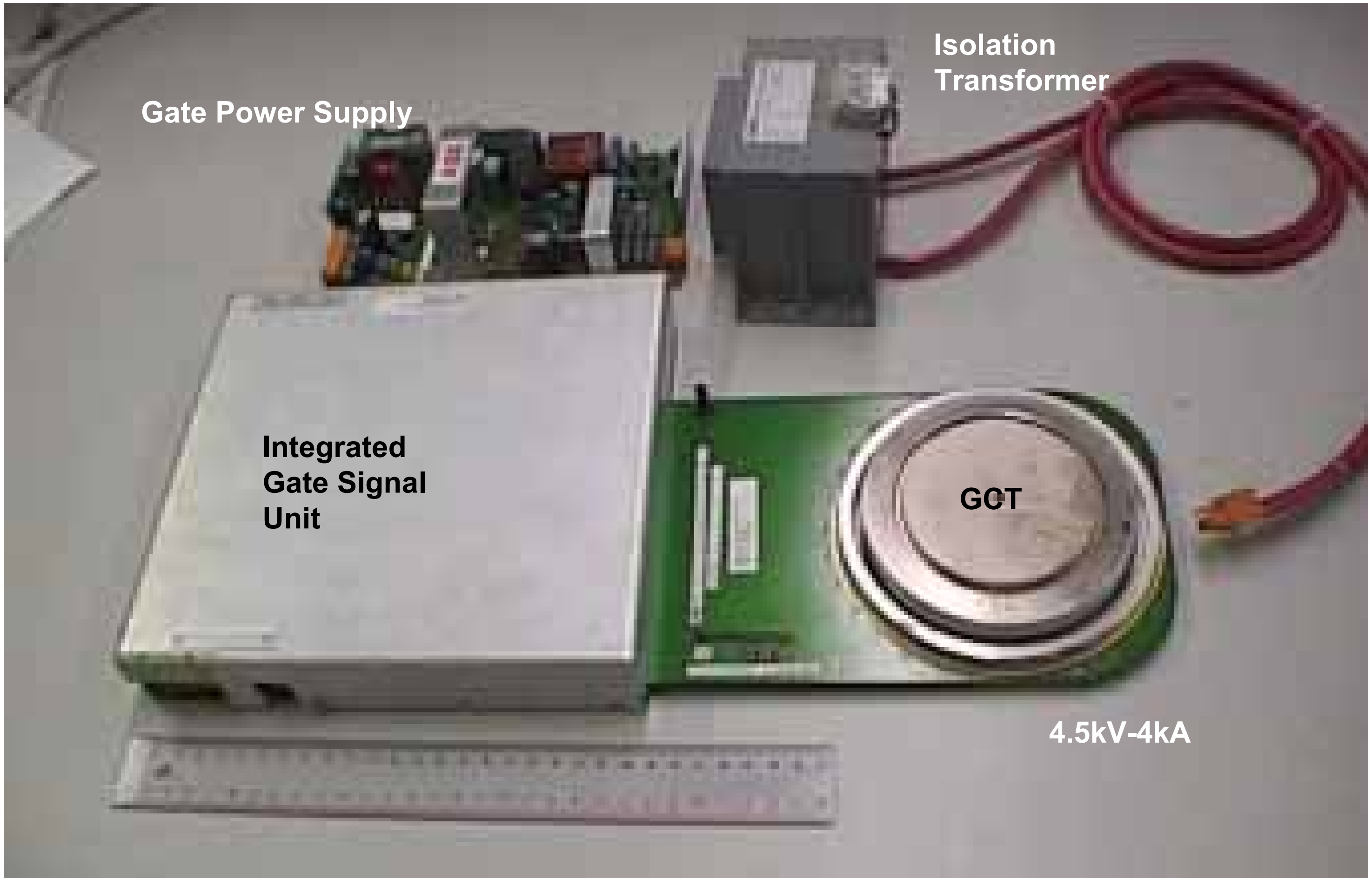
GTO Gate Driver & Cell Stack Equipment

GE GTO-IMD Example

- Liquid-cooled configuration
- Many discrete parts in firing and auxiliary parts
- Snubber network also shown
- Physically quite large

GCT Gate Driver Equipment

Covers on



GCT & Gate Driver Board

Covers off

4.5kV-4kA

4.5kV-800 A

36 Electrolytic caps

21 FET Switches

Typical IGBT & IGBT Gate Driver Circuit

IGBT

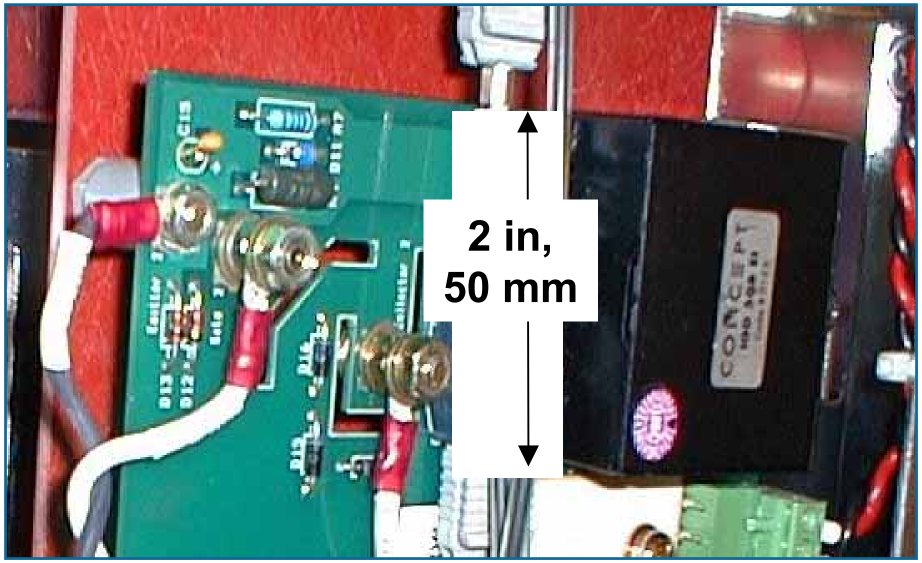
400 amp 3300 volt dual package
Larger ratings have 1/package

Approximate Size:

4 inches x 4.5 inches

Typical MV IGBT Dual Gate Driver

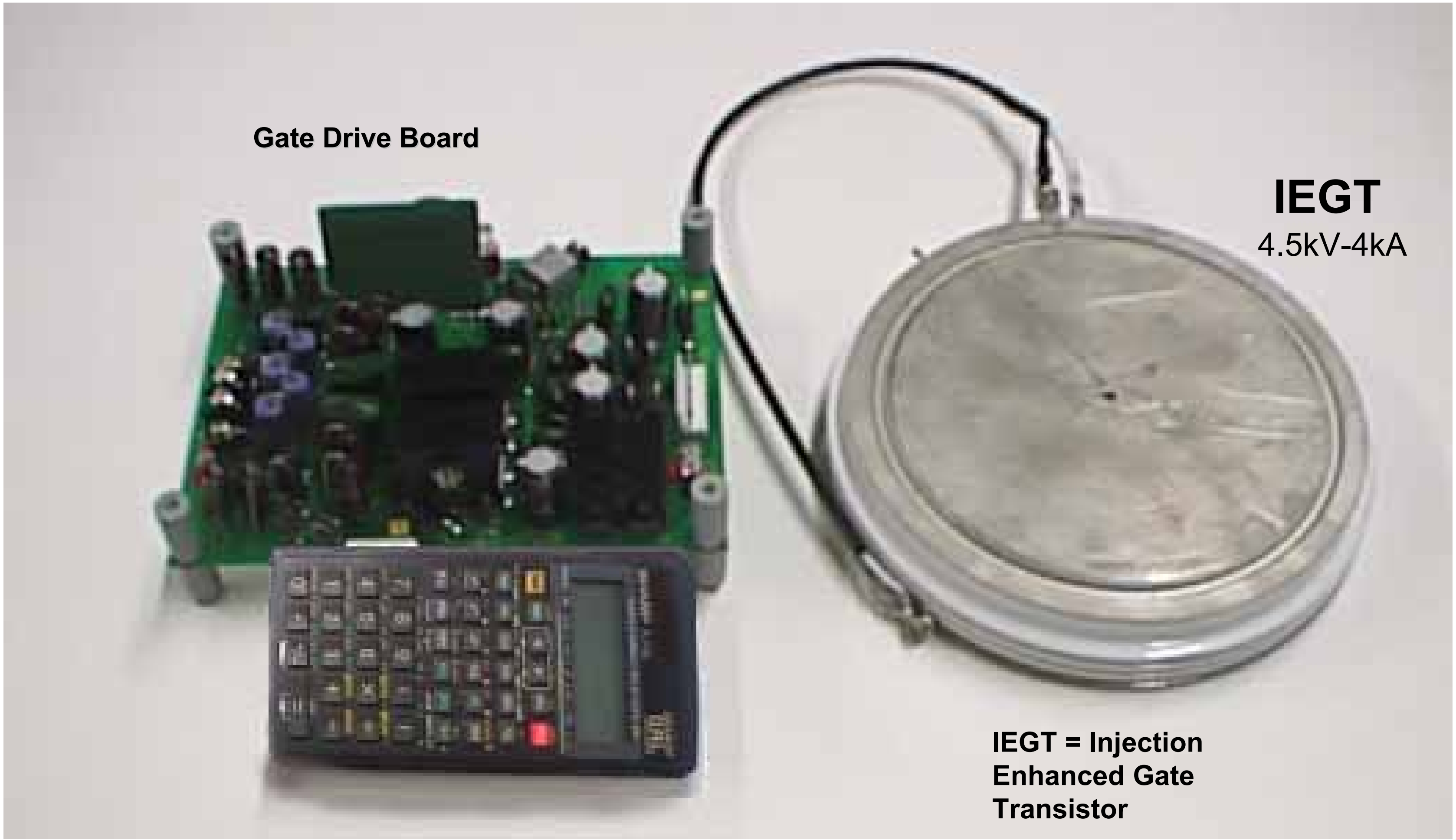
Each board has 2 drivers, & fires 2 IGBT's



IEGT – Latest Generation Voltage Switched Power Device

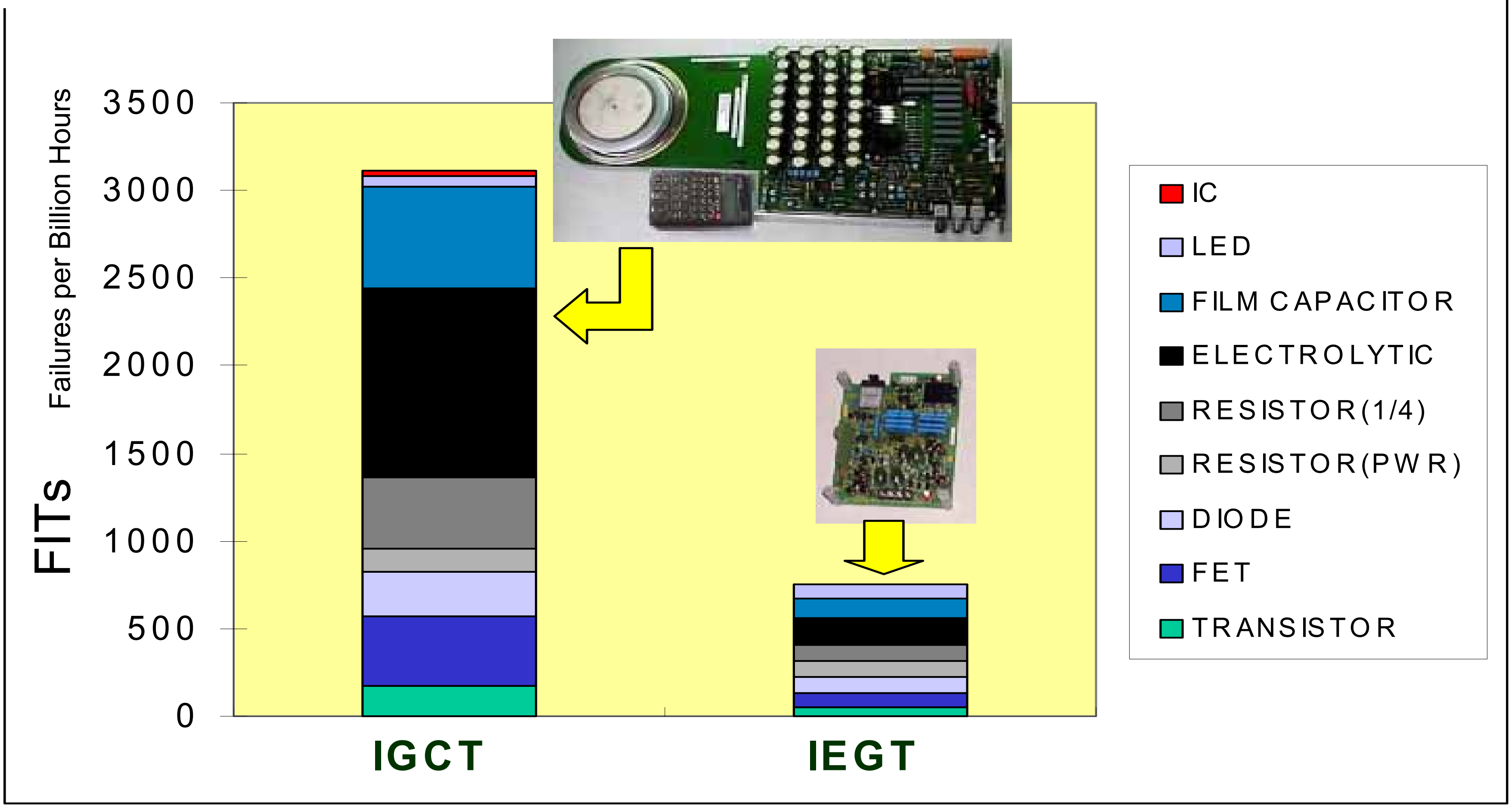
- IEGT = Injection Enhanced Gate Transistor
- Ratings to 4000 volts, 4500 amps
- Press pack or single sided
- Lower forward drop than IGBT, meaning higher power density, more efficiency.

IEGT Gate Driver Equipment



Calculated Reliability of Gate Drivers

IEGT Voltage Fired vs GCT Current Fired



Power Device Losses

Generally

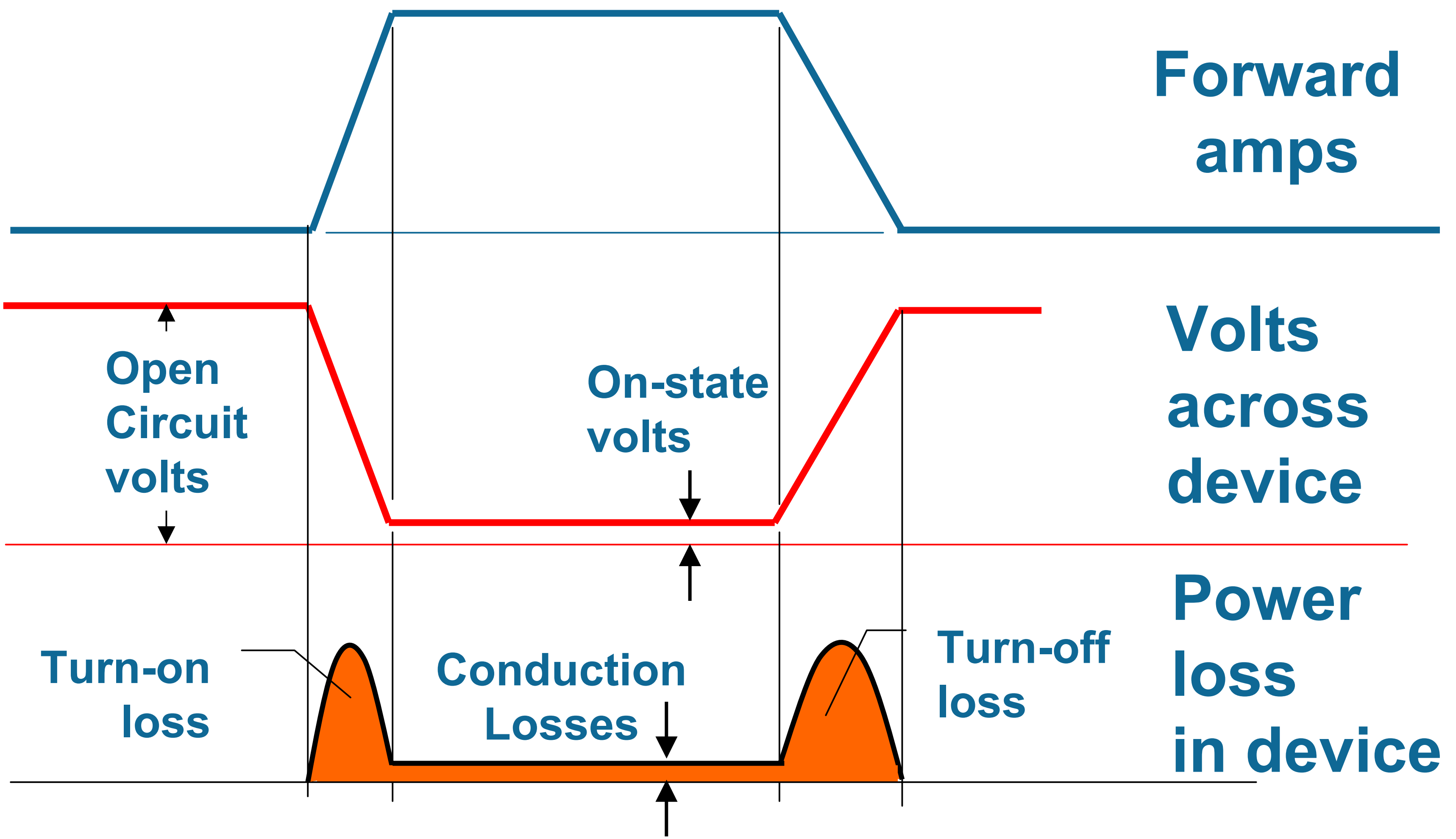
Volts across device X Current Through Device = Power Lost in Device

Two Categories of Device Loss:

1. **Losses During Turn-on & Turn-off –**
   - **Minimized by faster switching**
   - **Equals area under volt-amp product curve**

2. **Losses during conduction**
   - **Minimized by reducing device forward drop**
   - **Equals device forward volts x amps**

Power Device Losses



Power Device Switching Losses

Current Switched [IGCT] vs Voltage Switched MV IGBT

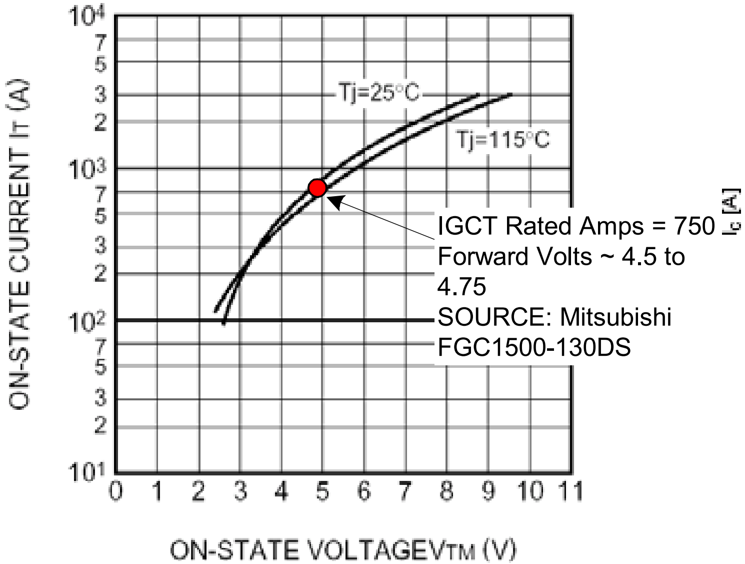
DEVICE	IGCT	IGBT
Device rating	750 AMP	800 AMP
Turn On Joules Lost / pulse	2.15	1.92
Turn-Off Joules Lost / pulse	12	1.02
Total Switching Energy Joules Lost / Pulse	**14.15**	**2.94**

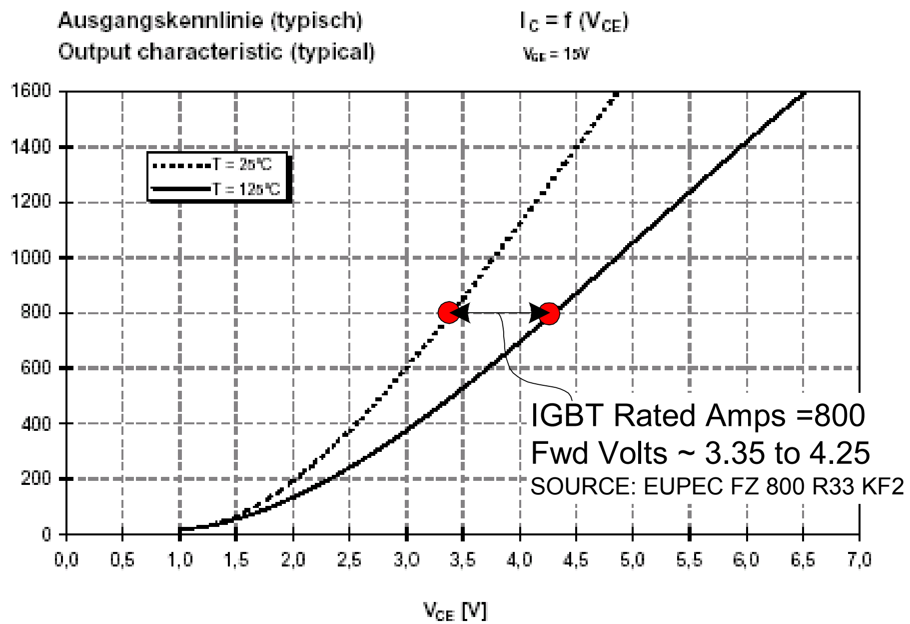
Almost 5:1 higher switching losses IGCT vs MV IGBT!

IGCT Rated Amps = 750
SOURCE: Mitsubishi FGC1500-130DS

IGBT Rated Amps =800
SOURCE: EUPEC FZ 800 R33 KF2

Power Device On-State Losses
IGCT vs MV IGBT Examples



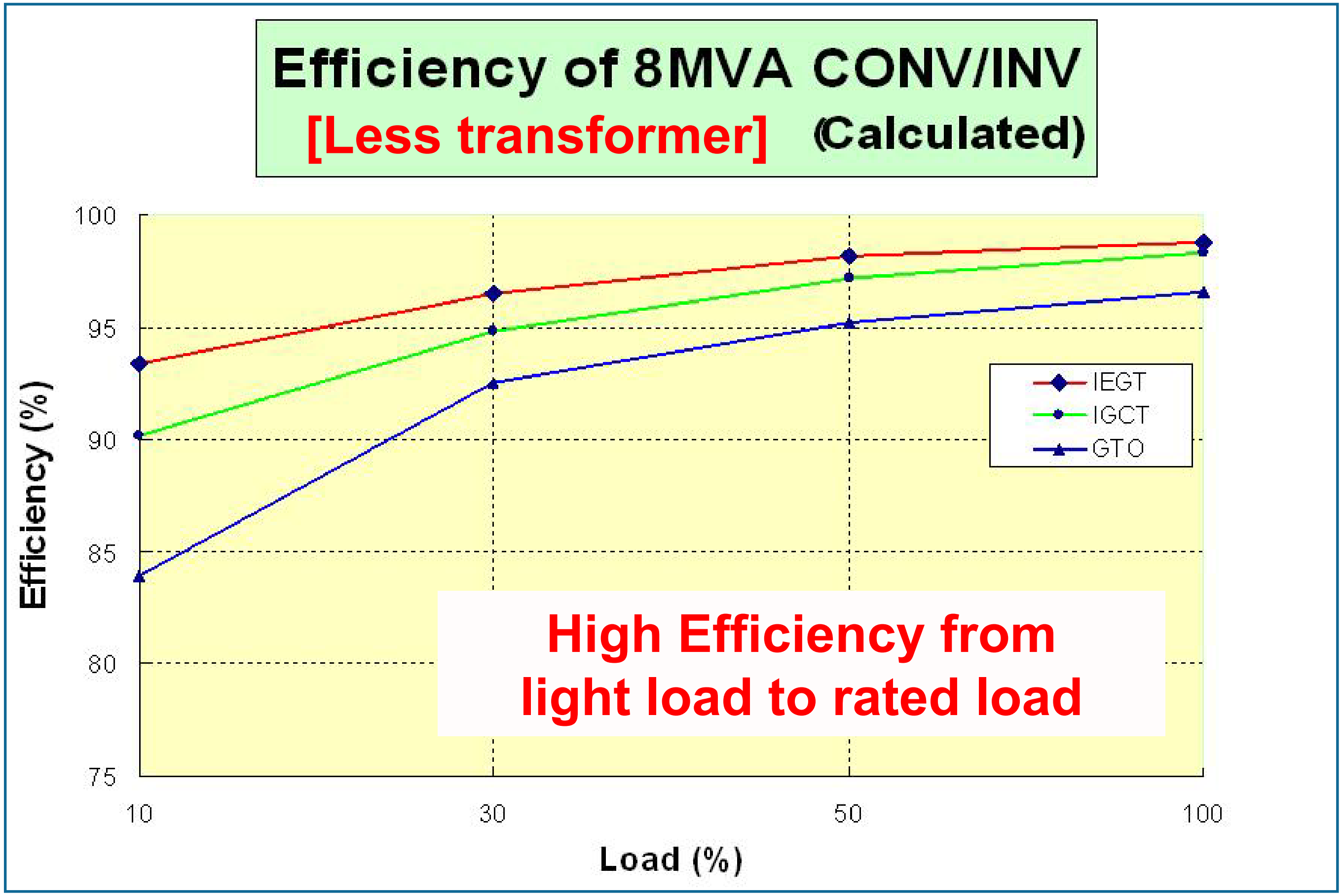


750 amp IGCT
Forward v = 4.5 - 4.75

800 amp MV IGBT
Forward v = 3.35 - 4.25

Comparing Large Inverter Efficiencies:

IEGT vs IGCT / SGCT vs GTO

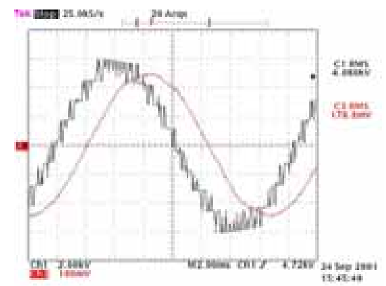


Note: IGBT drive efficiencies typically equivalent to IEGT

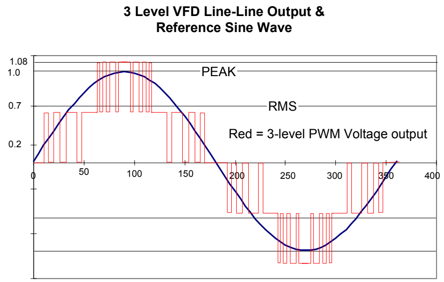
Power Switch Voltage and Current Ratings

Continuous current ratings
Forward & reverse blocking voltage
AFFECTS
Number of power devices, & system reliability

- Higher device *voltage* ratings mean fewer devices are needed to match load voltage rating
- Higher *current* ratings mean fewer devices can be used without requiring paralleling
- *Tradeoff*: Using fewer, higher voltage-rated devices gives output waveform fewer levels with larger voltage change. For >4 kv drives, this requires large output filters.



5 level 4000 volt Output
No sine filter needed



3 level 4000 volt Output
Large sine filter needed

- As of March 2003: **GCT: 4500 A, 6kV IGBT: 1200 A, 4500 V IEGT: 4000 A, 4500 V**

Power Switching Devices
Final Comparisons & Conclusions

- Current switched devices [SGCT, IGCT] require many more parts in firing / gate control than voltage switched devices [IGBT, IEGT].
- Voltage switched devices [IGBT, IEGT] have MUCH lower switching losses than current switched.
- Conduction losses are nearly equal for equivalent volt & amp-rated device SGCT, IGCT vs IGBT, IEGT
- Voltage switched devices allow higher switching rates and can give better output waveforms

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DURA-BILT 5i MV

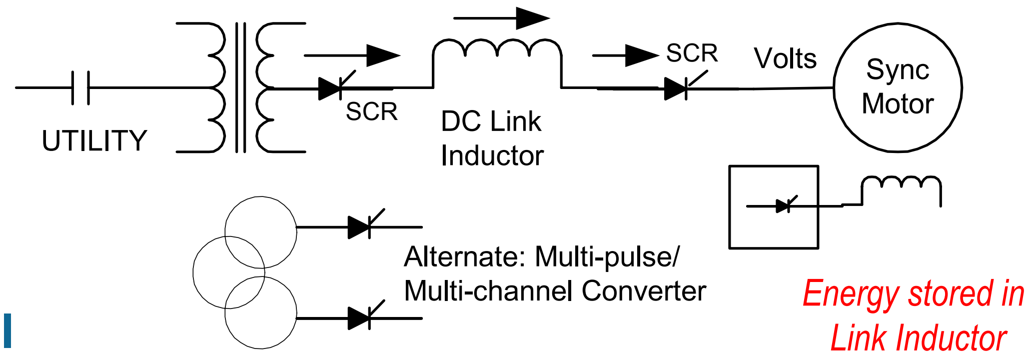
Comparisons of Major Drive Type Topologies

Comparing Topologies

- Current Source Drives
  - ✓LCI – Load Commutated Inverter
  - ✓GTO/SGCT Current Source Induction Motor Drive
- Voltage Source Drives
  - ✓LV IGBT “Paice” Multilevel PWM
  - ✓MV IGCT PWM – Diode or Active Source
  - ✓MV IGBT PWM – Integrated package
  - ✓MV IEGT PWM – Active or Diode Source

LCI – Current Source Load Commutated Inverter

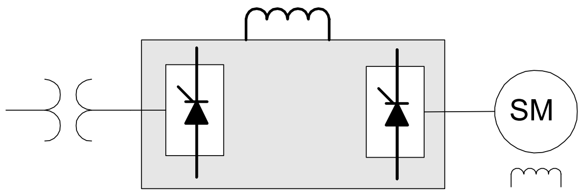
Example: GE-Innovation Series® LCI



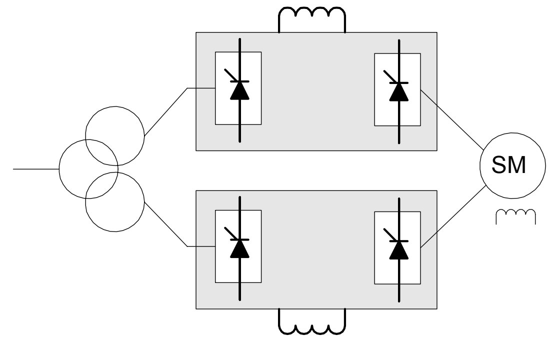
Inverter Topology	Advantages	Drawbacks	Practical Power Range
Current source Load-Commutated Inverter SCR = Silicon Controlled Rectifier, Thyristor	• Low Parts Count • Full Regen is inherent • Rugged – ultra reliable • Economical High HP • N+1 SCR device redundancy possible	• Requires a controlled front end • High motor current THD • Slow transient response • Narrow motor frequency range • Reduced Starting Torque • Limited starting performance • Poor PF at low motor speeds • High harmonics unless multiple channels used; filters may be needed.	Above 6 MW Synchronous Motors Only

Primarily being offered by: GE Toshiba, ABB, Siemens

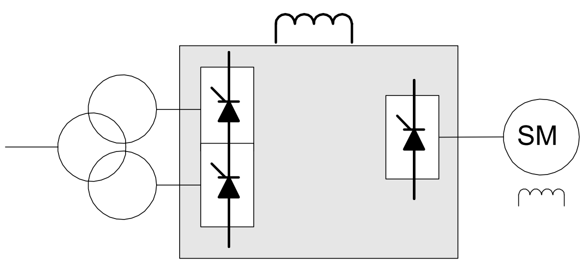
Alternate LCI Configurations



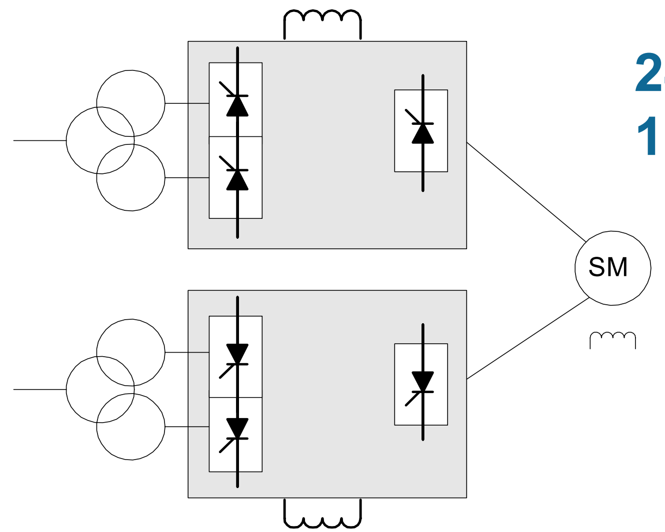
6-Pulse input
6-Pulse output



12-Pulse input
12-Pulse output



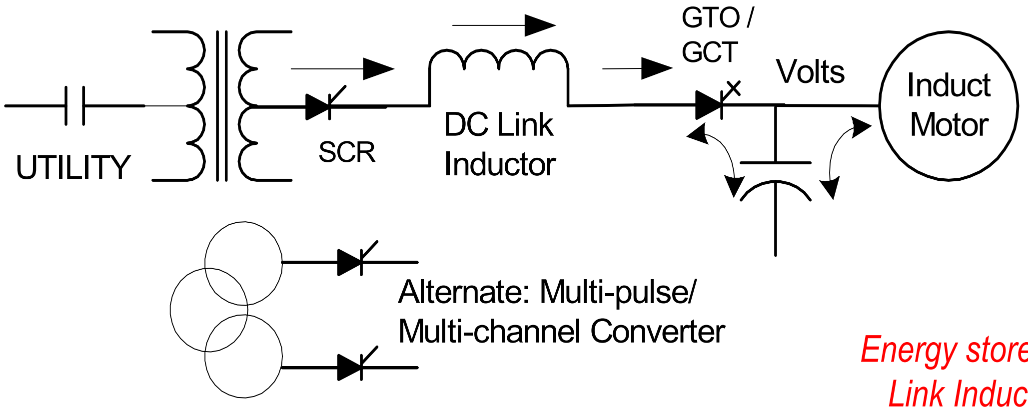
12-Pulse input
6-Pulse output



24-Pulse input
12-Pulse output

Current Source GTO / SGCT Induction Motor Drive

Example: GE-GTO IMD
Induction Motor Drive

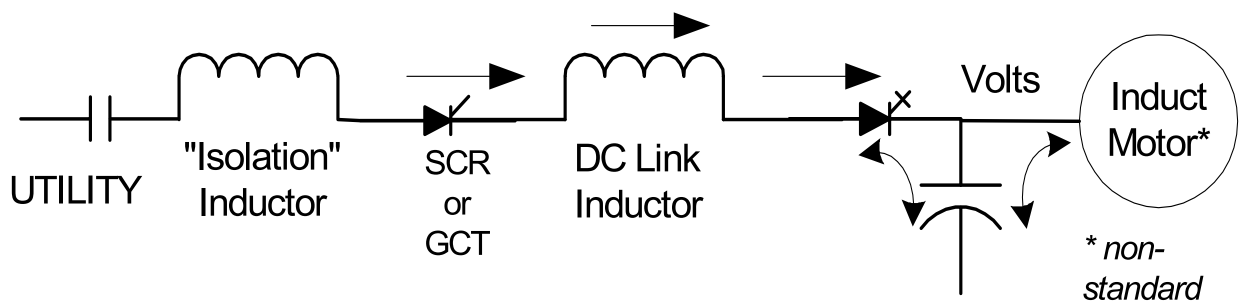


Energy stored in Link Inductor

Inverter Topology	Advantages	Drawbacks	Practical Power Range
Current Source GTO or SGCT PWM Inverter GTO = Gate Turn Off Thyristor SGCT = Symmetrical Gate-Controlled Thyristor	• Low power device (GTO/SGCT) parts count • Low motor THD • Low motor insulation stress when input isolation transformer is used	• Requires a controlled front end – extra complexity • Poor input power factor, with SCR front end • Slow transient response • Narrow speed range • Potential resonance between motor & caps • Limited availability of power devices • Complex firing circuit	2 - 15 MW Primarily induction motor load

Primarily being offered by: Allen Bradley

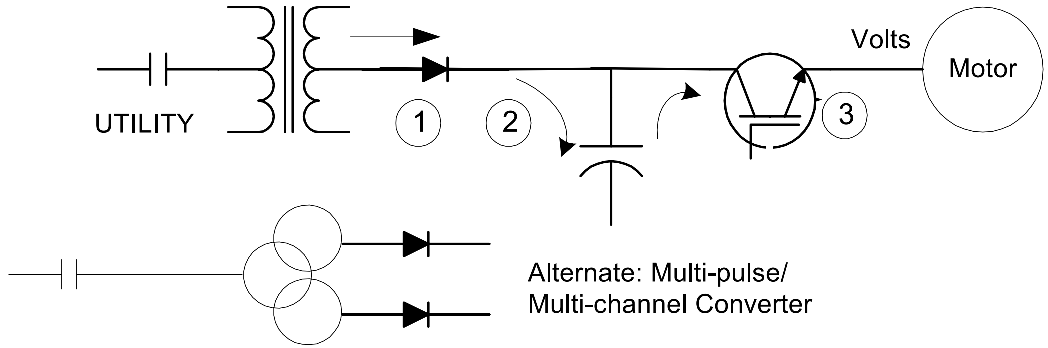
Current Source SGCT Induction Motor Drive With "Isolation" Reactor in Place of Transformer



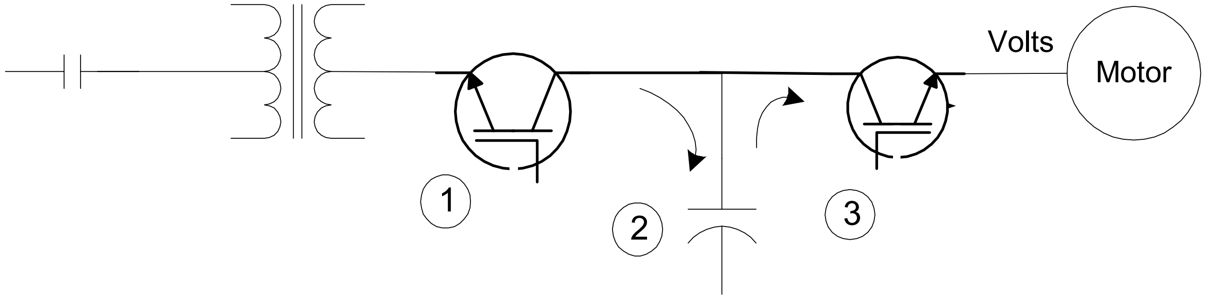
Energy stored in Link Inductor

Voltage Source General Drive Arrangements

Diode Rectifier Converter Fed



Active Rectifier Converter Fed



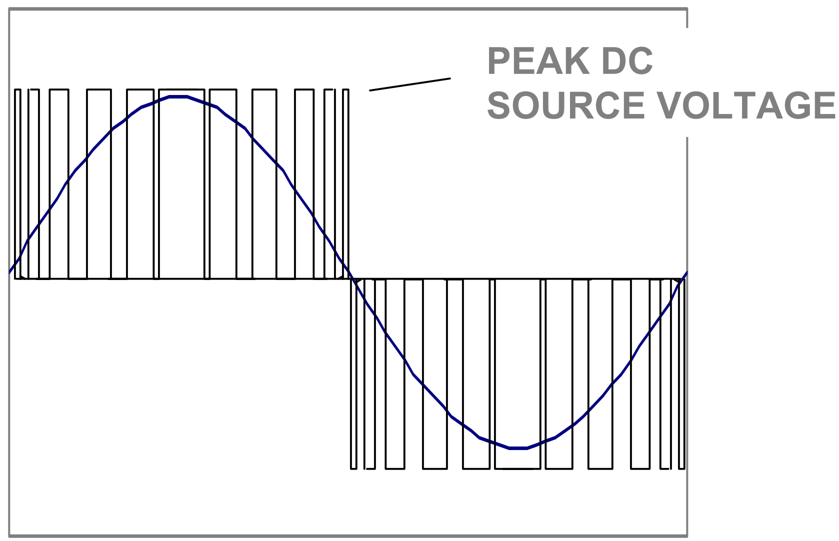
PWM: Pulse Width Modulation

A method of varying voltage by changing the average "ON" time of switches between source and load.

Example Pulse-Width-Modulated [PWM] Waveform

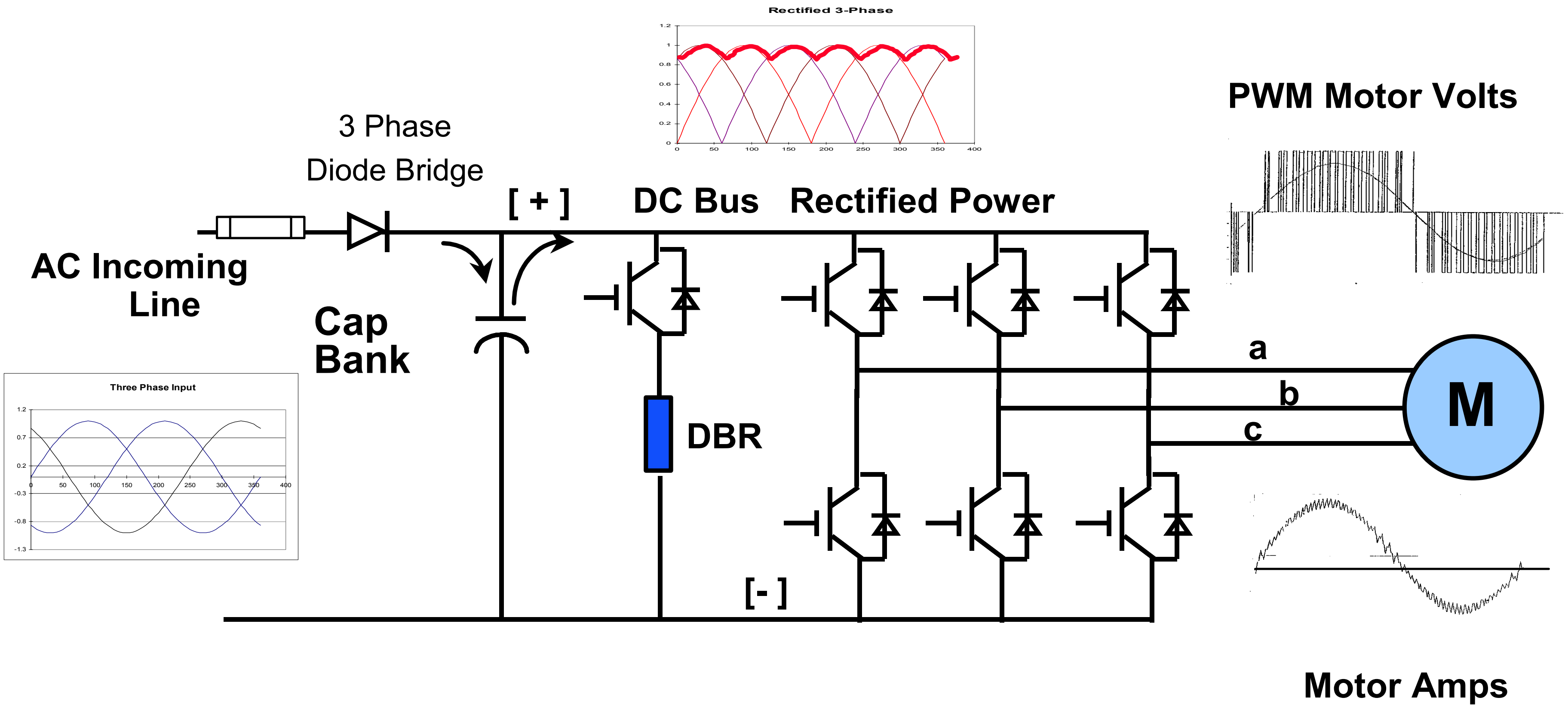
Voltage: The Average of the time the Voltage is on Plus the time the Voltage is Off.

Current: The Motor tends to smooth the resulting current



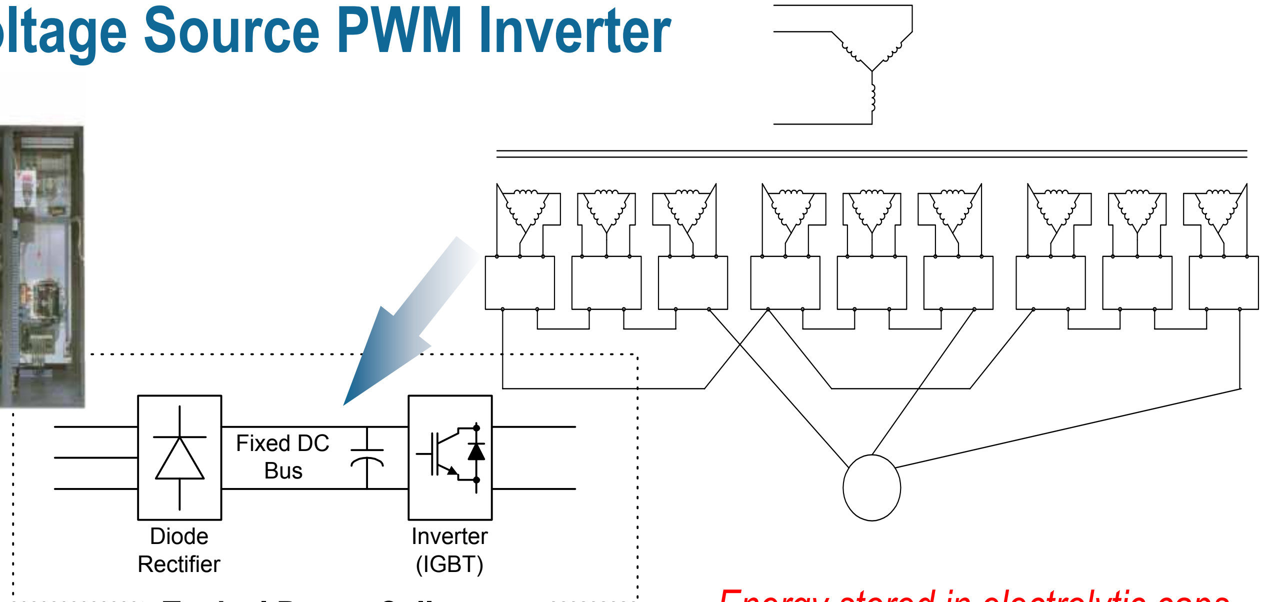
EXAMPLE SIMULATED SINE WAVE
PRODUCED BY 2-LEVEL
PWM INVERTER

Example Two-Level Voltage Source Inverter



LV IGBT Multi-level Voltage Source PWM Inverter

Example: GE Innovation Series® Type H



Typical Power Cell

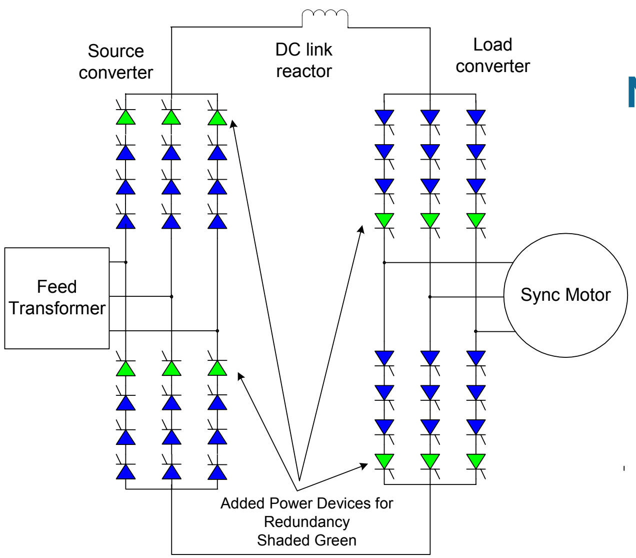
Energy stored in electrolytic caps

Inverter Topology	Major Advantages	Major Limitations	Practical Power Range
Multi-level Voltage Source LV IGBT PWM Inverter LV IGBT = Low-voltage Insulated Gate Bipolar Transistor	• Power Cell N+1 redundancy available • Low motor current THD • Fast transient response • Wide motor frequency range • No significant torque pulsations • High starting torque. • Multi-pulse converter for very low AC line harmonics • High true pf over all speeds	• No regen or DB possible • Large parts count – lowers base MTBF • N+1 redundancy adds parts and decreases MTBF • Large footprint in high HP • Electrolytic capacitors degrade with time and are sensitive to overvoltage	0.5 - 7 MW Sync or Induction motor

Primarily being offered by:
Robicon, Toshiba Japan

Power Cell "N+1" Redundancy

- "N+1 redundancy" originated in LCI drive design, defined as having an extra SWITCHING DEVICE per leg, with no other added parts.
- One Robicon method re-defines "N+1" as including a complete extra cell transformer secondary & SCR bypass switch:
  - ➢ Cell must be intact and control 100% functional to work
  - ➢ Added parts work all the time and decrease drive component MTBF
- Traditionally, increased reliability comes from reducing parts count and conservative design.

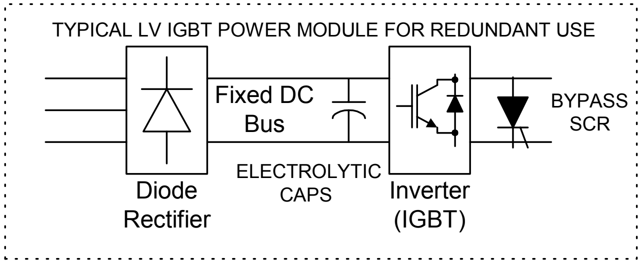


LCI drive

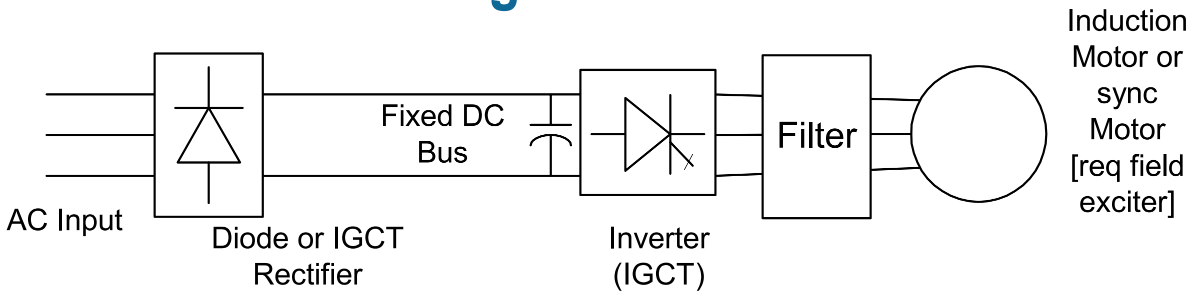
N+1 requires 12 SCR's

LV IGBT MV Drive

N+1 [3 extra power cells] adds
18 diode Rectifiers
12 LV IGBTs, 15 bypass SCRs
42 electrolytic Caps, Firing circuits
+ 3 added transf windings



IGCT PWM Voltage Source Inverter



Energy stored in liquid filled caps

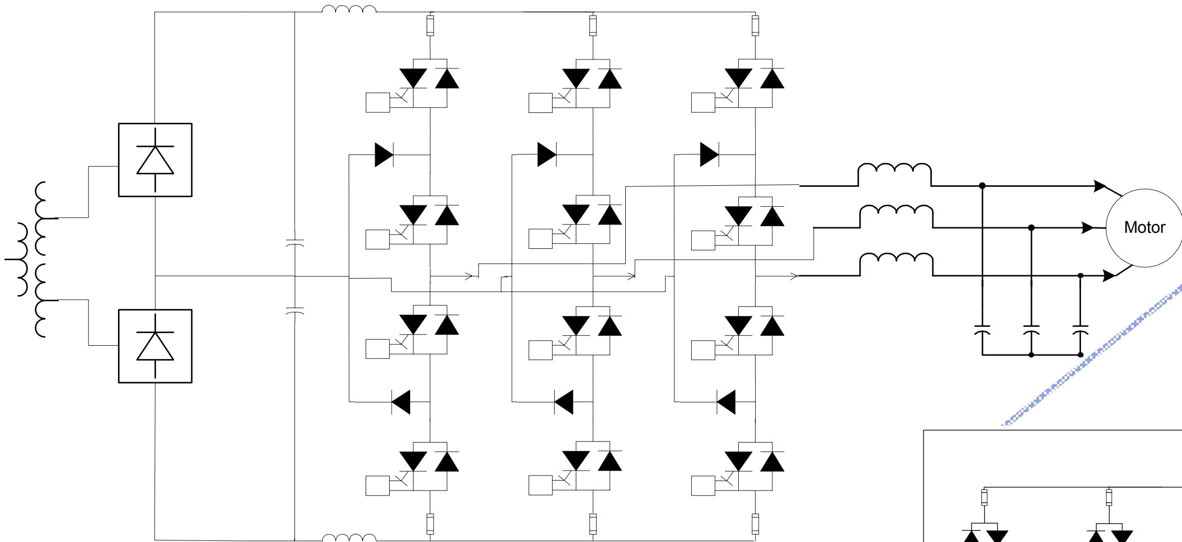
Example: GE-Innovation Series® SP IGCT Mill Drive

Inverter Topology	Major Advantages	Major Limitations	Practical Power Range
IGCT PWM Voltage Source Inverter Three Level	• Low power switch device count for voltage rating • Fast transient response & wide motor frequency range • High starting torque • High power levels with largest IGCT devices • Regen possible with active IGCT converter	• Complex high parts count firing circuit • 3-level output requires output sine filter. • Above 4 kV output requires output filter for low motor current distortion. • Potential for electrical and mechanical resonance between load and filter.	0.5 – 4.8 MVA per inverter, air cooled 4.8 – 9.6 MVA, dual channel

Primarily being offered by: ABB

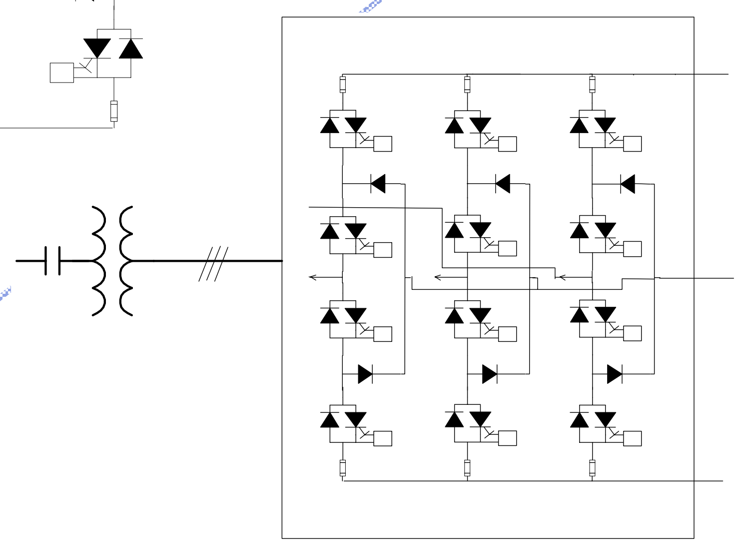
IGCT PWM Voltage Source Inverter

Details & Alternate Configurations



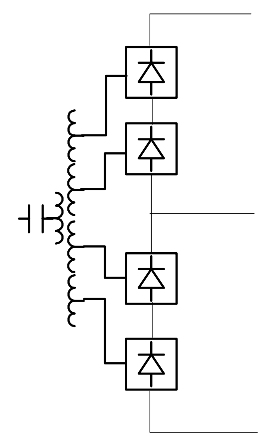
Alternate IGCT converter and 24-pulse diode converter

Typical Entry Level 12 pulse diode converter & IGCT PWM Drive



IGCT Active Converter

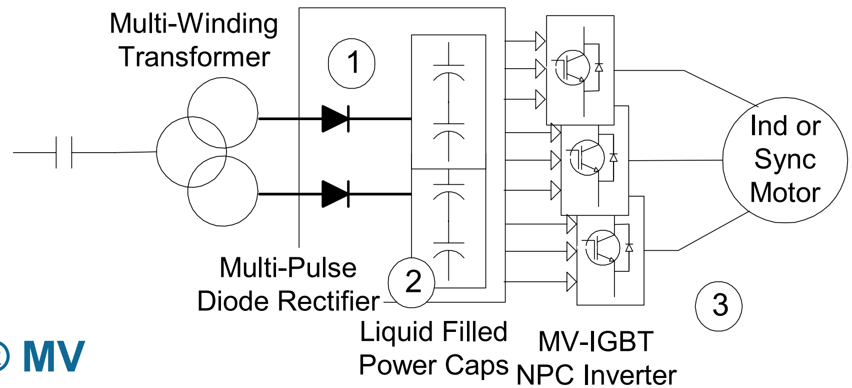
A

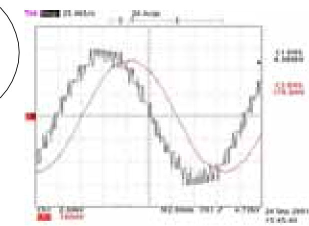


24 Pulse Diode Converter

B

MV IGBT NPC Voltage Source Drive



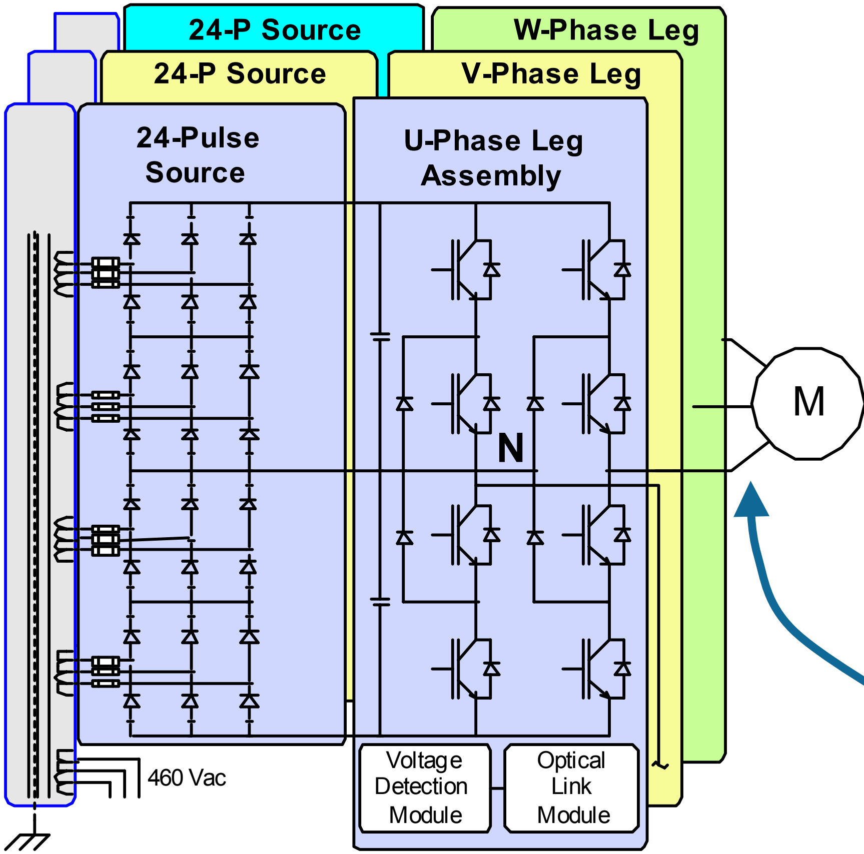


Example: GE-Toshiba Dura-Bilt5i® MV

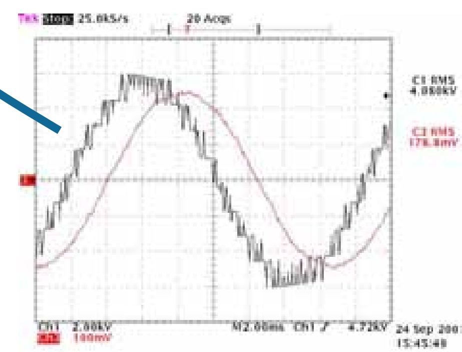
Inverter Topology	Major Advantages	Major Limitations	Practical Power Range
Three / Five Level Voltage Source MV IGBT PWM Inverter MV IGBT = Medium-Voltage Insulated Gate Bipolar Transistor	• Minimum parts count for voltage rating & waveform • Simple firing circuit. • High efficiency • Low motor current THD • Fast transient response • Wide motor frequency range • No significant torque pulsations • High starting torque. • Multi pulse converter for very low AC line harmonics • High true pf over all speeds	• No regeneration available • Fast rise time IGBT switching may require dv/dt output filter in some cases • Power Device redundancy not practical	0.5 – 4.8 MVA per inverter, air cooled 4.8 – 9.6 MVA, dual channel Sync or Induction Motors

Primarily being offered by: GE-Toshiba, Siemens

MV IGBT NPC Voltage Source Drive Details

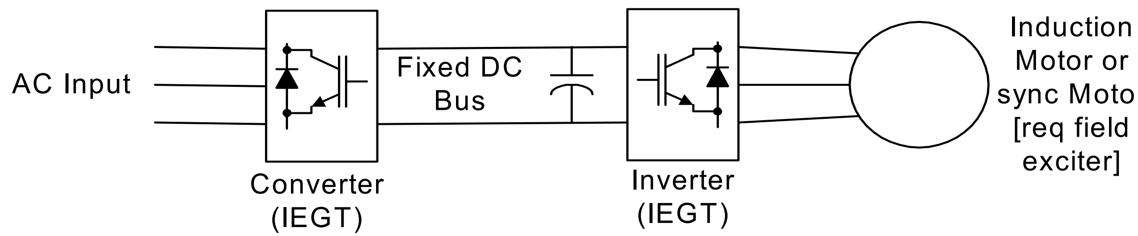


- Neutral Point Clamped [NPC] reduces voltage to ground
- 5 / 9 level waveform < 3% motor current distortion
- 24 pulse diode converter <2% line current distortion, better than IEEE 519 limits



Example 5/9 level motor voltage & current waveforms

IEGT PWM Voltage Source Inverter



Example: GE-Toshiba 8 MW T650 IEGT drive with active IEGT Source

Energy stored in liquid filled caps

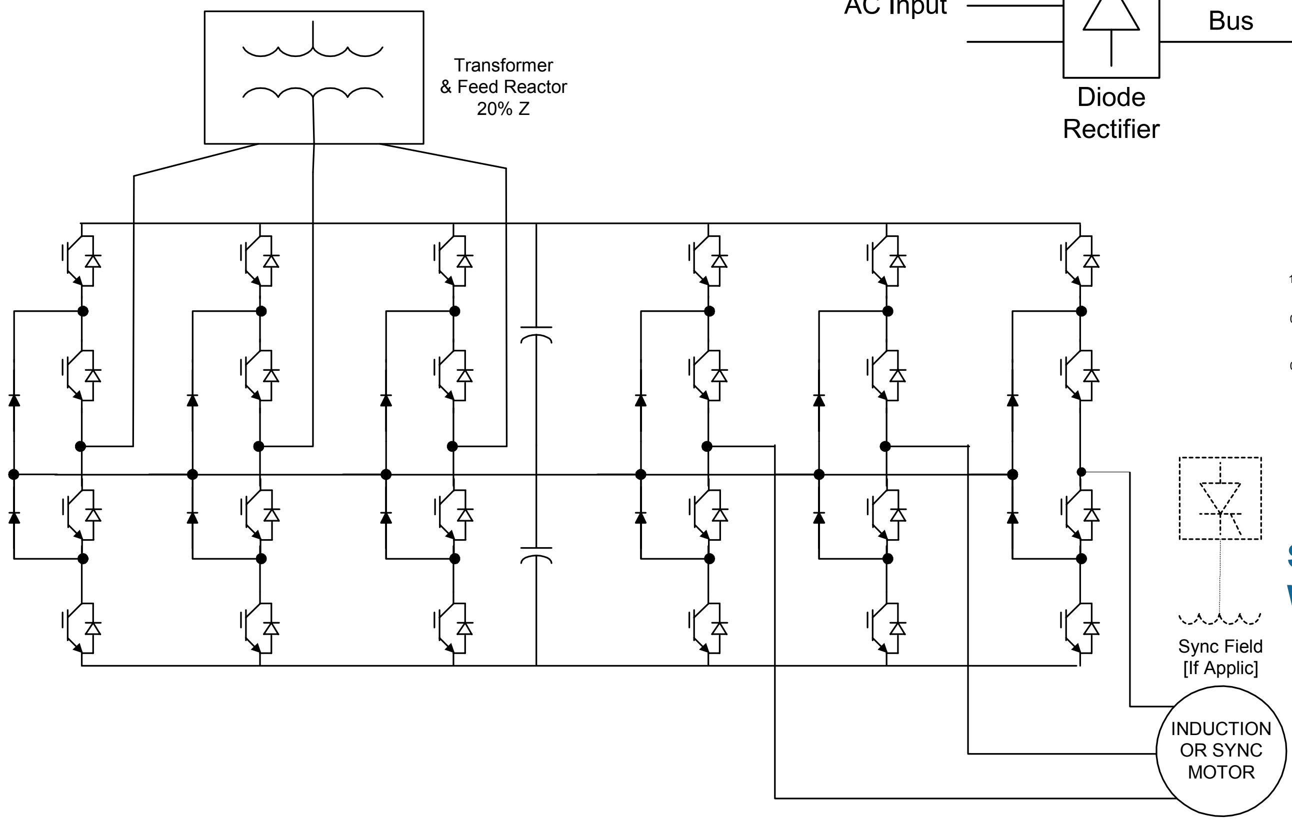
Inverter Topology	Major Advantages	Major Limitations	Practical Power Range
Three Level Voltage Source IEGT PWM Inverter IEGT = Injection Enhanced Gate Transistor	• Minimum power device count – 24 for complete 8 mw regen system • Simple firing circuit [4:1 more reliable than IGCT] and very high system MTBF. • Low motor current THD • Fast transient response & wide motor frequency range • High starting torque with no significant torque pulsations • Active front end for low harmonics, regeneration, unity or leading PF	• IEGT device limits allow 3300 volt motor output [European and Asian Standard] • 3300 volts is not as common as 4160 volts in North American applications.	6 to 26 MW, water cooled, one or two channel At 3300 volts Sync or Induction Motor

Primarily being offered by: GE-Toshiba

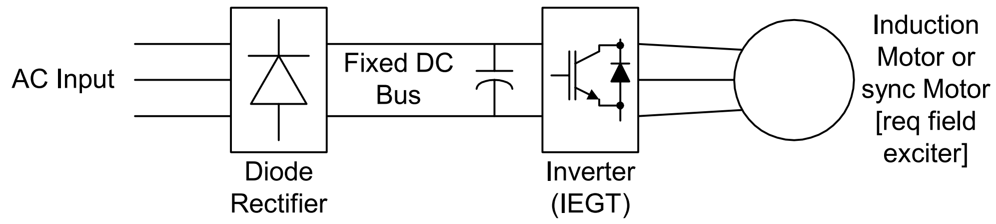
IEGT PWM Voltage Source Inverter & Active Converter

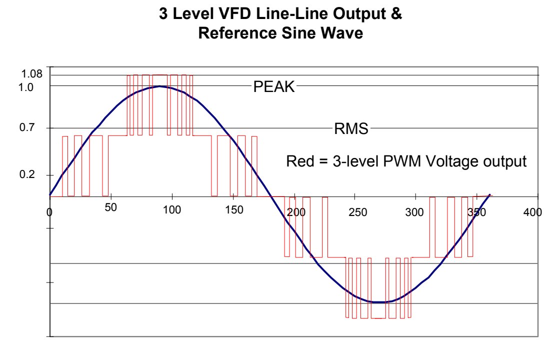
Circuit Details & Alternate Diode Converter Configuration

8 MW IEGT Inverter with active regen-capable source



IEGT PWM Voltage Source Inverter with Diode Converter





Simulated Inverter Voltage Waveforms of 3 / 5 level NPC PWM

Global Office Locations:

GE Toshiba Automation Systems, USA
1501 Roanoke Blvd.
Salem VA, 24153 USA
TEL: +1-540-387-5741; FAX: +1-540-387-7060
www.getoshiba.com

Toshiba GE Automation Systems
Mita 43 Mori Bldg.
13-16 Mita 3 chome, Minato-ku Tokyo
108-0073 Japan
TEL: +81-3-5444-3828; FAX: +81-3-5444-3820
www.toshiba-ge.co.jp