EE8412
Advanced AC Drive Systems

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Counseling Hours

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Topic 1 Introduction

- **Main Topics (Introduction)**

1. **Course Outline**
   - **Lecture Topics**
   - **Course Organization**
   - **Design Projects**
2. **Drive System Overview**
3. **Technical Requirements and Challenges**
4. **Converter Configurations**
5. **Industrial Drives**
6. **Industrial Applications**
7. **High-power Semiconductor Devices**

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Topic 1 Introduction

Course Outline

- **Lecture Topics**

1. **Introduction**
2. **Induction motor dynamic models**
3. **Power Converter Topologies**
4. **Voltage Source Inverter-Fed Drives**
5. **Current Source Inverter-Fed Drives**
6. **Field Oriented control (FOC)**
7. **Direct Torque Control (DTC)**

Topic 1 Introduction

Course Outline

- **Course Organization**

Lecture 2 hours per week
Laboratory 1 hour per week (simulation)

Textbook
Bin Wu, 'High-Power Converters and AC Drive'
Wiley - IEEE Press, 2006, ISBN: 0-4717-3171-4

Lecture Slides
Download from http://www.ee.ryerson.ca/~bwu/courses.html

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Topic 1 Introduction

Course Outline

- **Design Projects**

1. Induction Motor Transient Characteristics 20%
2. V/F Control of Induction Motor (IM) Drive 20%
3. Field Oriented Control (FOC) of IM Drive 30%
4. Direct Torque Control (DTC) of IM Drive 30%

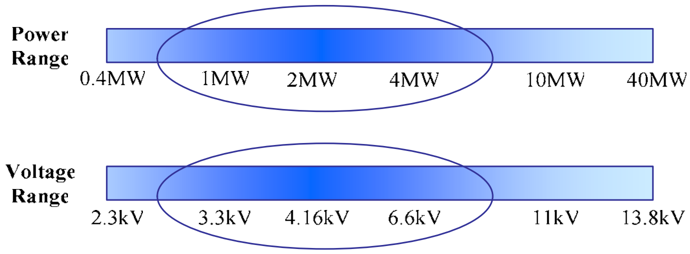
Total 100%

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Topic 1 Introduction

Drive System Overview

- **Power Rating and Market Survey**

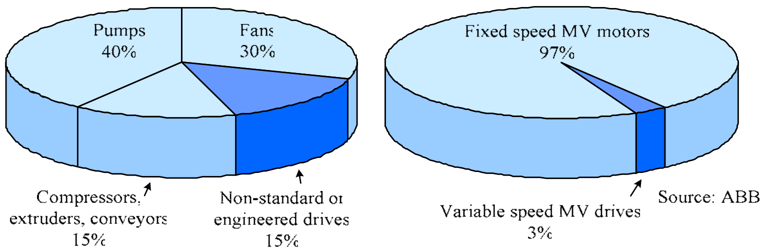


Source: Rockwell Automation

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Drive System Overview

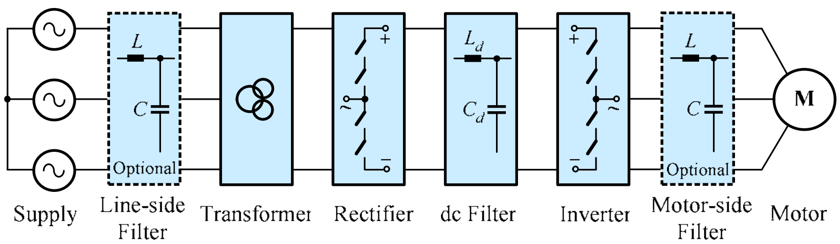
- **Power Rating and Market Survey**



(a) Load types for the MV drive (b) MV drives versus MV motors

Drive System Overview

- **Drive Block Diagram**



Technical Requirements and Challenges

• Line-side Requirements

1) Line Current Distortion
- Causes
  - Line current distortion is caused by rectifiers
- Problems
  - Nuisance tripping of computer controlled industrial processes
  - Overheating of transformers
  - Equipment failure
  - Computer data loss
  - Malfunction of communications equipment

2) High Input Power Factor
- PF > 0.9

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Technical Requirements and Challenges

• Line-side Requirements (Continued)

3) LC Resonance Suppression
- LC resonant mode
  - Line-side filter capacitor and line inductance
- LC resonant mode will be excited by
  - Harmonics in supply voltages
  - Harmonics generated by the rectifier
- Problems
  - Overvoltages caused by the LC resonance

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Topic 1 Introduction

Technical Requirements and Challenges

• **Motor-side Challenges**

1) ***dv/dt*** **and wave reflections**

- **Causes**
  - Fast switching speed of semiconductor devices
  - *dv/dt* > 10,000V/μs

- **Problems**
  - Voltage doubling effect at the rising and falling edges of PWM waveforms due to wave reflections
  - Premature failure of the motor winding insulation due to partial discharges

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Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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Topic 1 Introduction

Technical Requirements and Challenges

• **Motor-side Challenges** (Continued)

2) **Common-mode voltage stress**

- **Causes**
  - The switch action of the rectifier and inverter generates common-mode (CM) voltages

- **Problems**
  - CM voltage appears on the neutral of the stator winding with respect to ground
  - CM voltage is superimposed to the phase voltage of the the stator winding
  - Premature failure of the motor winding insulation

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Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Technical Requirements and Challenges

- **Motor-side Challenges (Continued)**

3) **Motor Derating**
   - **Causes**
     - Current harmonics in the stator winding.
   - **Problems**
     - Additional power losses in the motor winding and magnetic core. As a consequence,
     - Motor is derated and cannot operate at its full capacity
4) **LC Resonances**
5) **Torsional Vibration**

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Technical Requirements and Challenges

- **Switching Device Constraints**

1) **Device Switching Frequency**
   Switching frequency: < 1000Hz
   Typically: 500Hz for IGCT/IGBT, 200Hz for GTO
2) **Series Connection**

- **Drive System Requirements**

1) Low manufacturing cost
2) Small physical size
3) High reliability
4) Effective fault protection
5) Self-commissioning
6) Minimum downtime for repairs
7) High dynamic performance

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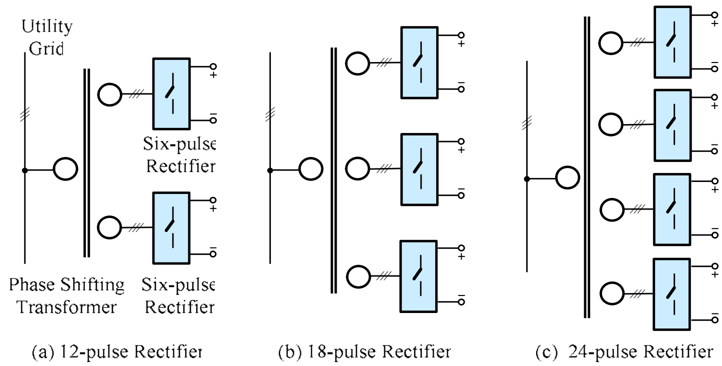
Converter Configurations

- **Multipulse rectifiers**



- **Features: Low line current distortion**

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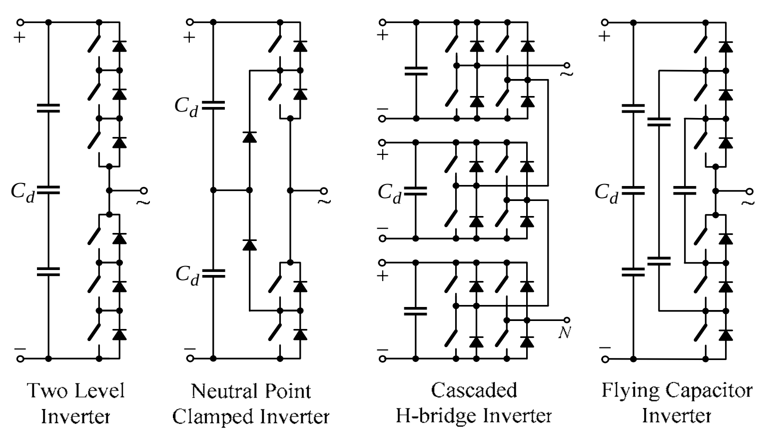
Topic 1 Introduction

Converter Configurations

- **Multilevel Voltage Source Converters**



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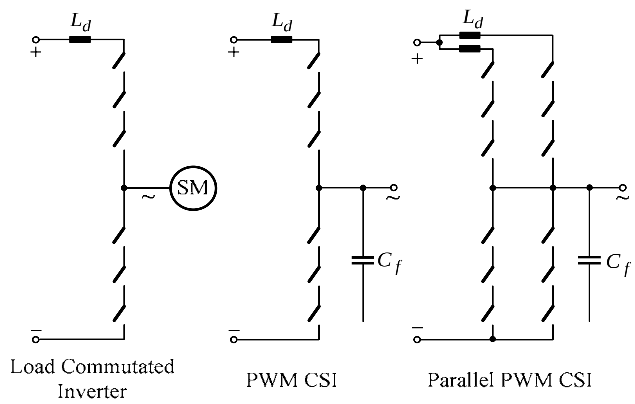
Converter Configurations

- **PWM Current Source Converters**



Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Industrial Drives

- **GCT based three-level NPC inverter fed MV drive**

Courtesy of ABB (ACS1000)

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Industrial Drives

• IGBT-based three-level NPC inverter fed MV drive

Courtesy of Siemens (SIMOVERT MV)

Industrial Drives

• IGBT cascaded H-bridge inverter fed MV drive

Courtesy of ASI Robicon (Perfect Harmony)

Industrial Drives

• **CSI fed MV drive using symmetrical GCTs**

Courtesy of Rockwell Automation (PowerFlex 7000)

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Industrial Drives

• **Summary**

Inverter Configuration	Switching Device	Power Range	Manufacturer
Two-Level Voltage Source Inverter	IGBT	1.4MVA – 7.2MVA	Alstom (VDM5000)
Three-Level Neutral Point Clamped Inverter	GCT	0.3MVA – 5MVA 3MVA – 27MVA	ABB (ACS1000) (ACS6000)
	GCT	3MVA – 20MVA	General Electric (Innovation Series MV-SP)
	IGBT	0.6MVA – 7.2MVA	Siemens (SIMOVERT-MV)
	IGBT	0.3MVA – 2.4MVA	General Electric–Toshiba (Dura-Bilt5 MV)
Multilevel Cascaded H-Bridge Inverter	IGBT	0.3MVA – 22MVA	ASI Robicon (Perfect Harmony)
		0.5MVA – 6MVA	Toshiba (TOSVERT-MV)
		0.45MVA – 7.5MVA	General Electric (Innovation MV-GP Type H)

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Topic 1 Introduction

Industrial Drives

• Summary (continued)

Inverter Configuration	Switching Device	Power Range	Manufacturer
Two-Level Voltage Source Inverter	IGBT	1.4MVA – 7.2MVA	Alstom (VDM5000)
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	GCT	3MVA – 20MVA	General Electric (Innovation Series MV-SP)
	IGBT	0.6MVA – 7.2MVA	Siemens (SIMOVERT-MV)
	IGBT	0.3MVA – 2.4MVA	General Electric–Toshiba (Dura-Bilt5 MV)
Multilevel Cascaded H-Bridge Inverter	IGBT	0.3MVA – 22MVA	ASI Robicon (Perfect Harmony)
		0.5MVA – 6MVA	Toshiba (TOSVERT-MV)
		0.45MVA – 7.5MVA	General Electric (Innovation MV-GP Type H)

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Topic 1 Introduction

Industrial Drives

• Summary (continued)

NPC/H-bridge Inverter	IGBT	0.4MVA – 4.8MVA	Toshiba (TOSVERT 300 MV)
Flying-Capacitor Inverter	IGBT	0.3MVA – 8MVA	Alstom (VDM6000 Symphony)
PWM Current Source Inverter	Symmetrical GCT	0.2MVA – 20MVA	Rockwell Automation (PowerFlex 7000)
Load Commutated Inverter	SCR	>10MVA	Siemens (SIMOVERT S)
		>10MVA	ABB (LCI)
		>10MVA	Alstom (ALSPA SD7000)

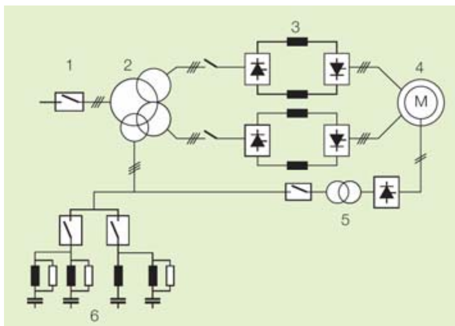
Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

Topic 1 Introduction

Industrial Applications

- **100MW Wind Tunnel Drive**

  - Application: NASA wind tunnel
  - Motor: Six-phase, synchronous
  - Load: High power fan
  - Speed Range: 360 - 600rpm



Source: ABB

1. Supply system
2. Transformer
3. Converters
4. Motor
5. Excitation system
6. Filter

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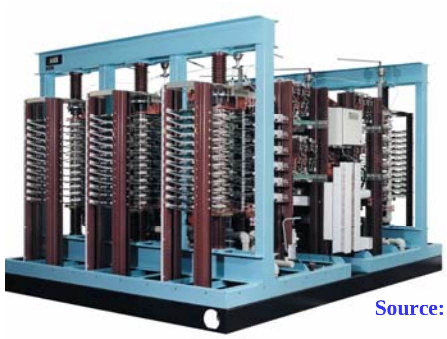
Topic 1 Introduction

Industrial Applications

- **100MW Wind Tunnel Drive**



Source: ABB

Picture of one of the 4 converters used in the drive

- Inverter type: current source
- Switching device: SCR thyristor
- # of devices in series: 12
- Total # of devices: (12 x 6) x 4 = 288
- Converter efficiency: > 99%

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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Industrial Applications

- **High Speed Train**

Source: Fuji Electric

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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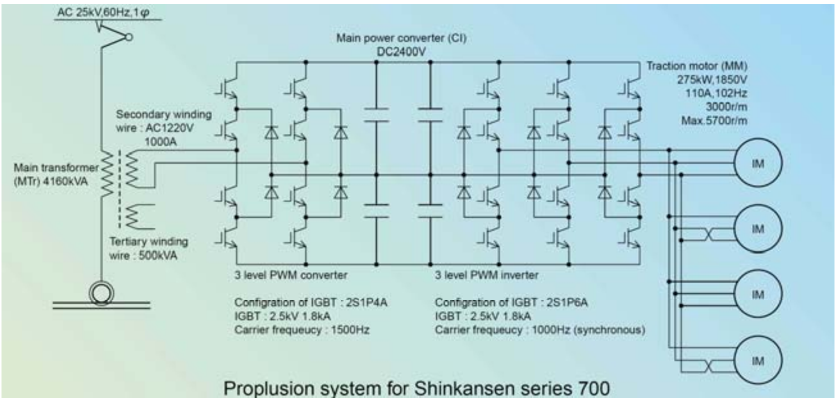
Topic 1 Introduction

Industrial Applications

- **High Speed Train**



Source: Fuji Electric

Rectifier: Single-phase three-level diode clamped
Inverter: Three-phase three-level diode clamped
Ratings: 1.1MW, 1850V

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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Topic 1 Introduction

Industrial Applications


Mining / cement


Petrochemical


Iron / steel


Paper / pulp


Marine


Oil / gas


Power generation


Water / waste water

Source: Robicon

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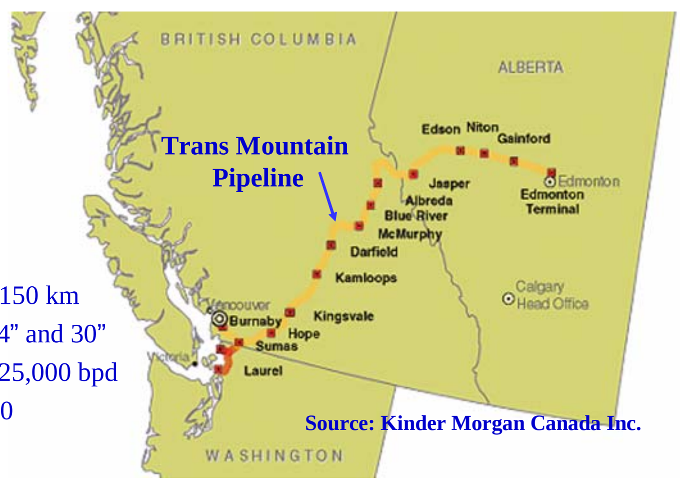
Topic 1 Introduction

Industrial Applications

- **Megawatt Drive for Pipeline Pumps**



Length: 1,150 km
Pipe Size: 24" and 30"
Capacity: 225,000 bpd
Pump stations: 10

Source: Kinder Morgan Canada Inc.

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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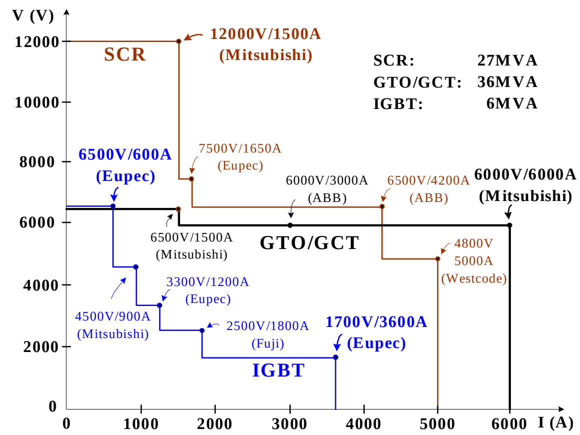
Topic 1 Introduction

High-Power Semiconductor Devices

• Device Ratings



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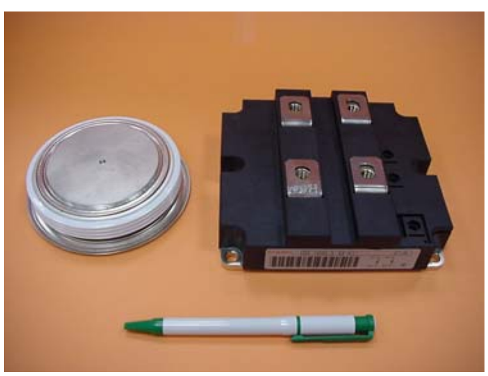
Topic 1 Introduction

High-Power Semiconductor Devices

• Diode



4500V/800A press pack and 1700V/1200A module diodes

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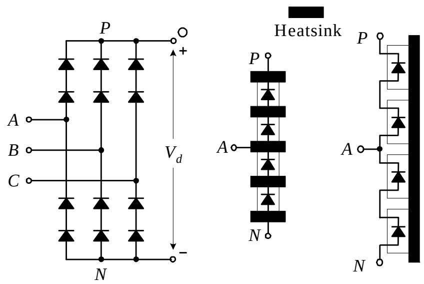
Topic 1 Introduction

High-Power Semiconductor Devices

• **Heatsink Assembly**



(a) Diode Rectifier (b) Press pack (c) Module

Press pack device:
- **Double sided cooling**
- **Low assembly cost and high power density**
- **Preferred choice for high voltage high power applications**

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Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

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High-Power Semiconductor Devices

• **SCR – Silicon Controlled Rectifier**

4500V/800A and 4500V/1500A SCRs

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High-Power Semiconductor Devices

• **Gate Turn-Off (GTO) Thyristor**

4500V/800A and 4500V/1500A GTOs

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High-Power Semiconductor Devices

• **Symmetrical *versus* Asymmetrical GTOs**

Type	Blocking Voltage	Example (6000V GTOs)	Applications
Asymmetrical GTO	$V_{RRM} << V_{DRM}$	$V_{DRM} = 6000V$ $V_{RRM} = 22V$	For use in voltage source inverters with anti-parallel diodes.
Symmetrical GTO	$V_{RRM} \approx V_{DRM}$	$V_{DRM} = 6000V$ $V_{RRM} = 6500V$	For use in current source inverters.
V_{DRM} - Maximum repetitive peak (forward) off-state voltage V_{RRM} - Maximum repetitive peak reverse voltage			

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley-IEEE Press, 2006, ISBN: 0-471-73171-4

High-Power Semiconductor Devices

• GTO Specifications

4500V/4000A Asymmetrical GTO Thyristor

Maximum Rating	V_{DRM}	V_{RRM}	I_{TGQM}	I_{TAVM}	I_{TRMS}	-
	4500V	17V	4000A	1000A	1570A	-
Switching Characteristics	**Turn-on Switching**	**Turn-off Switching**	di_T/dt	dv_T/dt	di_{G1}/dt	di_{G2}/dt
	$t_{don} = 2.5\mu s$ $t_r = 5.0\mu s$	$t_{doff} = 25.0\mu s$ $t_f = 3.0\mu s$	$500A/\mu s$	$1000V/\mu s$	$40A/\mu s$	$40A/\mu s$
On-state Voltage	$V_{T(on-state)} = 4.4V$ at $I_T = 4000A$					

V_{DRM} - Repetitive peak off-state voltage
V_{RRM} - Repetitive peak reverse voltage
I_{TGQM} - Repetitive controllable on-state current
I_{TAVM} - Maximum average on-state current
I_{RRMS} - Maximum rms on-state current
Part number - 5SGA 40L4501 (ABB)

High-Power Semiconductor Devices

• Integrated Gate Commutated Thyristor (GCT)

6500V/1500A Symmetrical GCT

GCT = Improved GTO + Integrated Gate + Anti-parallel Diode (optional)

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High-Power Semiconductor Devices

• GCT Classifications

Type	Anti-parallel Diode	Blocking Voltage	Example (6000V GCT)	Applications
Asymmetrical GCT	Excluded	$V_{RRM} << V_{DRM}$	$V_{DRM} = 6000V$ $V_{RRM} = 22V$	For use in voltage source inverters with anti-parallel diodes.
Reverse Conducting GCT	Included	$V_{RRM} \approx 0$	$V_{DRM} = 6000V$	For use in voltage source inverters.
Symmetrical GCT (Reverse Blocking)	Not required	$V_{RRM} \approx V_{DRM}$	$V_{DRM} = 6000V$ $V_{RRM} = 6500V$	For use in current source Inverters.

V_{DRM} - Maximum repetitive peak forward off-state voltage

V_{RRM} - Maximum repetitive peak reverse voltage

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Topic 1 Introduction

High-Power Semiconductor Devices

• GCT Specifications

6000V/6000A Asymmetrical GCT

Maximum Rating	V_{DRM}	V_{RRM}	I_{TQRM}	I_{TAVM}	I_{TRMS}	-
	6000V	22V	6000A	2000A	3100A	-
Switching Characteristics	Turn-on Switching	Turn-off Switching	di_T/dt	dv_T/dt	di_{G1}/dt	di_{G2}/dt
	$t_{don} < 1.0\mu s$ $t_r < 2.0\mu s$	$t_{doff} < 3.0\mu s$ t_f - N/A	$1000A/\mu s$	$3000V/\mu s$	$200A/\mu s$	10,000 $A/\mu s$
On-state Voltage	$V_{T(on-state)} < 4V$ at $I_T = 6000A$					

V_{DRM} - Repetitive peak off-state voltage

V_{RRM} - Repetitive peak reverse voltage

I_{TGRM} - Repetitive controllable on-state current

I_{TAVM} - Maximum average on-state current

I_{RRMS} - Maximum rms on-state current

Part number – FGC6000AX120DS (Mitsubishi)

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High-Power Semiconductor Devices

• **Insulated Gate Bipolar Transistor (IGBT)**

1700V/1200A and 3300V/1200A IGBT modules

High-Power Semiconductor Devices

• **IGBT Specifications**

3300V/1200A IGBT

Maximum Rating	V_{CE}	I_C	I_{CM}	-
	3300V	1200A	2400A	-
Switching Characteristics	t_{don}	t_r	t_{doff}	t_f
	$0.35\mu s$	$0.27\mu s$	$1.7\mu s$	$0.2\mu s$
Saturation Voltage	$I_{CE\,sat} = 4.3V$ at $I_C = 1200A$			

V_{CE} - Rated collector-emitter voltage

I_C - Rated dc collector current

I_{CM} - Maximum repetitive peak collector current

Part number – FZ1200 R33 KF2 (Eupec)

High-Power Semiconductor Devices

• Comparison

Item	GTO	IGCT	IGBT
Maximum switch power (Device $V \times I$)	36MVA	36MVA	6MVA
Active di/dt and dv/dt control	No	No	Yes
Active short circuit protection	No	No	Yes
Turn-off (dv/dt) snubber	Required	Not required	No required
Turn-on (di/dt) snubber	Required	Required	No required
Parallel connection	No	No	Yes
Switching speed	Slow	Moderate	Fast
Behavior after destruction	Shorted	Shorted	Open in most cases
On-state losses	Low	Low	High
Switching losses	High	Low	Low
Gate Driver	Complex, separate	Complex, integrated	Simple, compact
Gate Driver Power Consumption	High	High	Low

EE8412 Advanced AC Drive Systems

Topic 1
Introduction

Thanks