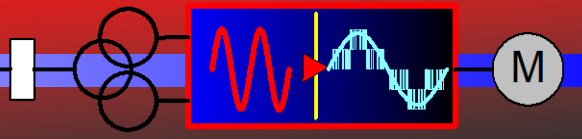
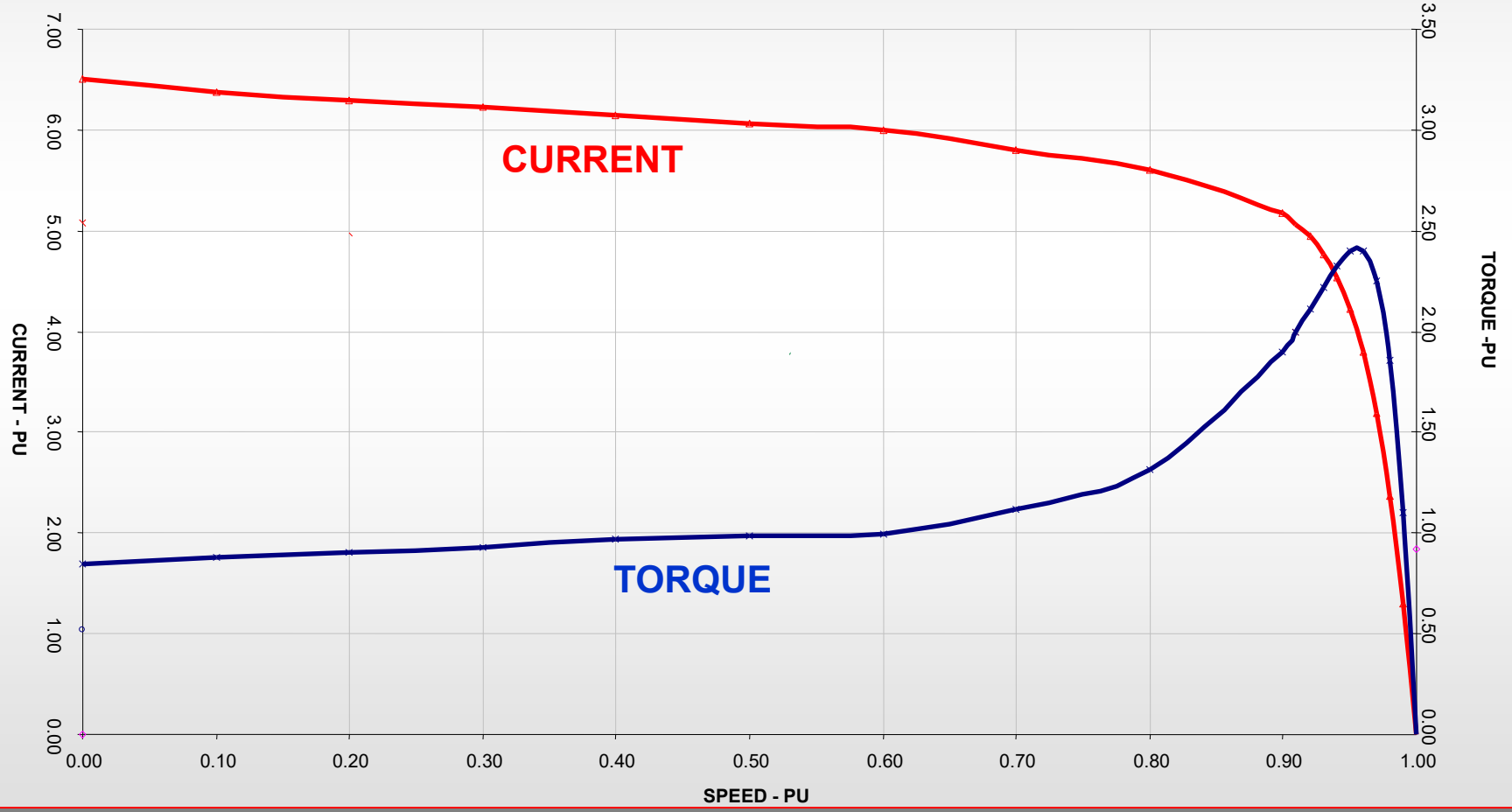


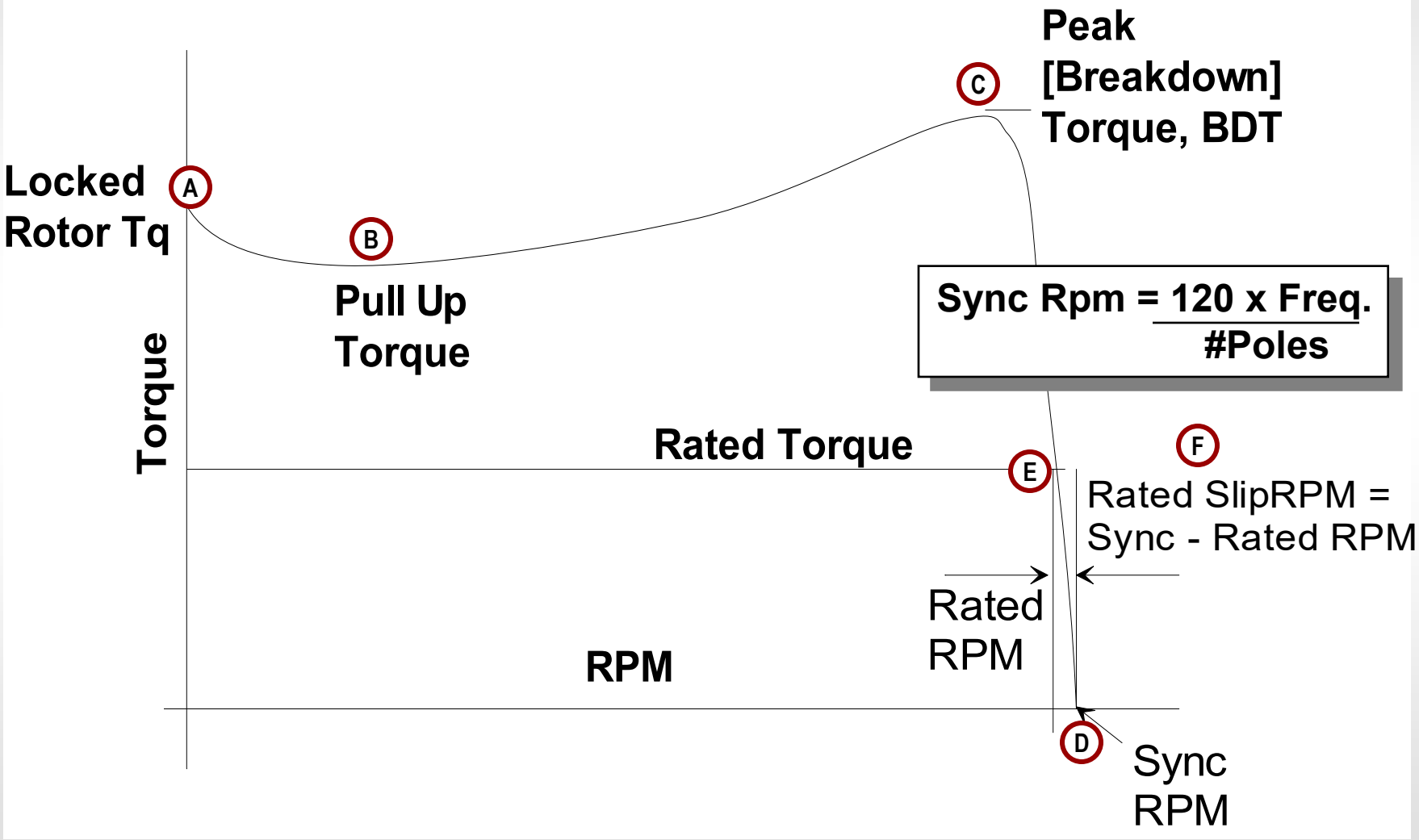
ASD Fundamentals & MV Drive Evolution

INDUCTION MOTOR STARTING CHARACTERISTICS

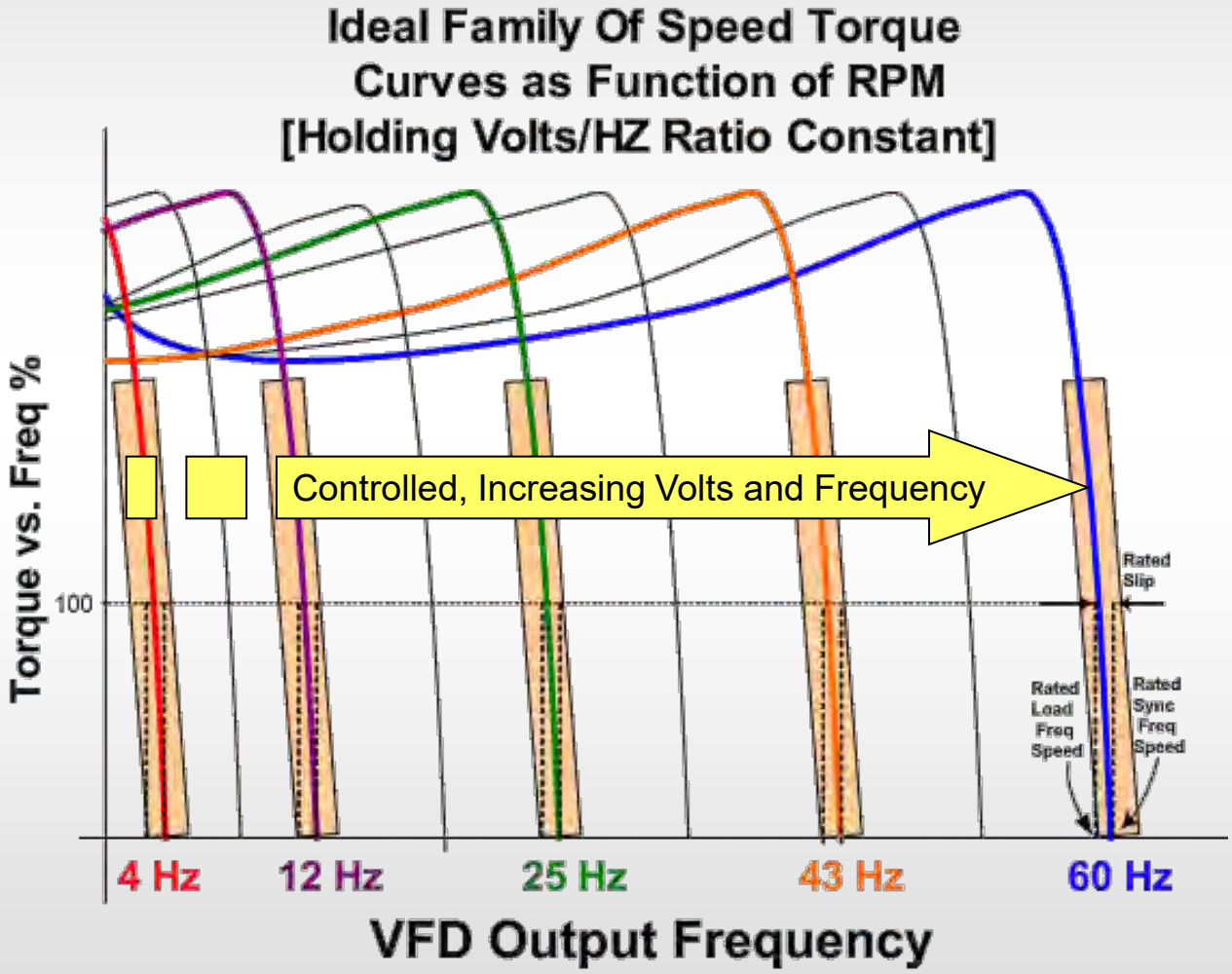
Current and Torque vs. Speed

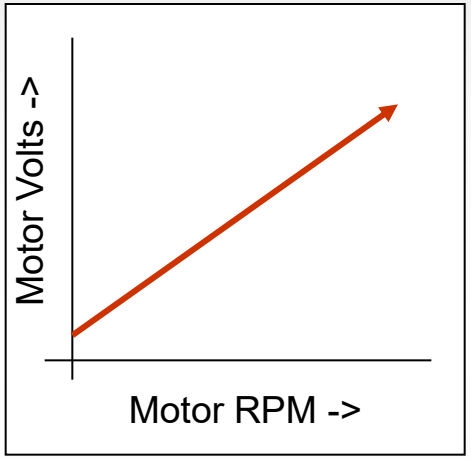


Induction Motor Speed-Torque Profile



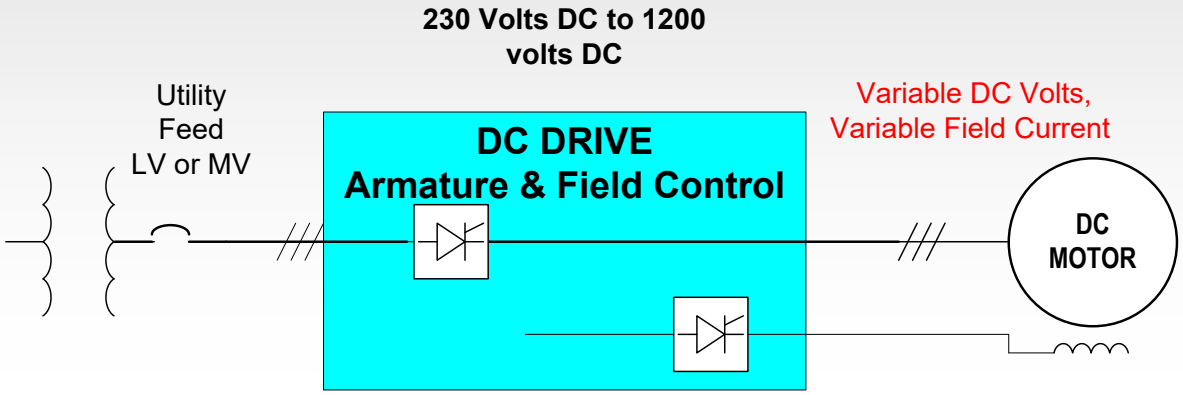
AC Drives Accelerate Load by Increasing Volts and Frequency



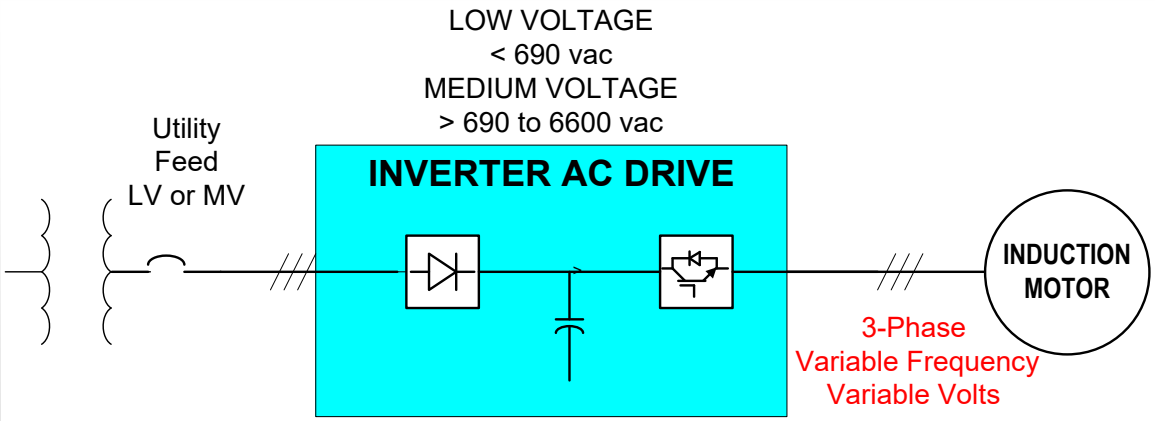


Operational torque must be regulated to remain in the shaded near- linear zones.

Control of DC & AC motors



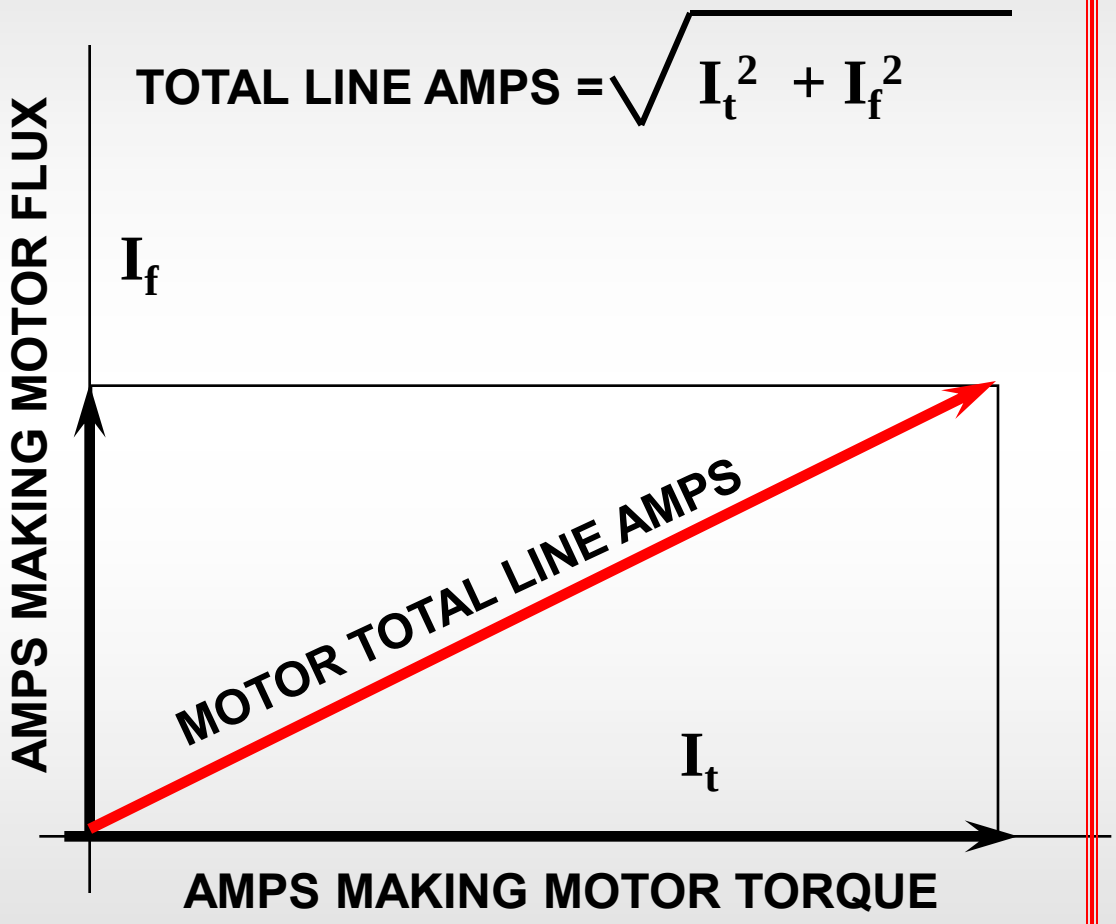
DC Drive



AC Inverter Drive

Rectifiers and inverter power devices change with drive type and configuration

Scalar vs. Vector Control



Scalar Control

Measures only total line amps and regulates V/Hz ratio.

Torque Vector

[tachless]
can determine and control torque producing amps.

Flux Vector

can determine and control both flux and torque producing amps

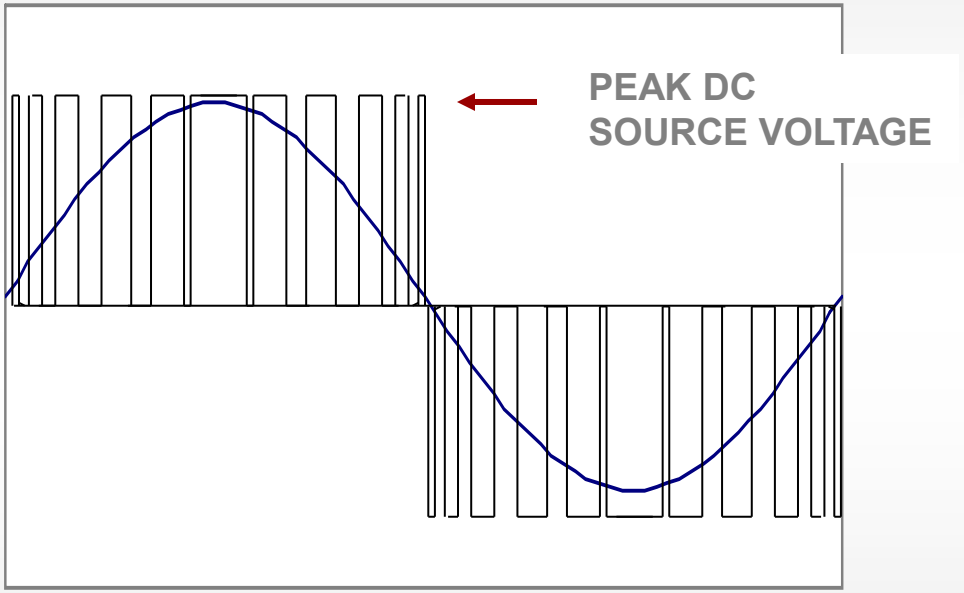
Pulse-Width-Modulated [PWM] Wave Form

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

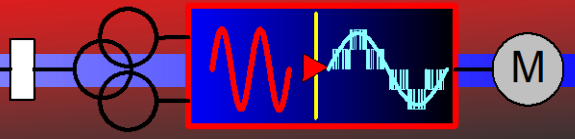
The Motor tends to smooth the voltage wave

Present designs use IGBT devices to produce smooth current waves.

IGBT devices switch at rates up to 20K Hz.



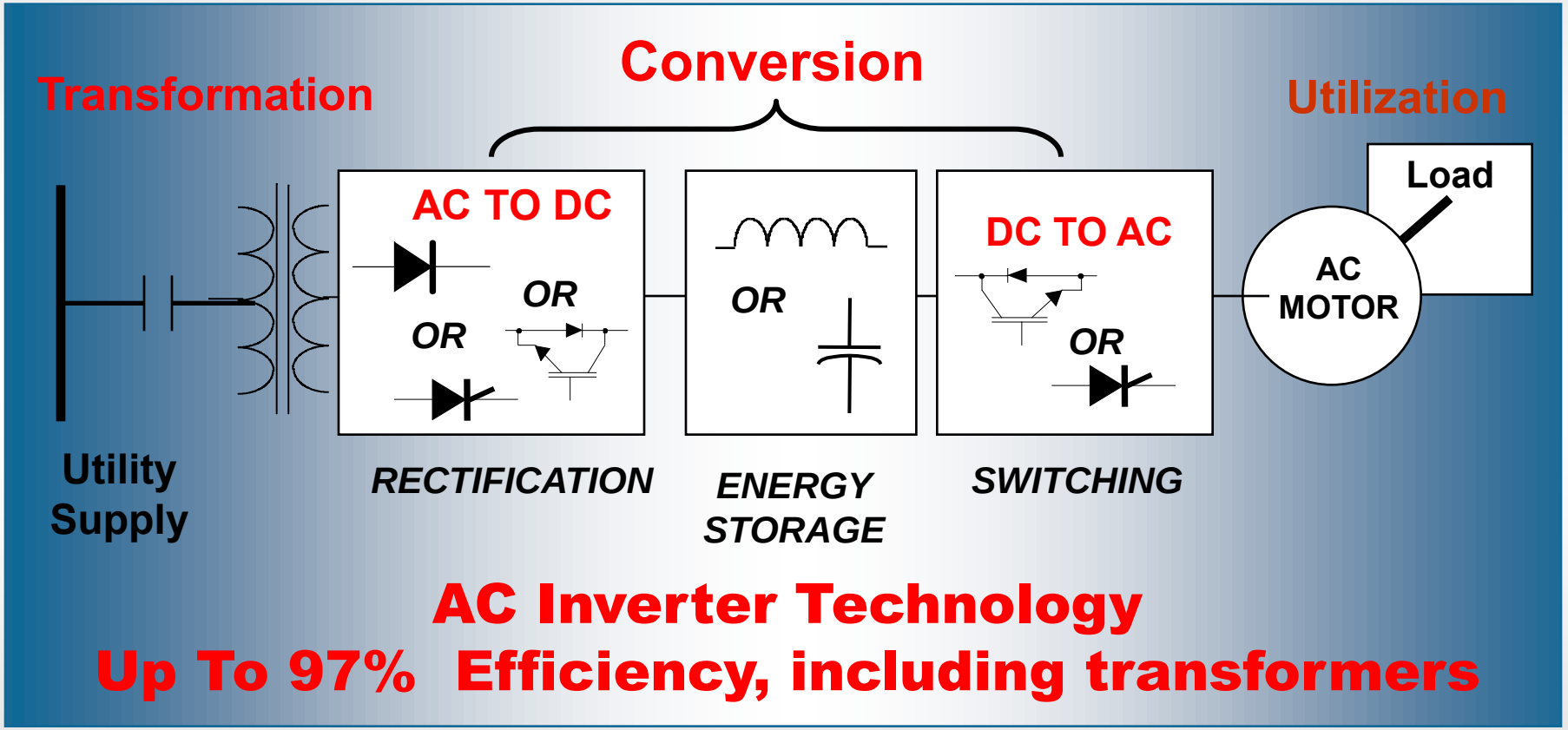
EXAMPLE SIMULATED SINE WAVE PRODUCED BY 2-LEVEL PWM INVERTER



MV Drive Development Past to present

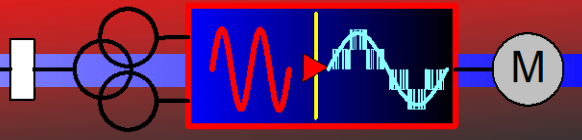
MV Drive Evolution

Typical AC Inverter System



AC Inverter Technology

Up To 97% Efficiency, including transformers



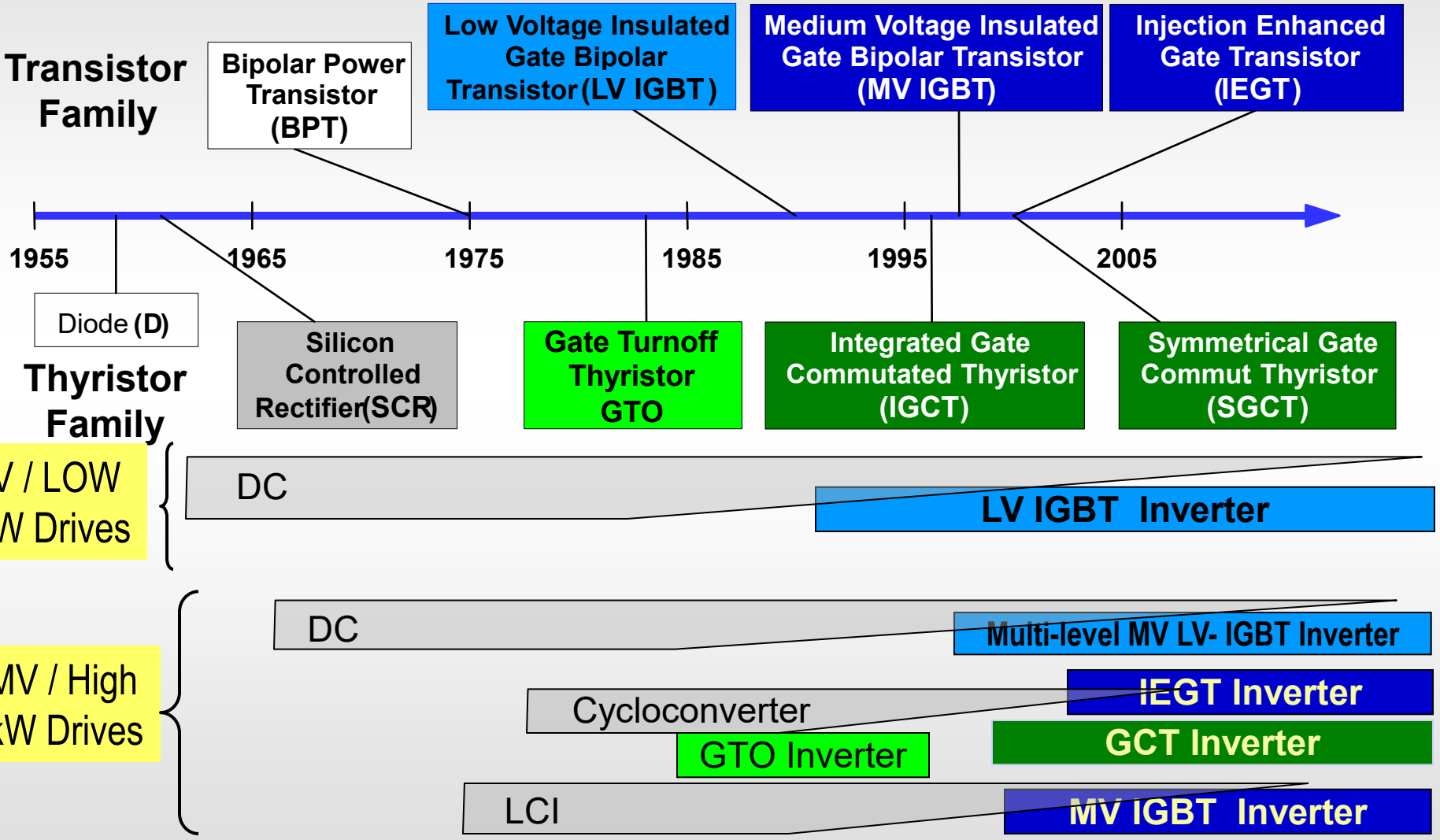
AC Drive Topology:

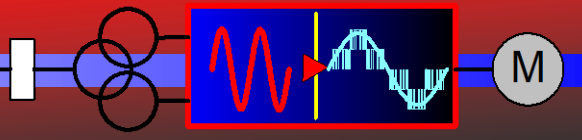
A map-like diagram showing the elements of an AC drive and the relationships between them.

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.

Time Line of Power Semiconductors & Drives

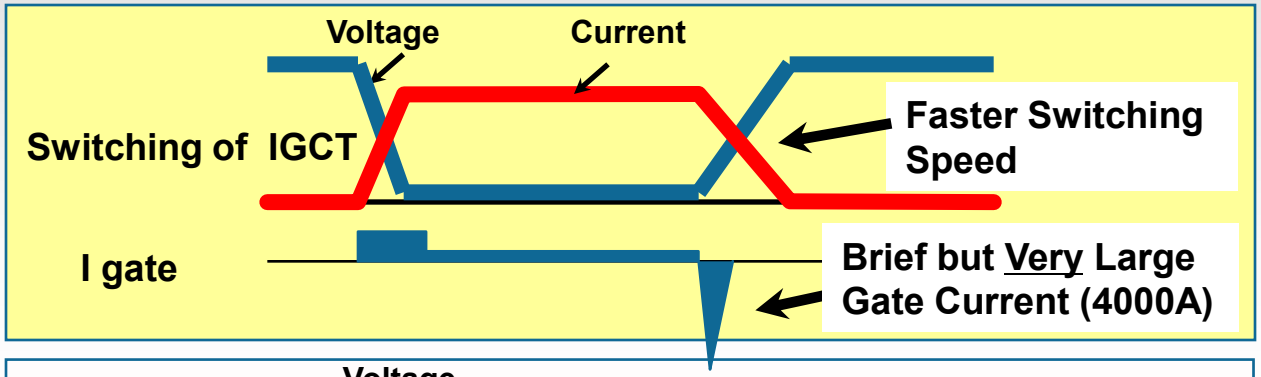




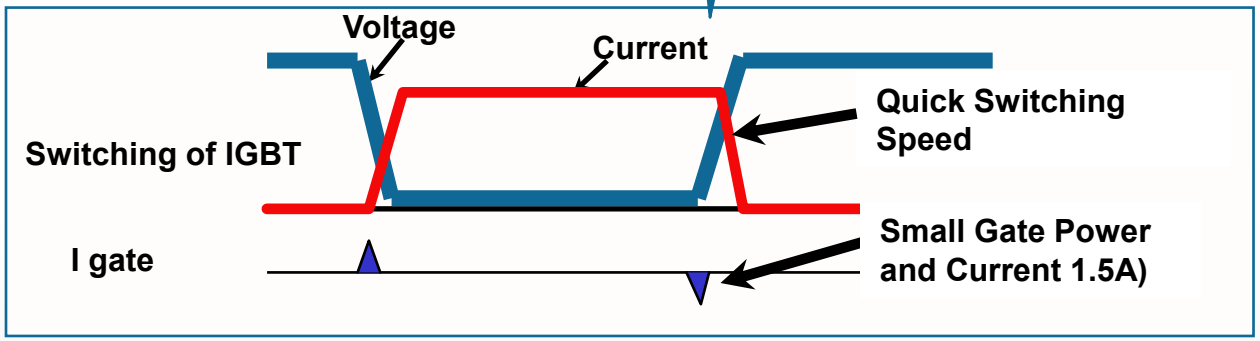
Comparison Areas for Drive Power Switching Devices

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

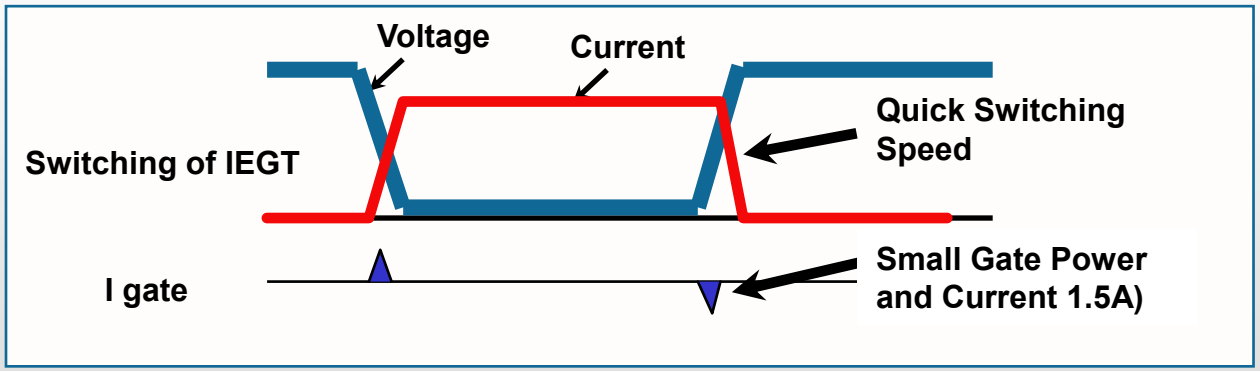
Comparing Gate Power of Devices



Current Switched GCT Device



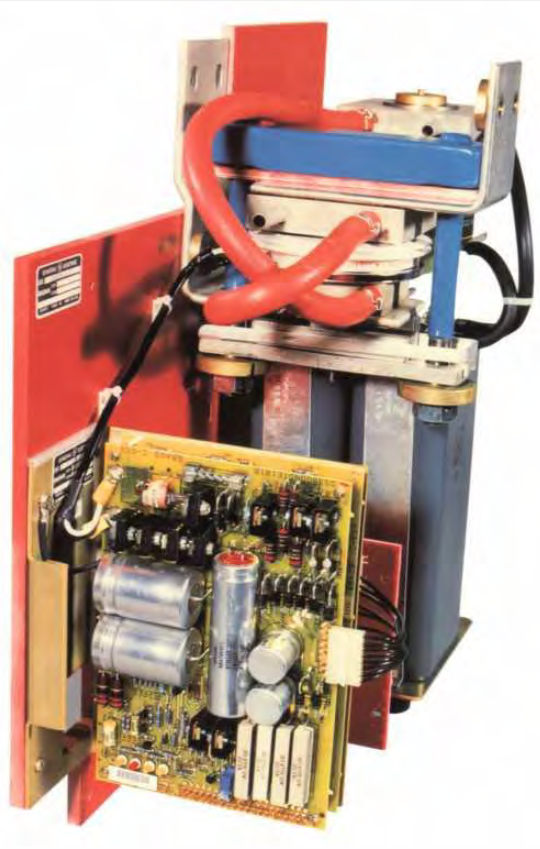
Voltage Switched MV IGBT Device



Voltage Switched MV IEGT Device

GTO Gate Driver & Cell Stack Equipment

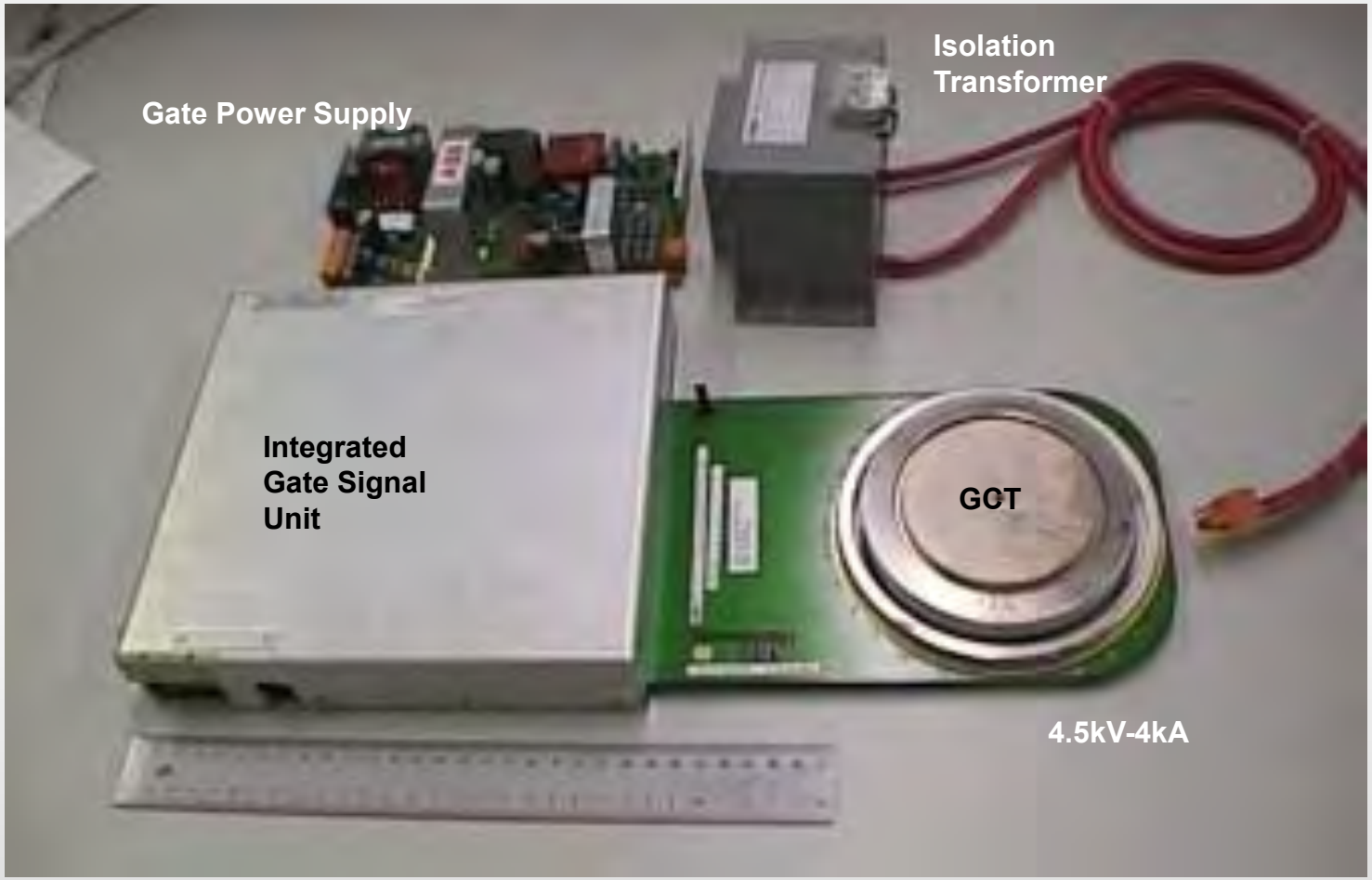
GE GTO-IMD Example



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

GCT Gate Driver Equipment

Earlier Design, Covers on



Early Standard GCT & Gate Driver Boards

Earlier Design, Covers off

4.5kV-4kA

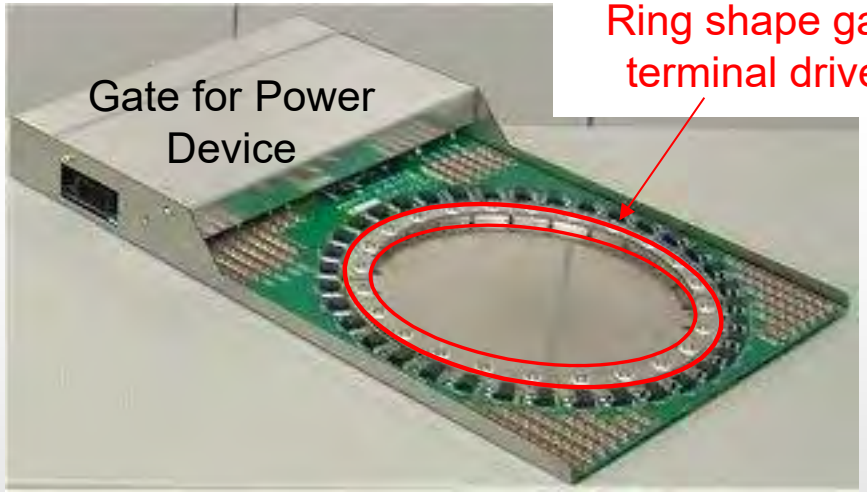
4.5kV-800 A

36 Electrolytic caps
21 FET Switches

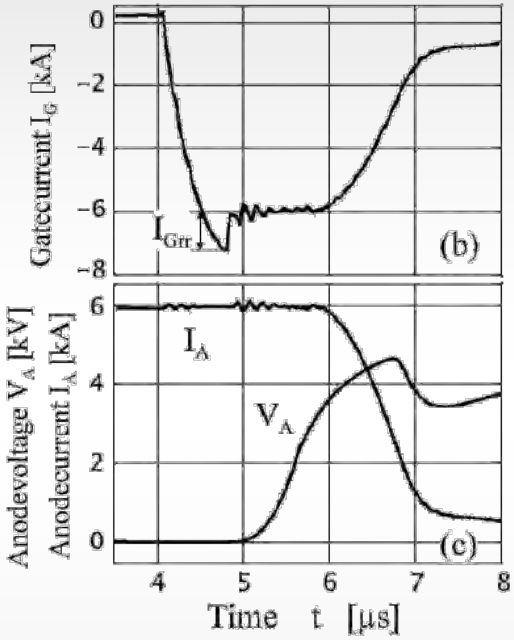
High Reliability GCT Device & Firing Control

Latest TMEIC Design

GCT power device with newly developed ring shape gate terminal



Newly Developed GDU Model



New design IGCT with 1:1 gate current to anode shutoff ratio vs 5:1with old design.

BOTTOM LINE: fewer gate firing devices, higher reliability!

Typical IGBT & IGBT Gate Driver Circuit

IGBT

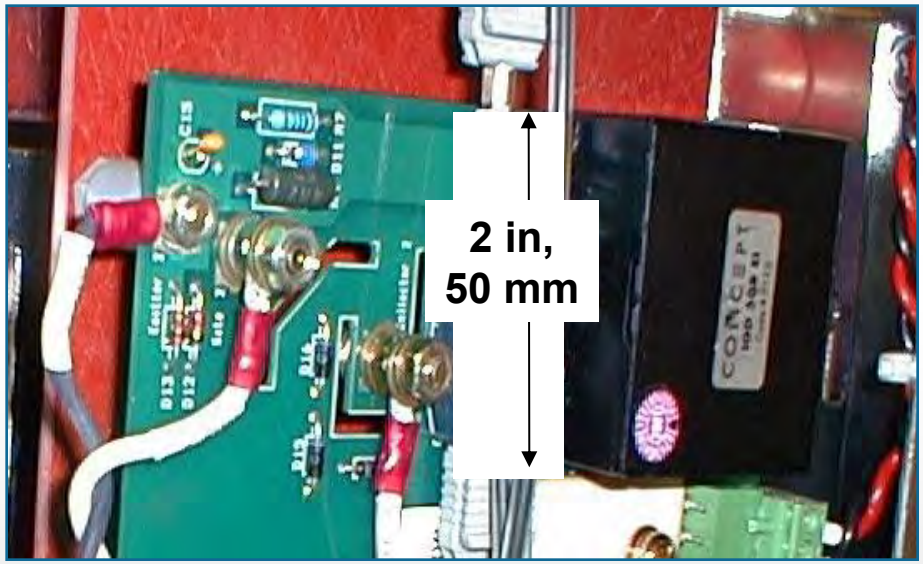
400 amp 3300 volt dual package
Larger ratings have 1/package

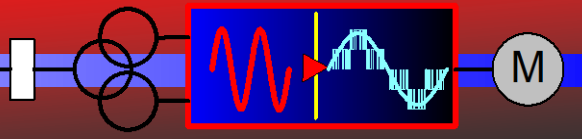
Approximate Size:

4 inches x 4.5 inches

Typical MV IGBT Dual Gate Driver

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

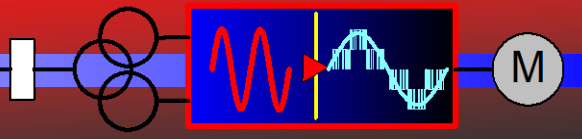




IEGT – Latest Generation Voltage Switched Power Device

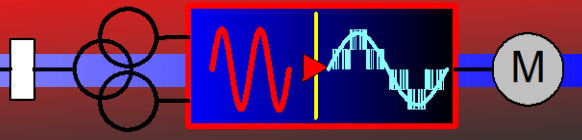
- IEGT = Injection Enhanced Gate Transistor
- Ratings to 4500 volts, 4000 amps
- Press pack or single sided
- Lower forward drop than IGBT, meaning higher power density, more efficiency.

IEGT Voltage Controlled Gate Driver Equipment



Gate Circuit Summary

- Control of switched power devices has come a long way:
  - Fewer, smaller parts
  - Reliability improved
- Fewer parts and strict quality control have resulted in highly reliable systems.



Power Device Losses

Generally

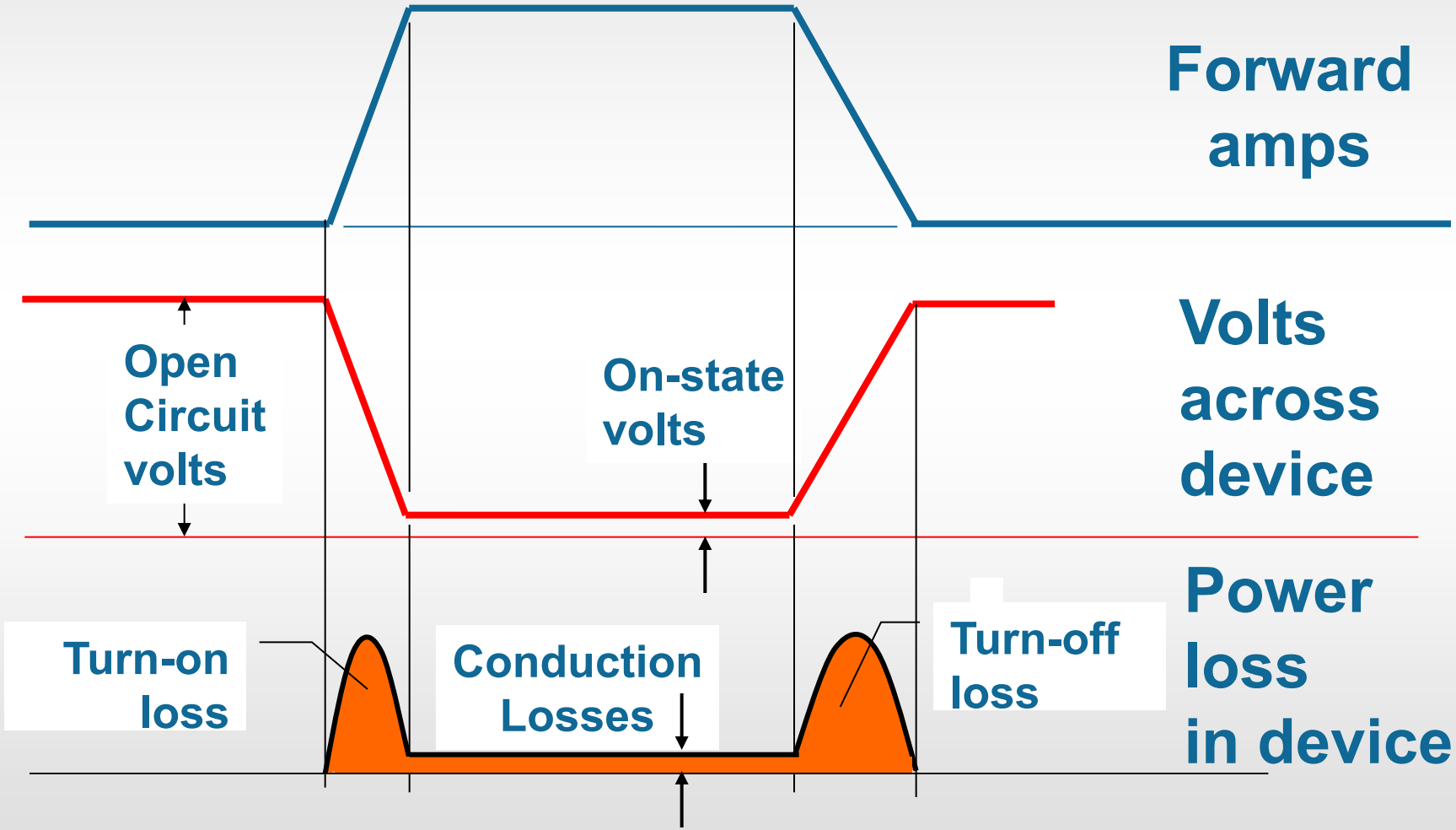
Volts across device X Current Through Device = Power Lost in Device

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



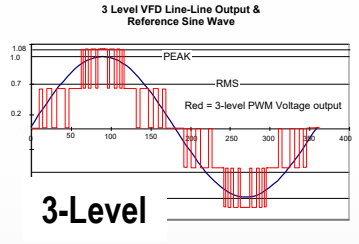
Power Switch Voltage and Current Ratings

Continuous current ratings
Forward & reverse blocking voltage

AFFECTS

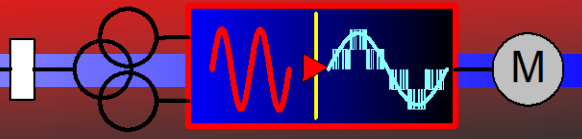
Number of power devices, & potential system reliability

Device Rating	Design Impact	Consequence	Comments
Higher Operating Voltage	Fewer Devices for given output	Fewer steps in output wave	Above 3300 volts, sine filter required for 3 step output
Higher Operating Current	Fewer Devices / No paralleling needed	Power density requires good heat exchange	Highest power drives are liquid cooled



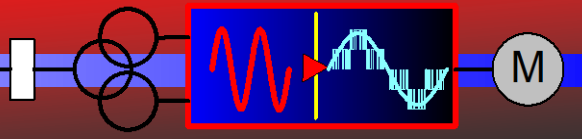
3-Level


5-Level



Drive Topologies: So What?

- For drives with lots more parts, they must be very conservatively applied if reliability is to be achieved.
- Inherent design characteristics should be carefully considered when selecting.
- In-service reliability is the best indicator of real reliability.



Comparing Drives with All Topologies

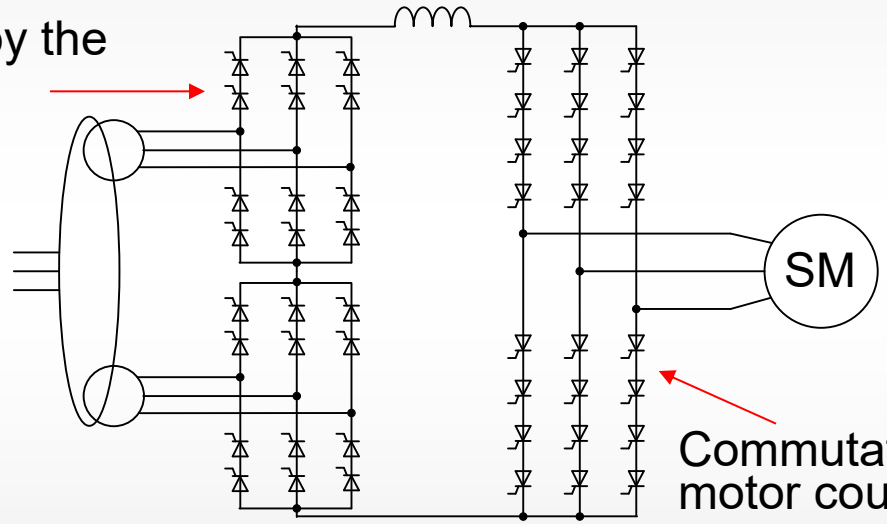
- Current Source Drives
  - LCI – Load Commutated Inverter
  - GTO/SGCT Current Source Induction Motor Drive
- Voltage Source Drives
  - LV IGBT “Paice” Multilevel PWM
  - MV IGCT PWM – Diode or Active Source
  - MV IGBT PWM – Integrated package
  - MV IEGT PWM – Active or Diode Source

LCI: Load Commutated Inverter

Earliest MV Drives [LCI and Cycloconverter] with thyristors

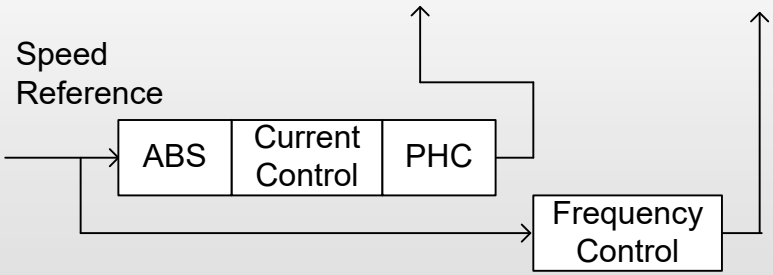
Commutation is done by the Input power voltage

-- Lower power factor



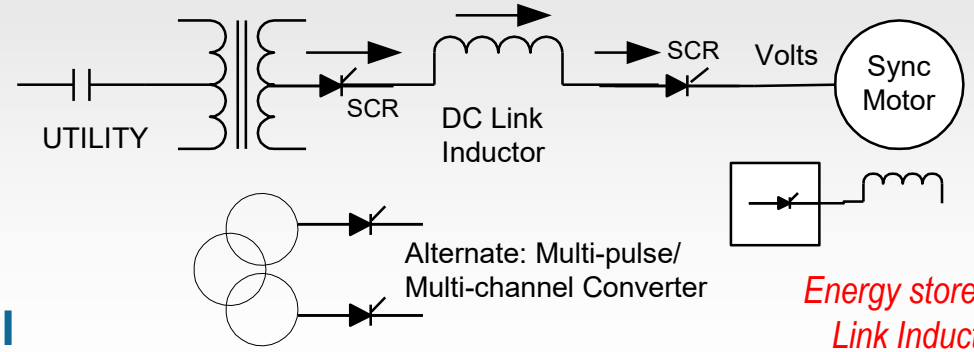
Commutation is done by the motor counter voltage

Limited output frequency range



LCI –Load Commutated Inverter [Current Source]

Example: GE-Innovation Series® LCI



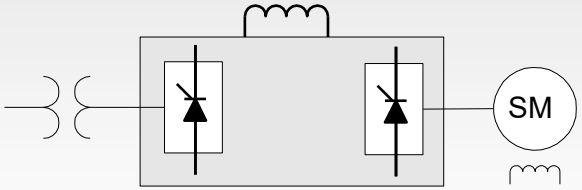
Energy stored in Link Inductor

Inverter Topology	Advantages	Limitations	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 • 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

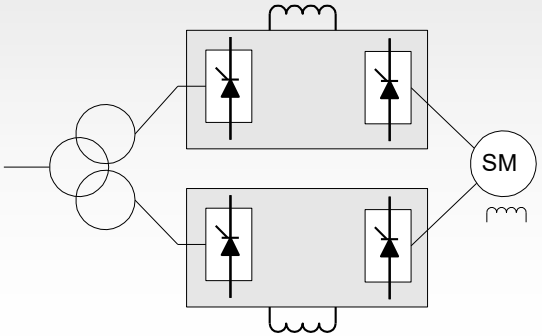
Currently offered by: TM GE, ABB, Siemens

We drive industry

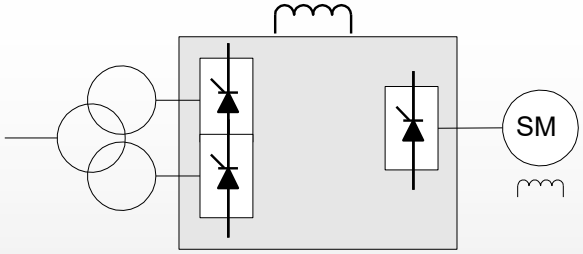
Alternate LCI Configurations



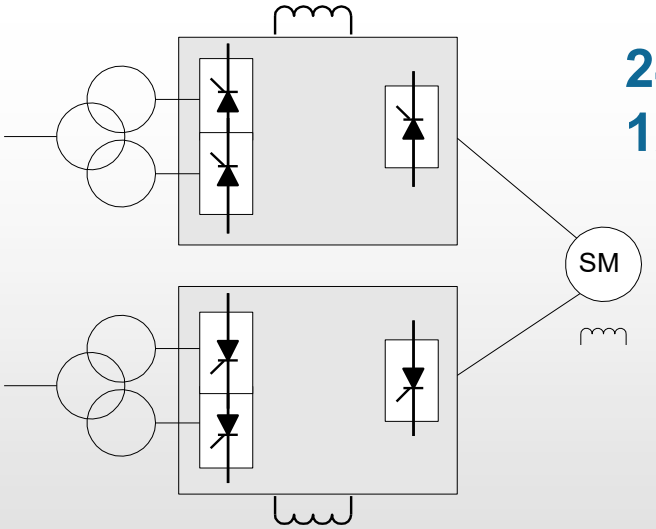
6-Pulse input
6-Pulse output



12-Pulse input
12-Pulse output



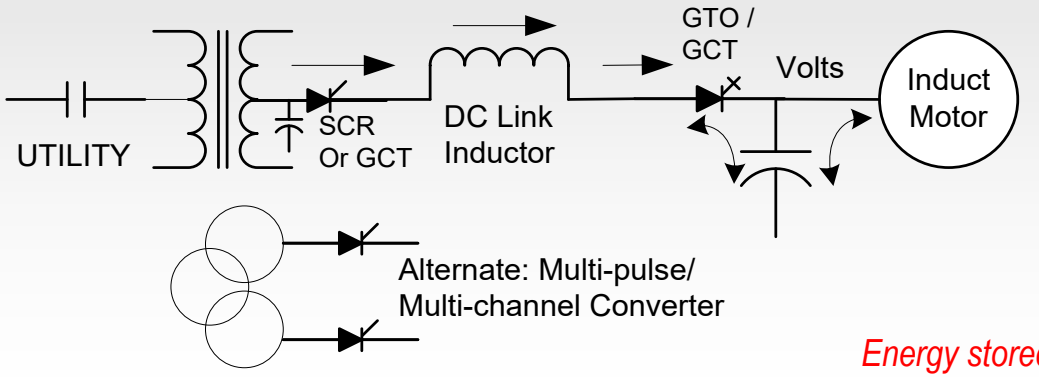
12-Pulse input
6-Pulse output



24-Pulse input
12-Pulse output

Current Source GTO / SGCT Induction Motor Drive

Example: 1980 – 1995 GE-GTO Induction Motor Drive

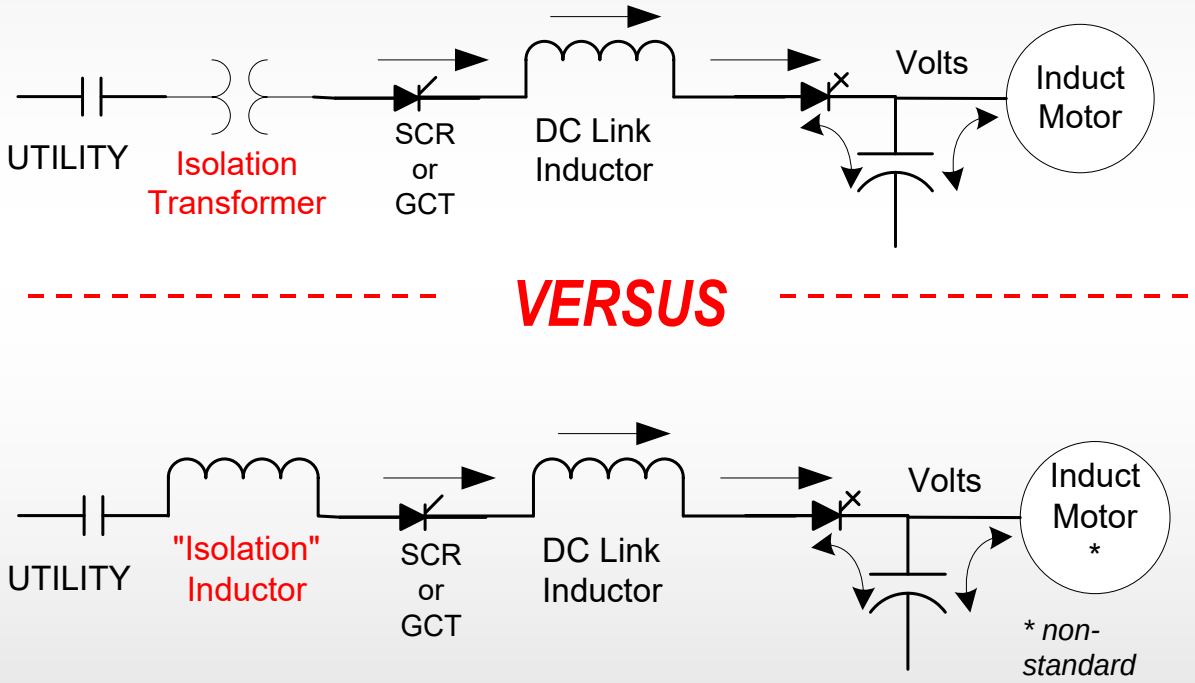


Energy stored in Link Inductor

Inverter Topology	Advantages	Limitations	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 • Potential resonance between motor & caps • Complex firing circuit • Potential for self excitation on overhauling load • PWM source filter can induce system resonance	2 - 15 MW Primarily induction motor load ***Currently offered by:*** ***Allen Bradley***

Current Source SGCT Induction Motor Drive

"Isolation" Reactor vs Isolation Transformer

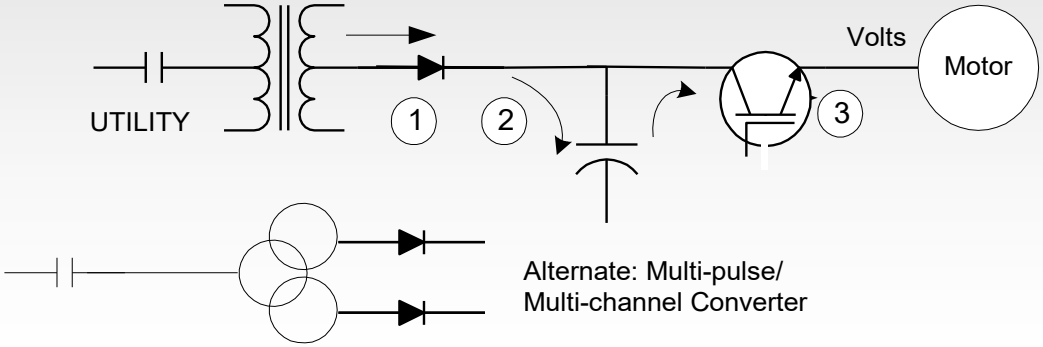


- Easy on Motor ground Insulation
- Drive Ground faults do not affect other equipment & vice versa.

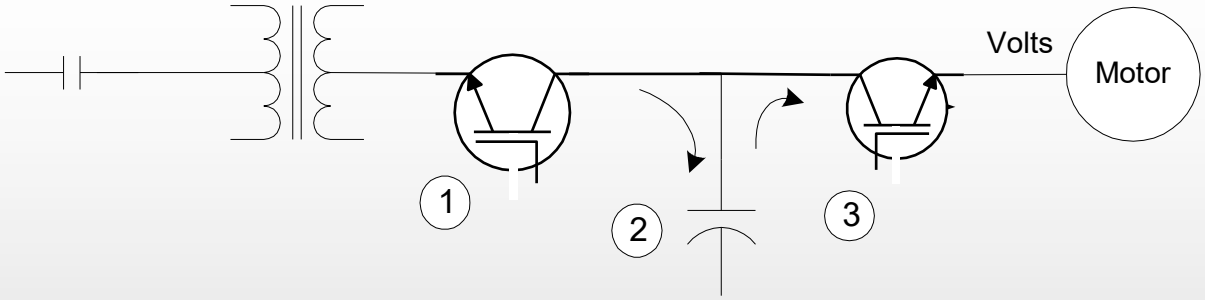
- Potentially tough on motor ground Insulation
- Drive Ground faults do affect other equipment & vice versa.
- Cheaper
- Smaller

Voltage Source General Drive Arrangements

Diode Rectifier Converter Fed



Active Rectifier Converter Fed



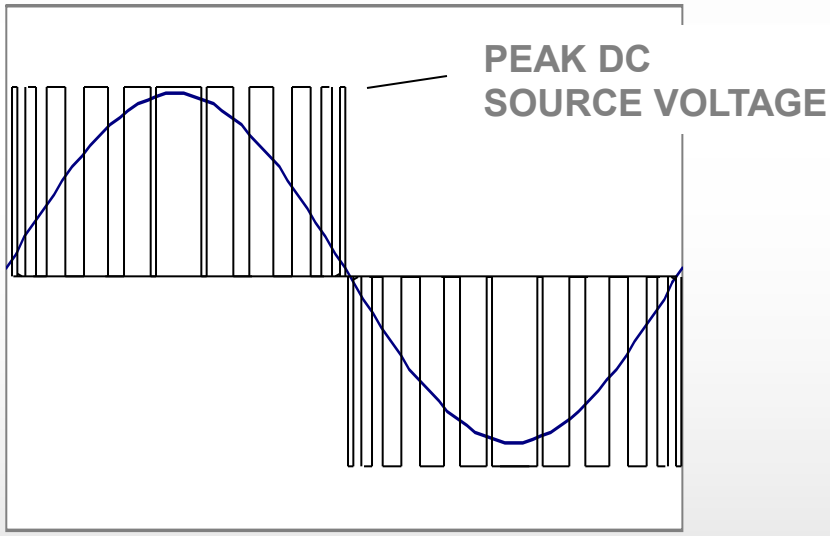
PWM: Pulse Width Modulation

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

Example Pulse-Width-Modulated [PWM] Waveform

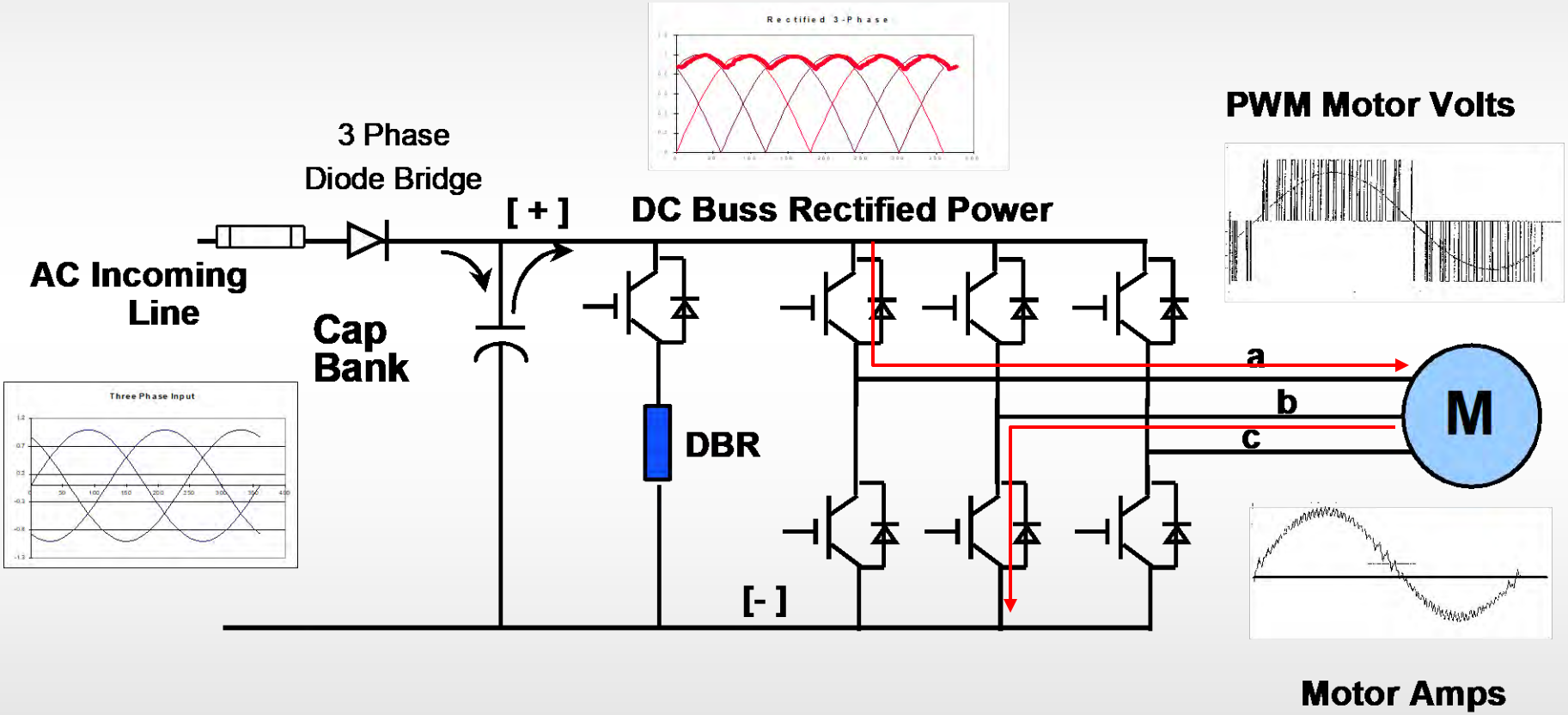
Voltage: The Average of the time the Voltage is on Plus the time the Voltage is Off.

Current: The Motor tends to smooth the resulting current



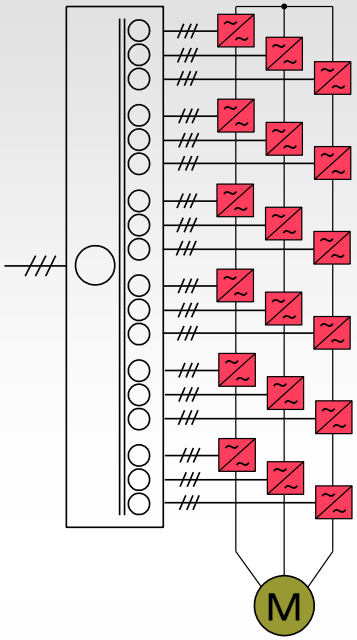
EXAMPLE SIMULATED SINE WAVE PRODUCED BY 2-LEVEL PWM INVERTER

Example Two-Level Voltage Source Inverter

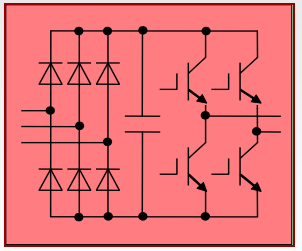


LV IGBT Multi-level Voltage Source PWM Inverter

Example:
TMEIC
TMdrive-MV-G



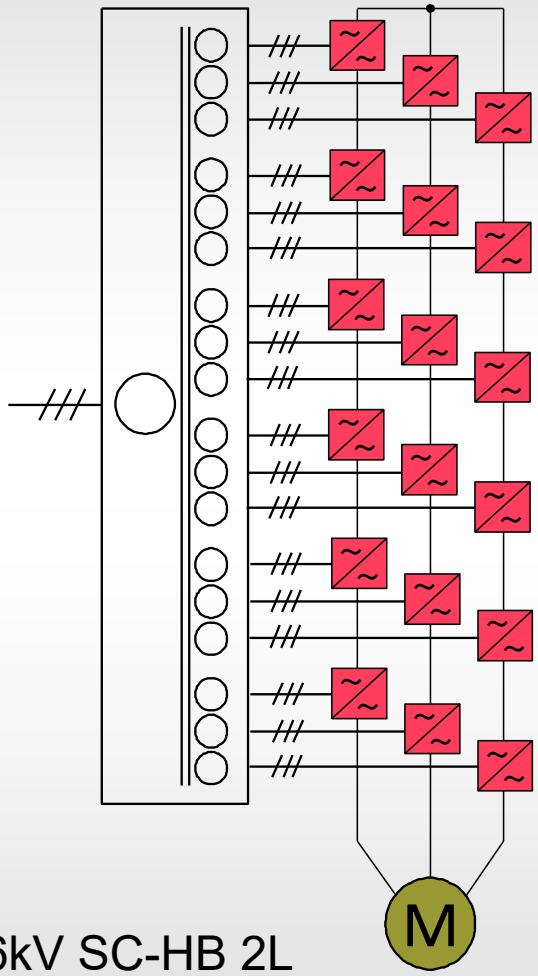
Typical Power Cell



Energy stored in electrolytic caps

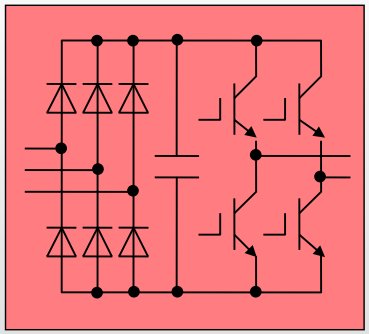
Inverter Topology	Major Advantages	Major Limitations	Practical Power Range
Multi-level Voltage Source LV IGBT PWM Inverter LV IGBT = Low-voltage Insulated Gate Bipolar Transistor	• Power Cell N+1 redundancy available • Low motor current THD • Fast transient response • Wide motor frequency range • No 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 - 12 MW 3300 volts to 13500 volts output Sync or Induction motor

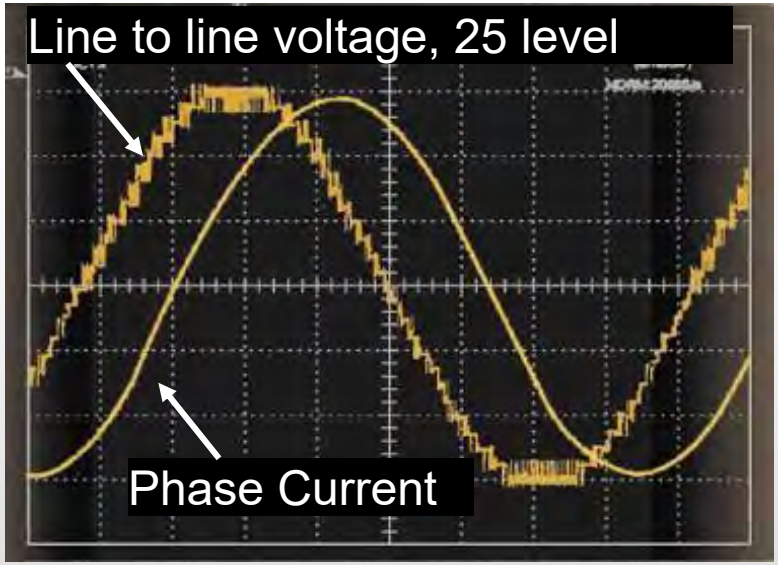
Multi-Level Medium Voltage Inverter



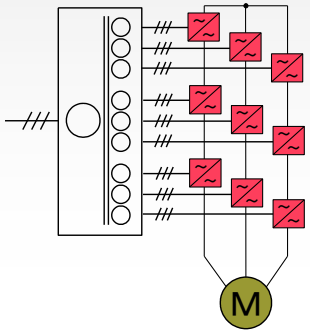
6.6kV SC-HB 2L

- Circuit: SC-HB 2L (Series Conn., H-Bridge, 2-Level)
- Multi-winding transformer
- Typical output AC voltage: 3kV, 6kV, 11kV
- Series connection of Low Voltage IGBT Inverters
- Connected in 3-phase star connection
- Very clean waveform



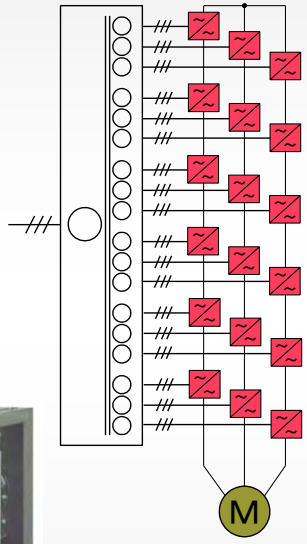


< 3.3kV >
7 Level



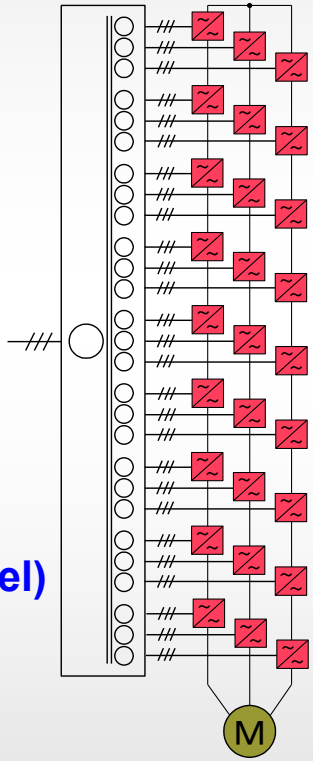
(Line to line 13 level)

< 6.6kV >
13 Level



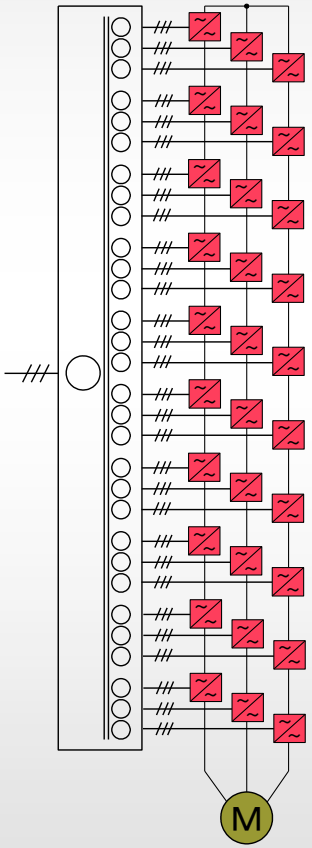
(Line to line 25 level)

< 10kV >
19 Level

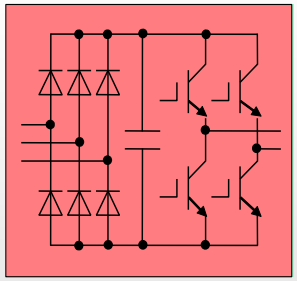


(Line to line 37 level)

< 11kV >
21 Level



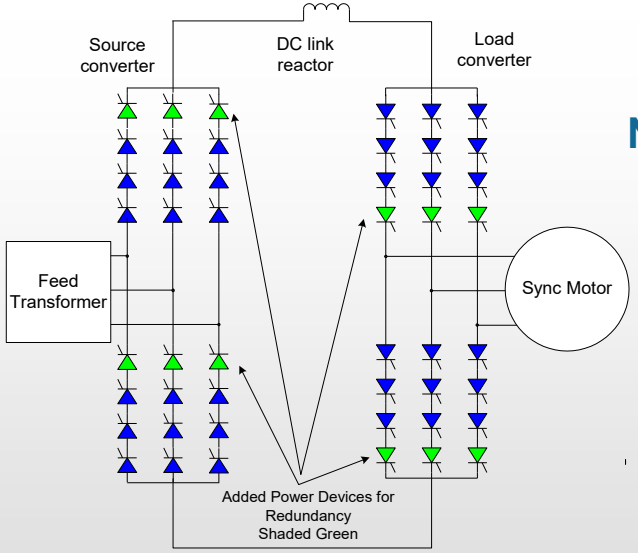
(Line to line 41 level)



Cell Inverter
(Single Phase Output Inverter)

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 [example: TMEIC TM-MVG has 12 year fleet MTBF]

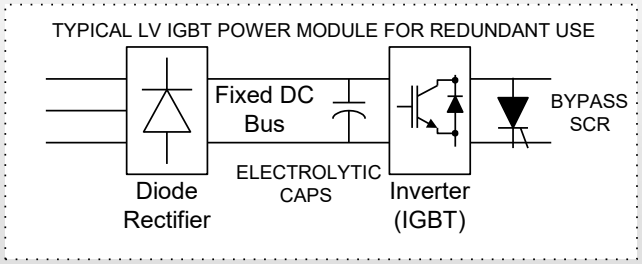


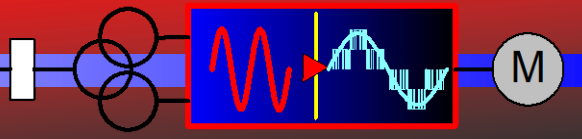
LCI drive

N+1 requires
12 SCR's

LV IGBT MV Drive

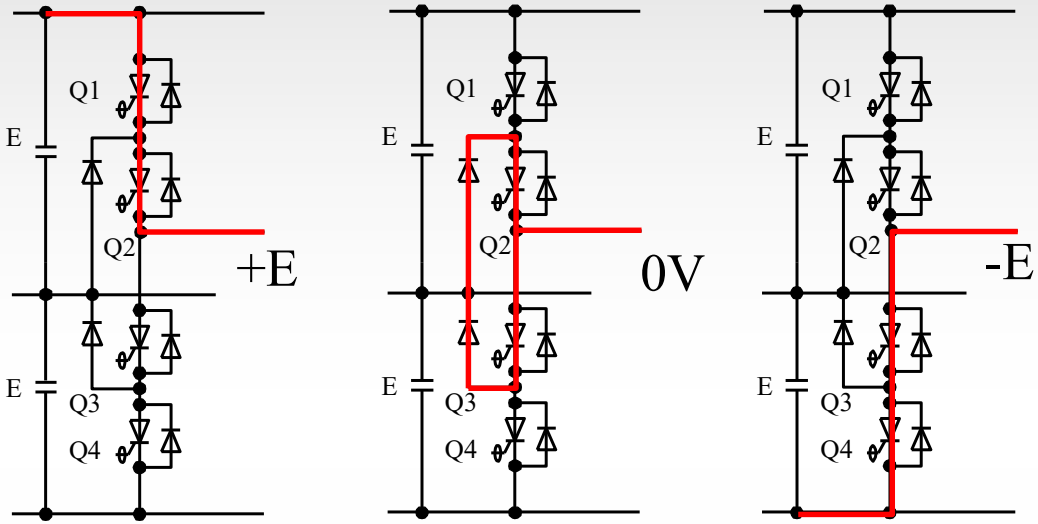
N+1 [3 extra power cells] adds
18 diode Rectifiers
12 LV IGBTs, 15 bypass SCRs
42 electrolytic Caps, Firing circuits
+ 3 added transf windings





Voltage Source MV Drives With MV Devices

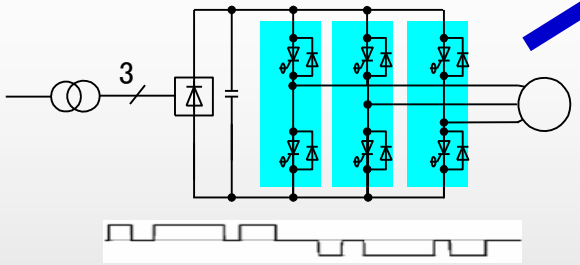
Building Block for MV PWM Drives



- NPC: Neutral Point Clamped Configuration
- Multiple supply voltage levels allows good waveforms
- Compatible with IGBT, GCT, IEGT Devices

Progress of Inverter Circuits to High Capacity

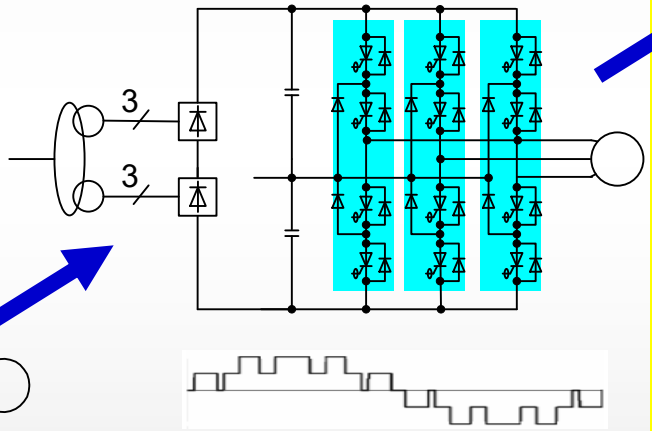
2 Level Inverter



Low voltage application

460V, 690V

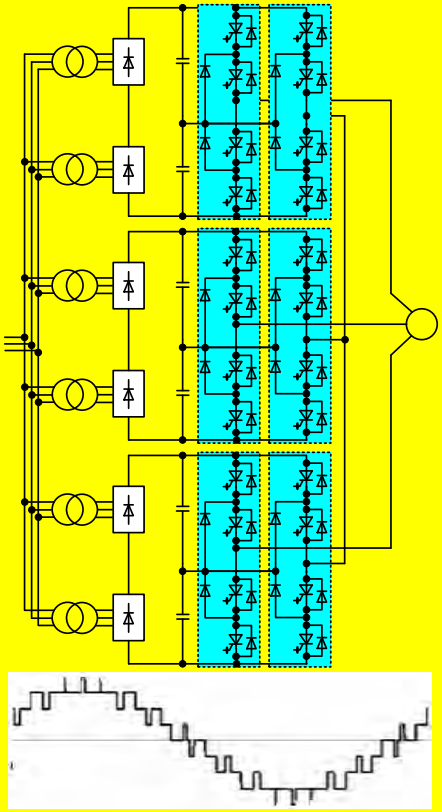
3 Level Inverter



Large capacity

3kV - 15MVA

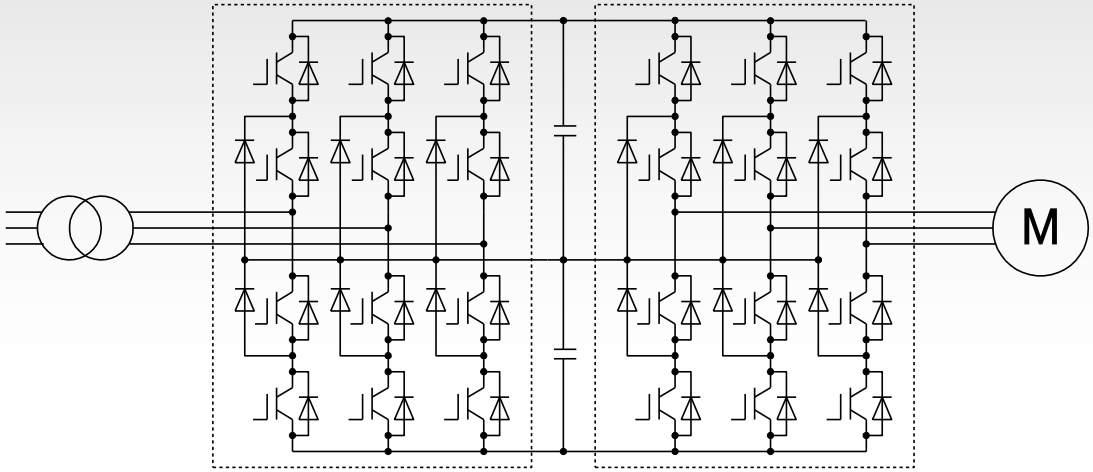
5 Level Inverter



6kV～7kV, 8MVA～120MVA

High voltage, large capacity, clean waveform

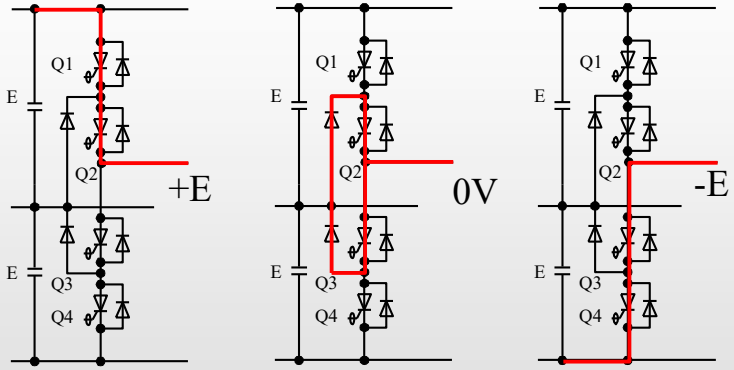
Complete 3 Level Circuit, Neutral Point Clamped



3 Level Inverter

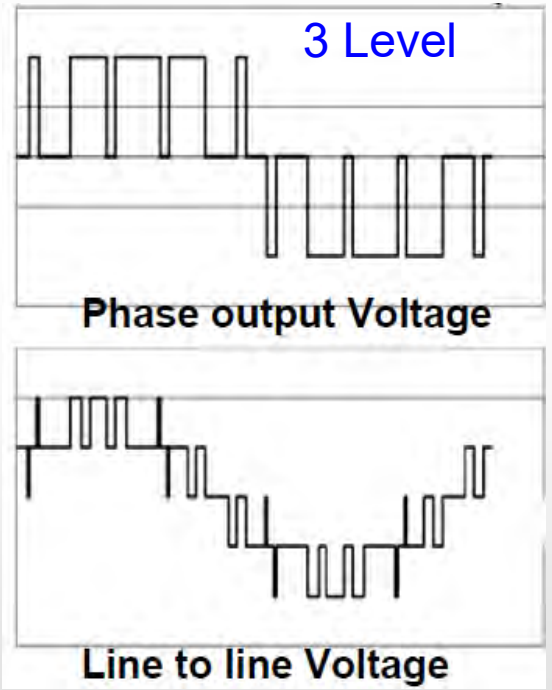
3 Level inverter is

- 2 times higher output voltage
- 2 times larger capacity
- Twice as clean waveform



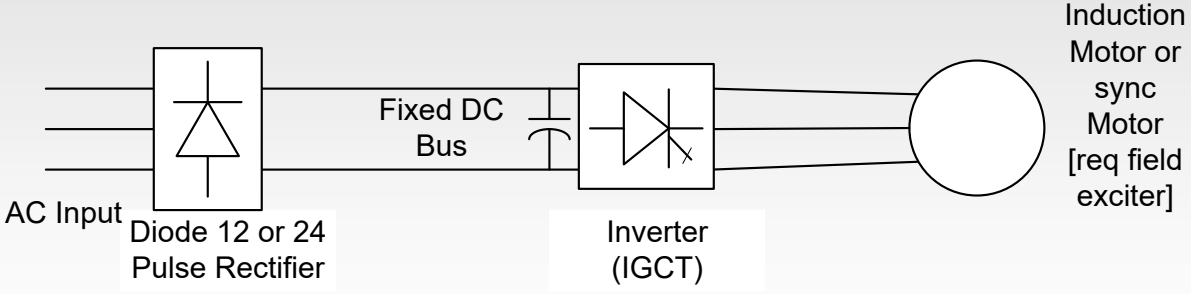
3 Level phase output voltage

Line to Line
3 / 5 levels
Including zero



Output voltage of 3 Level Inverter

IGCT PWM 3-Level Voltage Source Inverter

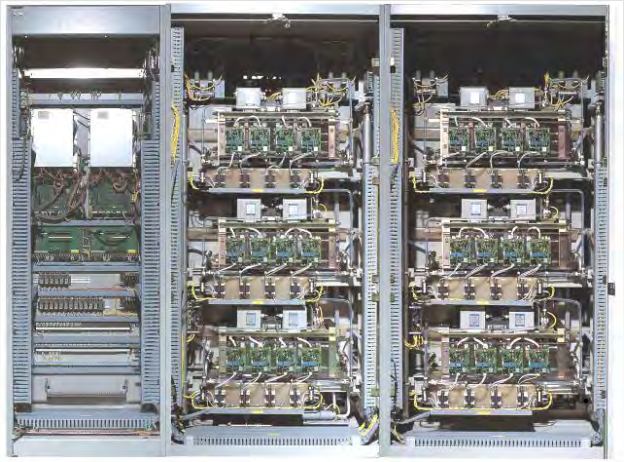


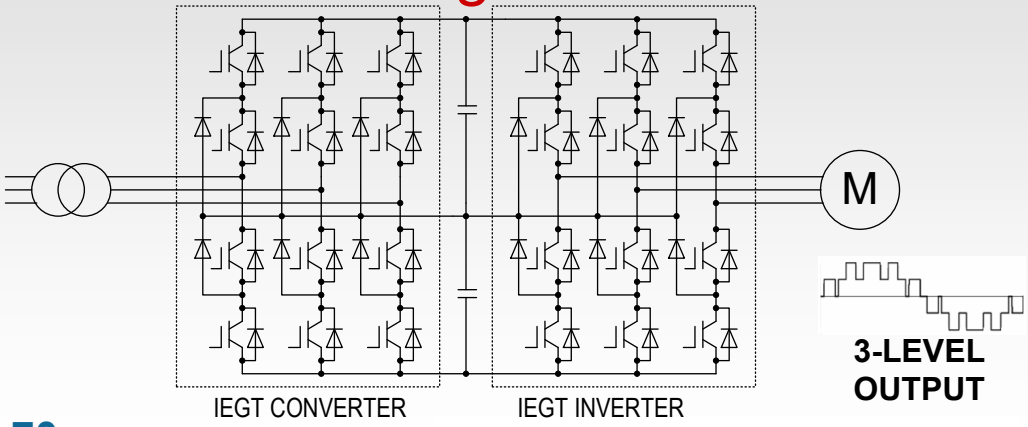
Energy stored in dry or liquid filled caps

Example: TMEIC TMdrive XL80 IGCT 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 • Water cooling for compact package	• High parts count firing circuit – latest design and extra high quality, conservative design to achieve reliability • Top motor speed / frequency limited by device switch rate.	10- 15 MVA per inverter [3.3-3.8 kv] 15 – 30 MVA, multiple channel Sync or Induction Motor

IEGT PWM Voltage Source Inverter



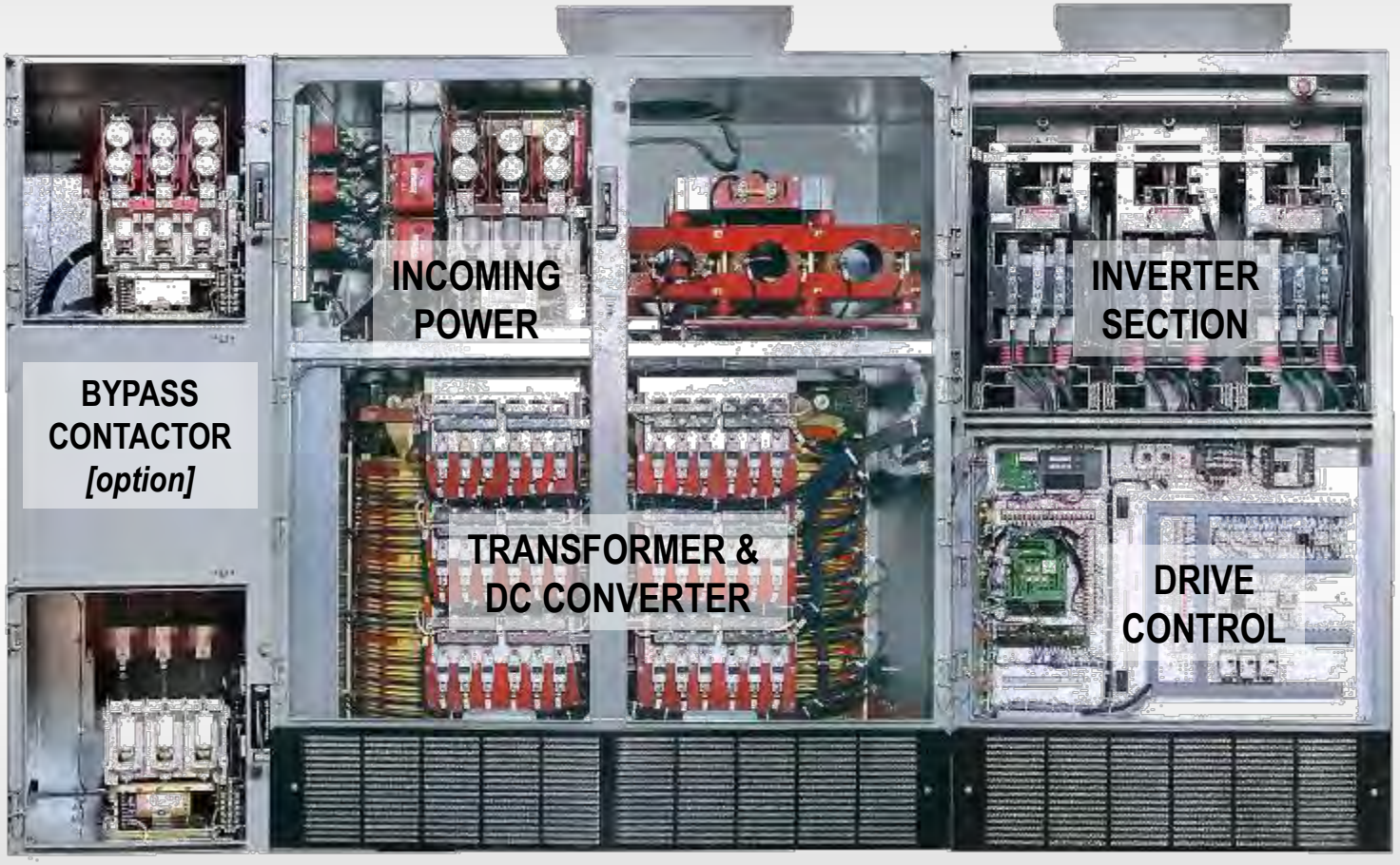


Example: TMEIC GE 8 / 10 MW TMdrive 70

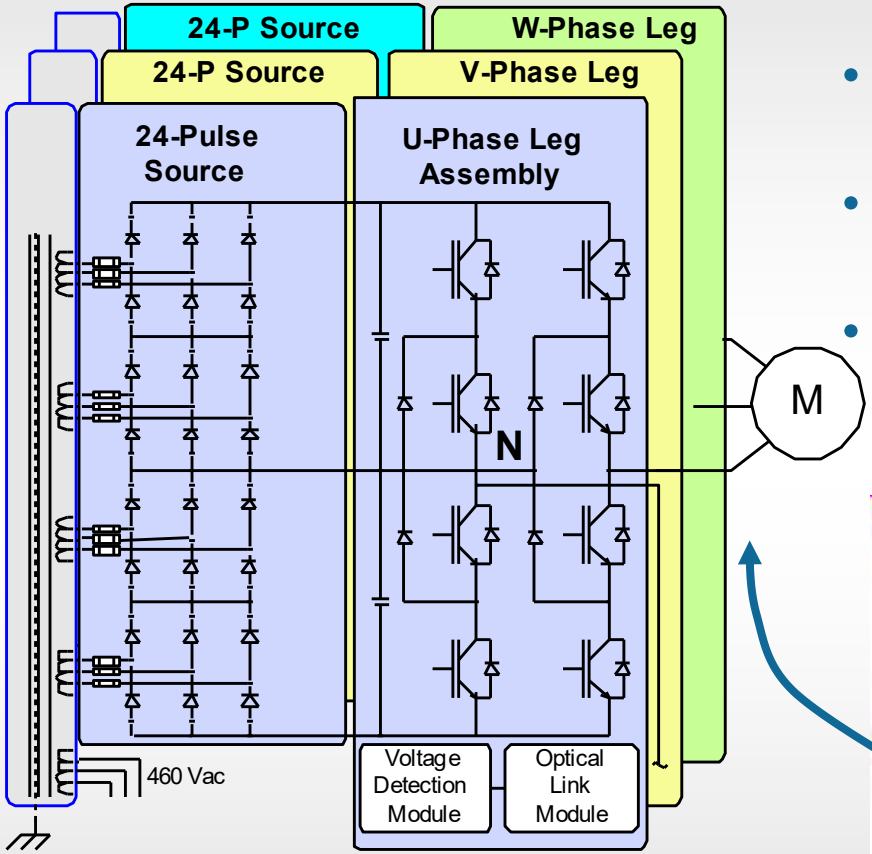
Energy stored in liquid filled caps

Inverter Topology	Major Advantages	Major Limitations	Power Range
Three Level Voltage Source IEGT PWM Inverter IEGT = Injection Enhanced Gate Transistor	• Minimum power device count – 24 for complete 8-10 mw regen system • Very Compact • Simple firing circuit • 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	• 3300 volts is not as common as 4160 volts in North American applications.	8 to 40 MW, water cooled, one to four channel At 3300 volts Sync or Induction Motor

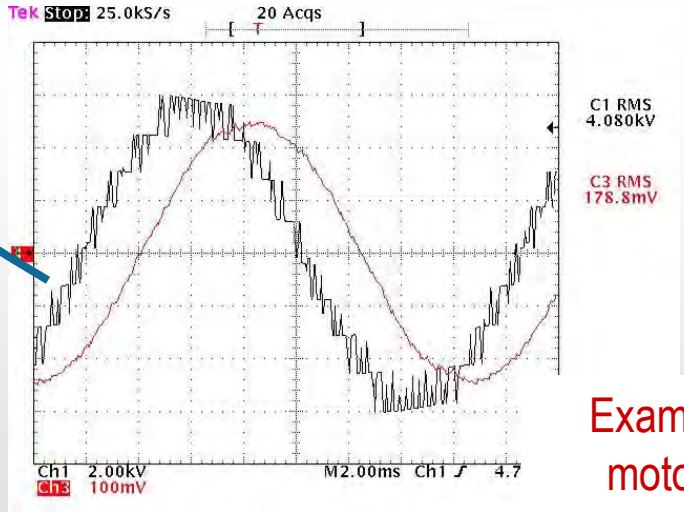
MV IGBT Drive with Integral Transformer



Example MV IGBT NPC Voltage Source Drive Details



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



Example 5/9 level motor voltage & current waveforms

TM-MVe2 Drive

TMdrive-MVe2 can be used with standard Induction or Synchronous Motor, for general purpose applications.

>20-Year MTBF

Unique source converter design easily **meets IEEE519** harmonic current limits, ***provides line regenerative braking capability*** and extended power loss ride-through protection

Simpler input transformer design allows potential to locate transformer remote from drive

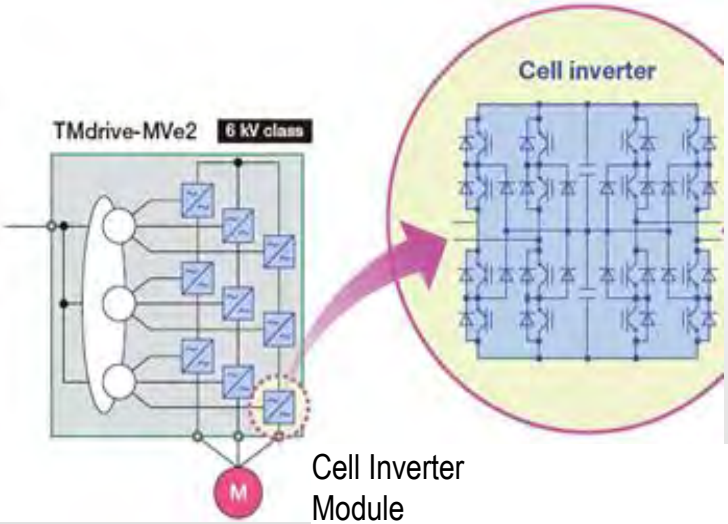
Multi-Level output gives Sinusoidal Voltage & Current waveforms,

500 ~ 2,760kVA @ 4160V (9/17 level)

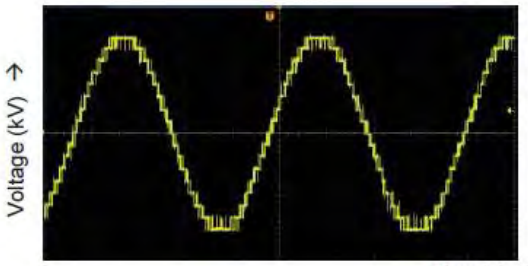
400 ~ 4,378kVA @6/6.6kV (13/23 level)

660 ~ 7,297kVA @10/11kV (21/41 level)

Long Service Life
- Conservatively applied components
- Film type capacitors
- Long life cooling fans
- Modular Drive using Cell Inverter
- Air Cooled System
- 100% PF
- 2% THID



Cell Inverter Module



*Example of the actual test result of the standard 4.16 kV VFD

Differentiating Features

- Compact design saves valuable floor space making retrofits of old equipment easier
- Compartmentalized panels provide voltage class segregation and top or bottom cable feeds
- Integral isolation transformer provides reliable operation and simplifies installation.
- Significant reduction in parts, reducing spare parts requirements

Input Power Disconnect Option[1]

- A visible, bolted pressure, isolation switch offers mechanical interlocking to allow for maintenance personnel to service the drive.
- The fused (Class E rated) vacuum contactor provides critical fault current protection to the drive.

Main Power Input

Four voltage levels are available:

- 3-3.3 kV, 3-phase, 50/60 Hz
- 4-4.16 kV, 3-phase, 50/60 Hz
- 6-6.6 kV, 3-phase, 50/60 Hz
- 10-11 kV, 3-phase, 50/60 Hz

Internal Pre-Charge AC Reactor*

An ac reactor and medium voltage contactor mitigate the transformer magnetizing inrush current, minimizing stress on the fusing and power components.

Input Isolation Transformer Standard.

The input transformer has multiple secondary windings to feed IGBT inverters (cell inverters). This design provides galvanic isolation between the power system and the motor-inverter system. Electrostatic shield is standard.

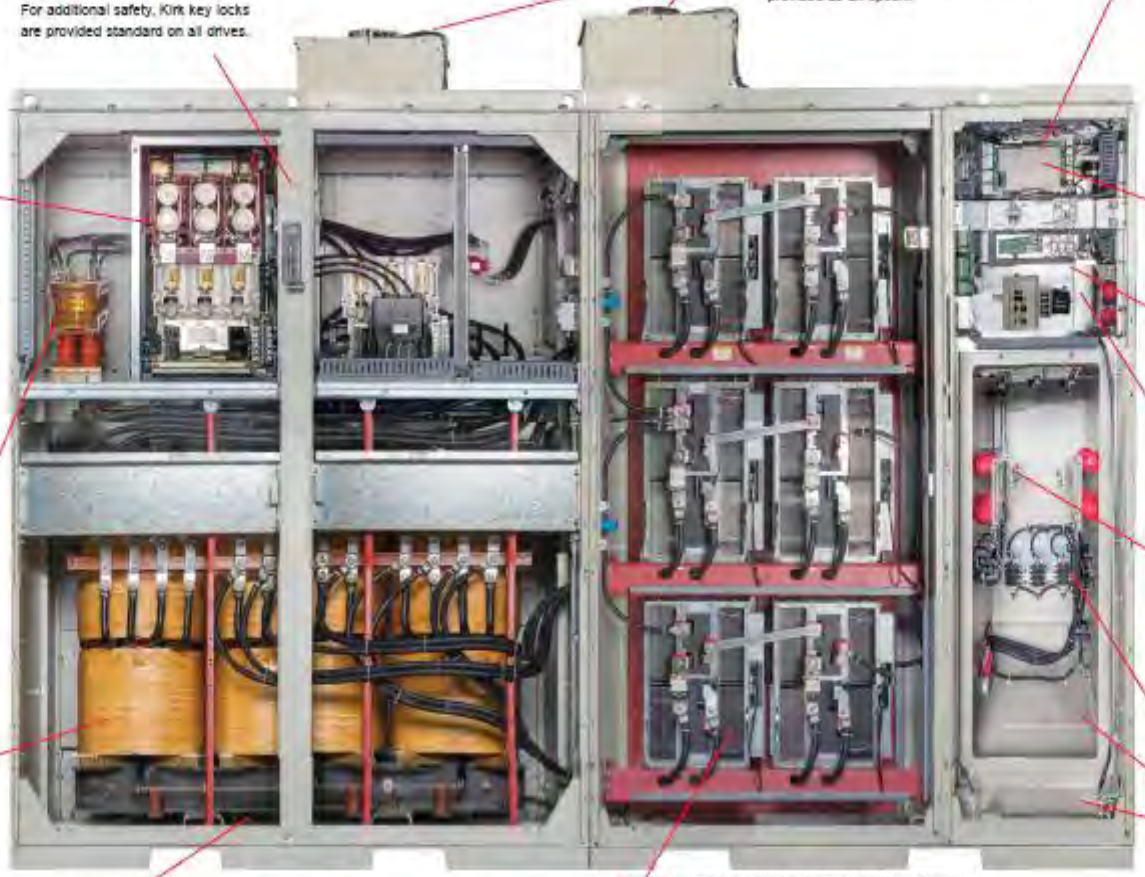
* Available in select frame sizes
[1]For 4 kV drive, CSA listed in U.S. and Canada only.

Kirk Key Interlocks[1]

For additional safety, Kirk key locks are provided standard on all drives.

Blower Assemblies

Quiet (<80 dB(A) at 1m), fans circulate air throughout enclosures pulling air from the front filter assemblies and venting it out the top of the cabinets. Redundant fan assemblies can be provided as an option.



Filtered Air Intake

Washable input air filters have front access for periodic maintenance.

Inverter/Converter Phase-Leg Assemblies

Each modular phase leg assembly includes:

- Robust IGBTs
- Gate driver circuit board
- DC bus capacitors, dry-film type for long life
- Fiber optic link interface circuit board

A phase leg assembly can be easily racked out and replaced in 30 minutes in case of failure.

Control

Single 32-bit microprocessor-based control board combines several key drive functions:

- Power semiconductor gating
- Speed and torque regulation
- Motor and drive protection
- I/O mapping
- Diagnostic functions
- High speed data capture buffering
- Hosting of optional LAN interface
- Drive is configured from the TMdrive-Navigator

Communications

An optional communications card can be provided to connect the VFD to the DCS/SCADA system.

Application Specific Controls

Each drive is matched to project requirements with custom control components.

Remote Connectivity Module Standard.

On-board Windows® based computer provides access to live variables, parameters & historical fault data.

Power & Motor Cabling Terminations

Conveniently located power cable terminations can be accessed from the front or rear. A metal cover prevents exposure to live parts when drive is running.

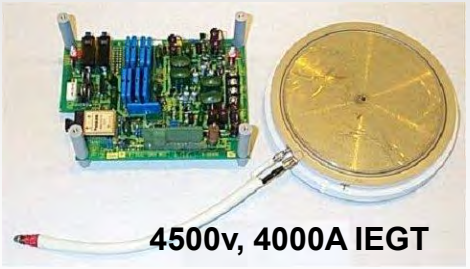
Lightning Arrestors[1]

Incoming power is protected by distribution class lightning arrestors for suppression of transient surges.

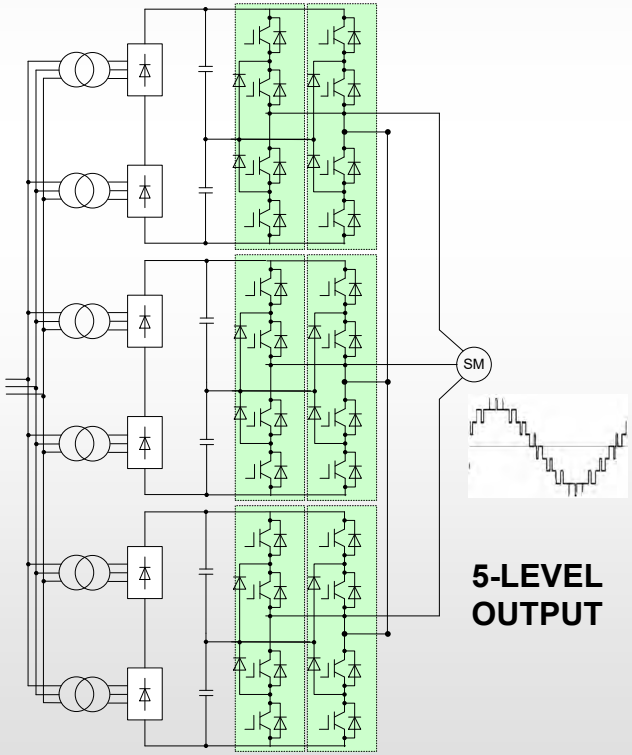
Control & Power Cables

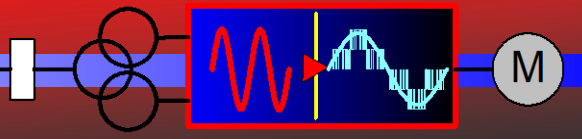
Gland plates are provided to enable cable entry. Top and bottom entry options are selectable onsite.

Example 5 level IEGT, TMdrive-XL75



Rated Single Unit Capacity : 20MVA
-Maximum Capacity : 80MVA
-Rated Output voltage : 6.0kV
-Line-side converter : 36 pulse Diode rectifier
-Inverter : 5 level PWM IEGT inverter
-Cooling method : Water cooled
-Dimensions : W6.6xD1.6xH2.3m(20MVA)
-Redundancy (option) : Main and/or control circuit
-Motor type : Induction or Sync motor
Applications : Large capacity Compressor
Fan, Blower or pump





What Is Now Evolving in MV Drives?

- Larger and larger driven loads require larger prime movers
- Environment factors and remote sites can favor large electric drives over turbines
- Topologies we have reviewed are tested and scaled up for large power loads

Line up of Large Capacity Inverters
6.0 – 7 kV, 5 level output

5 Level IGBT Inverter

Capacity: 6kV - 8MVA

5 Level IEGT Inverter

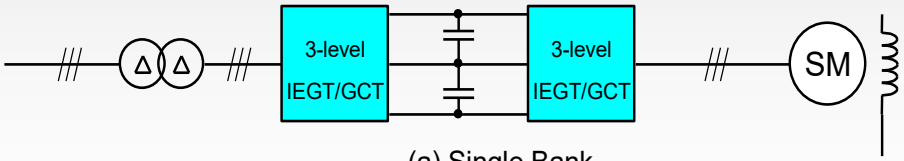
Capacity: 7kV - 30MVA

up to 30MVA x 4 = 120 MVA

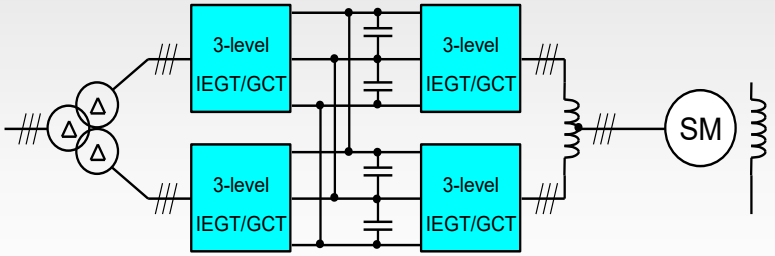
5 Level IEGT Inverter

Capacity: 6kV - 20MVA, up to 20MVA x 4 = 80 MVA

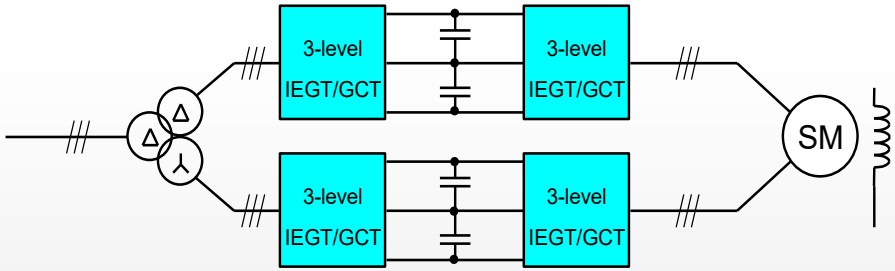
Parallel Connection for Higher Capacity



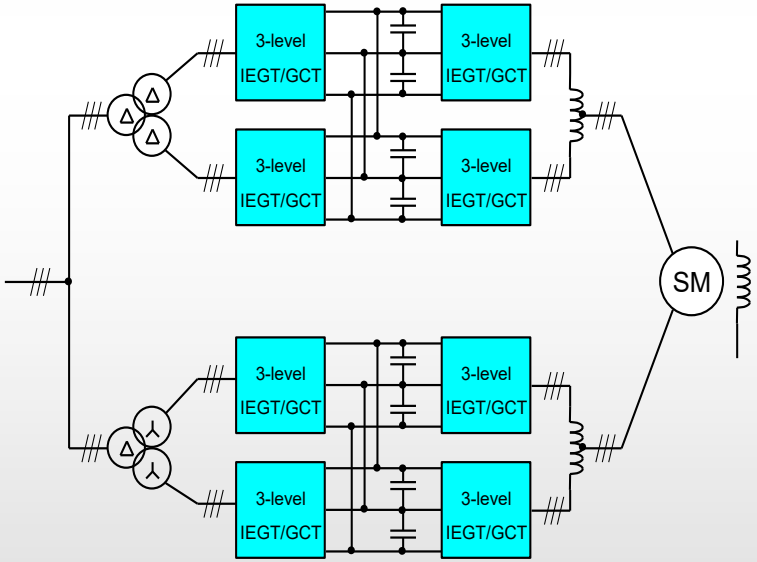
(a) Single Bank



(c) 2 Banks, 2 parallel bridge



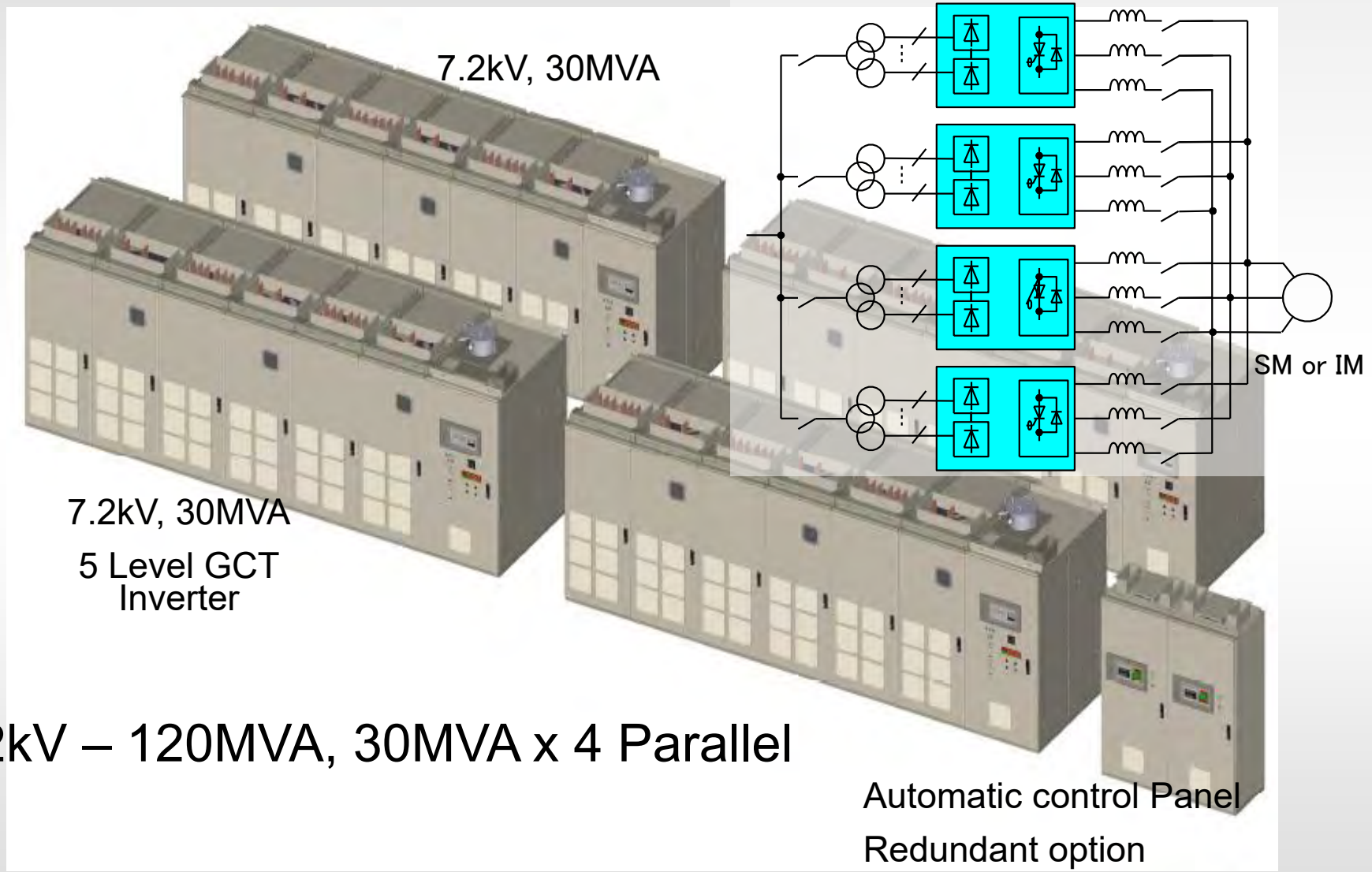
(b) Two Banks, dual windings motor



(d) 4 Banks, Dual windings motor x 2 parallel bridge

Wide range line up; 8MVA to 4x10MVA

Extra Large Capacity Inverter, 120MVA



7.2kV – 120MVA, 30MVA x 4 Parallel

Automatic control Panel

Redundant option

Questions?