High-Power Converters and Applications in Drive/Wind/Power Industries

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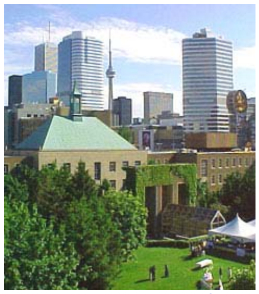


Ryerson Campus

High-Power Converters and Applications in Drive/Wind/Power Industries

Main Topics

1. Introduction
2. High-Power Rectifiers
3. High-Power Voltage Source Inverters
4. PWM Current Source Converters
5. Applications in Motor Drive Industry
6. Applications in Wind Energy Industry
7. Applications in Power/Utility Industry

Topic 1 Introduction

- Overview of High-Power Converters
- High-Power Semiconductor Devices
- Converter Design Requirements

Topic 1 Introduction

Overview of High-Power Converters

- **Converter Power Rating**

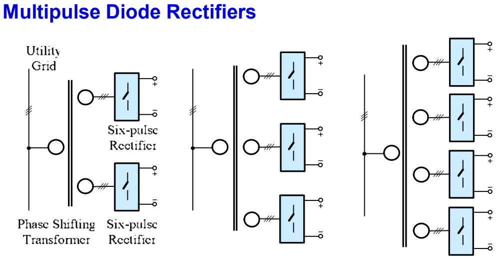
  - Electric Drive Systems: 100MW
  - Wind Energy Systems: 6MW
  - Power Systems FACTS: 300MVA
    HVDC: 3000MW

FACTS - Flexible AC Transmission System
HVDC - High Voltage DC Transmission

Topic 1 Introduction

Overview of High-Power Converters

- **Multipulse Diode Rectifiers**



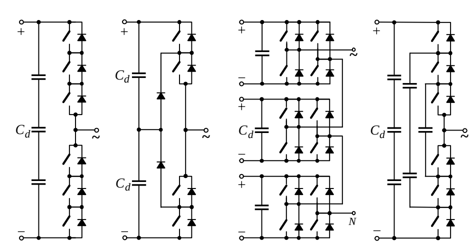
(a) 12-pulse Rectifier (b) 18-pulse Rectifier (c) 24-pulse Rectifier

Main Feature
Line current THD reduction

Topic 1 Introduction

Overview of High-Power Converters

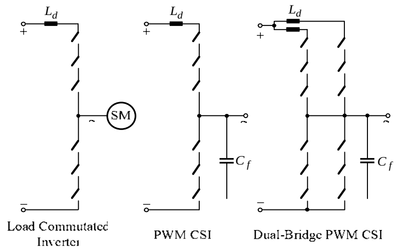
- **Multilevel Voltage Source Inverters** (per phase diagram)



Two Level Inverter — Neutral Point Clamped (NPC) Inverter — Cascaded H-bridge (CHB) Inverter — Flying Capacitor Inverter

Overview of High-Power Converters

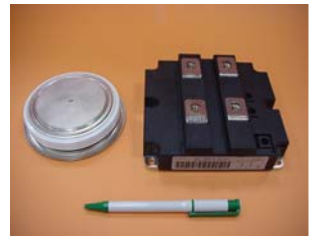
• **PWM Current Source Inverters** (per phase diagram)



Main feature
Simple converter configuration

Overview of Semiconductor Devices

• **Power Diode**



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

Overview of Semiconductor Devices

• **Silicon Controlled Rectifier (SCR)**

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

Overview of Semiconductor Devices

• **Gate Turn Off Thyristor (GTO)**

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

Overview of Semiconductor Devices

• **Integrated Gate Controlled Thyristor (IGCT/GCT)**

6500V/1500A Symmetrical GCT

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

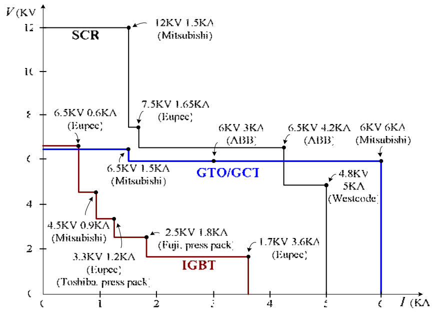
Overview of Semiconductor Devices

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

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

Overview of Semiconductor Devices

• **Device Voltage/Power Ratings**



Overview of Semiconductor Devices

• **Comparison**

Item	GTO	GCT	IGBT
Maximum voltage and current ratings	High	High	Low
Packaging	Press pack	Press pack	Module or Press pack
Switching speed	Slow	Moderate	Fast
Turn-on (*di/dt*) snubber	Required	Required	Not required
Turn-off (*dv/dt*) snubber	Required	Not required	Not required
Active overvoltage clamping	No	No	Yes
Active *di/dt* and *dv/dt* control	No	No	Yes
Active short circuit protection	No	No	Yes
On-state loss	Low	Low	High
Switching loss	High	Medium	Low
Behavior after destruction	Short circuited	Short circuited	Open circuited
Gate Driver	Complex, separate	Complex, integrated	Simple, compact
Gate Driver Power Consumption	High	Medium	Low

Converter Design Requirements

- **High energy efficiency**
- **High power density**
- **Low manufacturing cost**
- **High reliability**
- **Effective fault protection**

Topic 2
High-Power Rectifiers

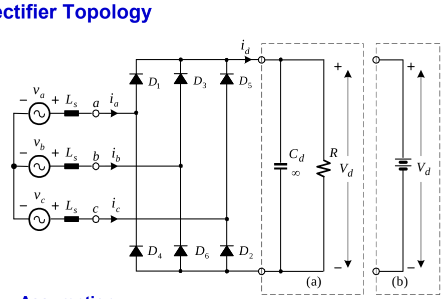
- **Six-pulse Diode Rectifier**
- **12-pulse Diode Rectifier**
- **18- and 24-pulse Diode Rectifiers**
- **Comparison**

Why Use Multipulse Rectifiers?

- **To reduce line THD**
- **To improve input power factor**
- **To avoid semiconductor devices in series**

Six-Pulse Diode Rectifier

• **Rectifier Topology**

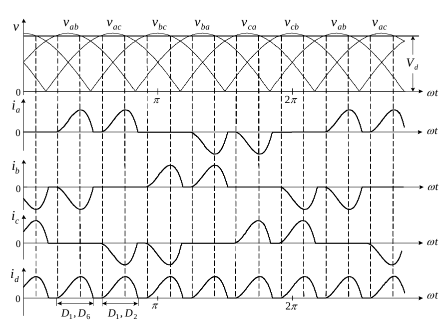


Assumption:

$$C_d = \infty \Rightarrow V_d = \text{constant}$$

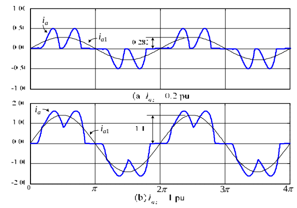
Six-Pulse Diode Rectifier

• **Simulated Waveforms**



Topic 2 High-Power Rectifiers
Six-Pulse Diode Rectifier

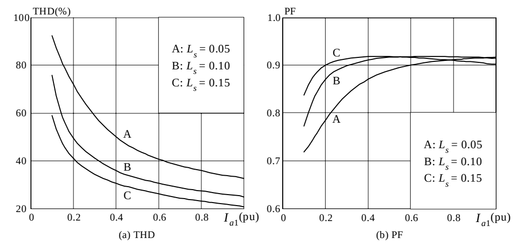
- **Harmonic Content**



Harmonics n	5	7	11	13	17	19	23	25	THD (%)
I_{an}/I_{a1} (%) $I_{a1}=0.2$pu	63.4	38.7	8.99	8.64	4.22	3.61	2.48	2.02	75.7
I_{an}/I_{a1} (%) $I_{a1}=1$pu	30.4	8.79	6.31	3.40	2.30	1.89	1.04	1.03	32.7

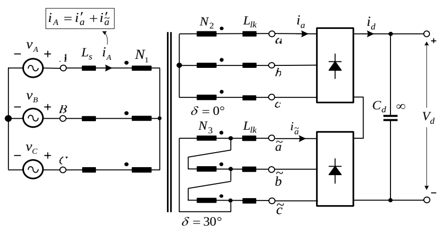
Topic 2 High-Power Rectifiers
Six-Pulse Diode Rectifier

- **THD and PF**



Topic 2 High-Power Rectifiers
12-Pulse Diode Rectifier

- **Rectifier Topology**

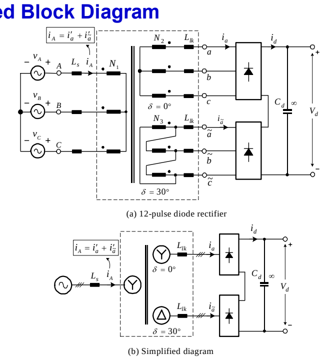


Phase Shifting Transformer

Phase angle: $\delta = \angle V_{\tilde{a}\tilde{b}} - \angle V_{AB} = 30°$

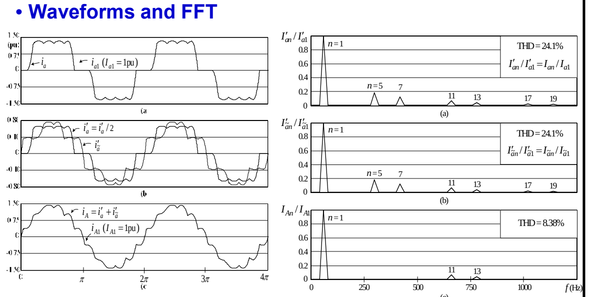
Topic 2 High-Power Rectifiers
12-Pulse Diode Rectifier

- **Simplified Block Diagram**



Topic 2 High-Power Rectifiers
12-Pulse Diode Rectifier

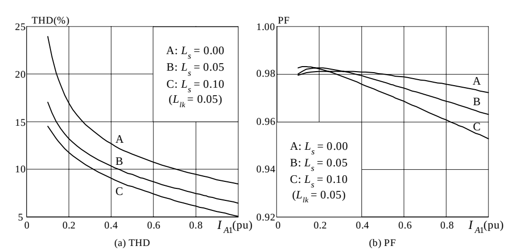
- **Waveforms and FFT**



- **No 5th or 7th harmonics in the line current.**
- **Primary line current THD: 8.38%**

Topic 2 High-Power Rectifiers
12-Pulse Diode Rectifier

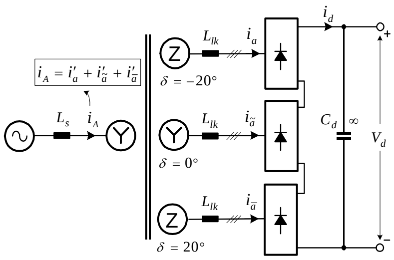
- **THD and PF**



Comparison with six-pulse rectifier:
- **THD is reduced**
- **PF is improved**

18-Pulse Diode Rectifier

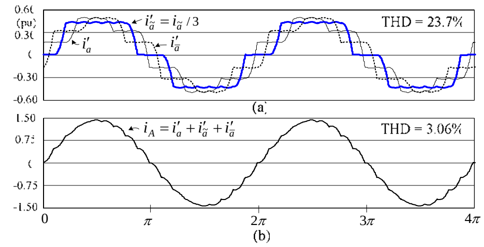
- **Rectifier Topology**



Phase-Shifting (Zigzag) Transformer

18-Pulse Diode Rectifier

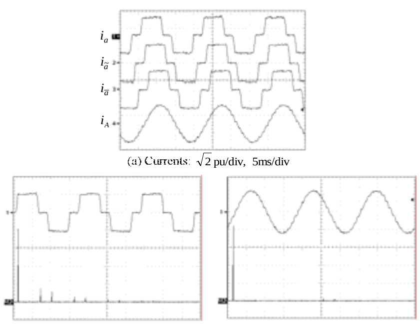
- **Simulated Waveforms**



- **No 5th, 7th, 11th or 13th harmonics in the line current**
- **Lowest harmonic: 17th**
- **Line current THD: 3.06%**

18-Pulse Diode Rectifier

- **Measured Waveforms**

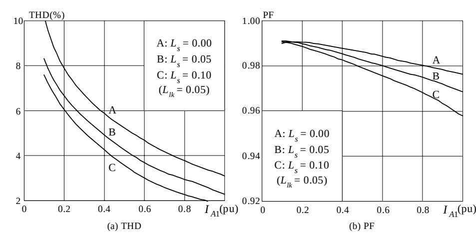


(a) Currents: $\sqrt{2}$ pu/div, 5ms/div

(b) Spectrum: $\sqrt{2}/5$ pu/div, 200Hz/div

18-Pulse Diode Rectifier

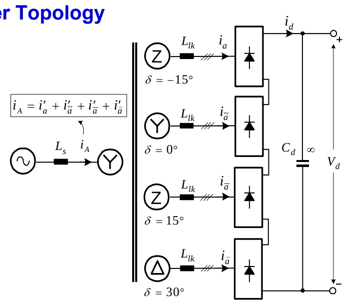
- **THD and PF**



Comparison with 12-pulse: Improved THD

24-Pulse Diode Rectifier

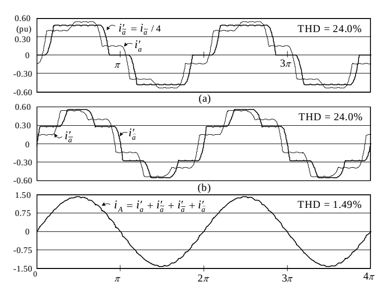
- **Converter Topology**



Phase-Shifting (Zigzag) Transformer

24-Pulse Diode Rectifier

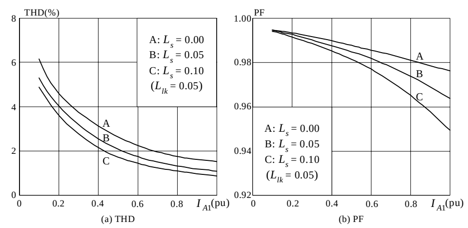
- **Typical Waveforms**



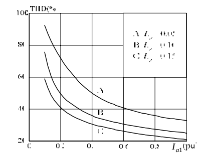
Line current THD: 1.49%

24-Pulse Diode Rectifier

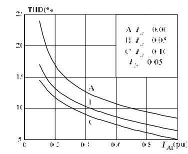
• THD and PF



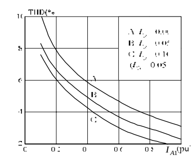
Comparison of Line Current THD



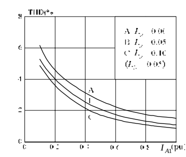
6-pulse rectifier



12-pulse rectifier



18-pulse rectifier



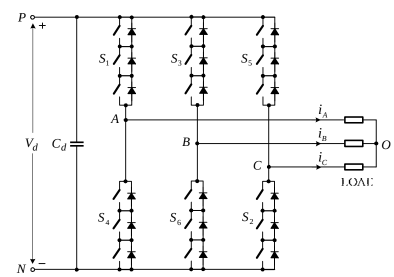
24-pulse rectifier

Topic 3
High-Power Voltage Source Inverters

- Two-Level Voltage Source Inverters (VSI)
- Multilevel Cascaded H-Bridge (CHB) Inverters
- Multilevel Neutral Point Clamped (NPC) Inverters
- Other Multilevel Voltage Source Inverters

Two-Level Voltage Source Inverter

• Inverter Configuration



Two-Level Voltage Source Inverter

• PWM Schemes

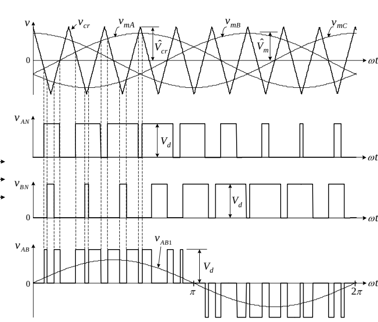
- Sinusoidal pulse width modulation (PWM)
- Space vector modulation (SVM)

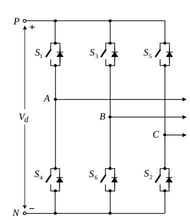
Why Use PWM Techniques?

- To control inverter output frequency (fundamental)
- To control inverter output voltage (fundamental)
- To minimize harmonic distortion

Two-Level Voltage Source Inverter

• Sinusoidal PWM

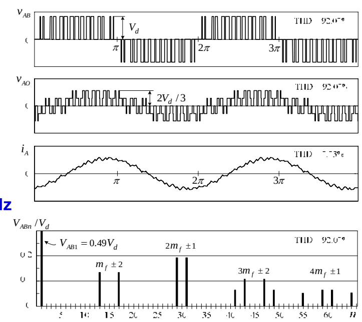




Topic 3 High-Power VSI

Two-Level Voltage Source Inverter

- **Waveforms and FFT**

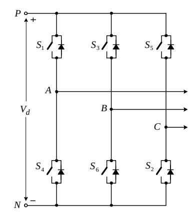


- m_a = 0.8, m_f = 15, f_m = 60Hz, f_{cr} = 900Hz
- Switching frequency $f_{sw} = f_{cr}$ = 900Hz

Topic 3 High-Power VSI

Two-Level Voltage Source Inverter

- **Space Vector Modulation**



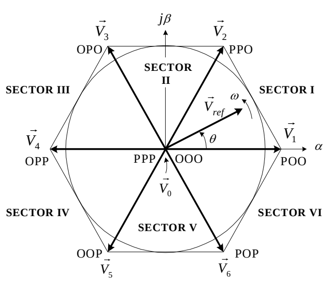
Switching State (Three Phases)	On-state Switch
[PPP]	S_1, S_3, S_5
[OOO]	S_4, S_6, S_2
[POO]	S_1, S_6, S_2
[PPO]	S_1, S_3, S_2
[OPO]	S_4, S_3, S_2
[OPP]	S_4, S_3, S_5
[OOP]	S_4, S_6, S_5
[POP]	S_1, S_6, S_5

Eight switching states

Topic 3 High-Power VSI

Two-Level Voltage Source Inverter

- **Space Vector Modulation**

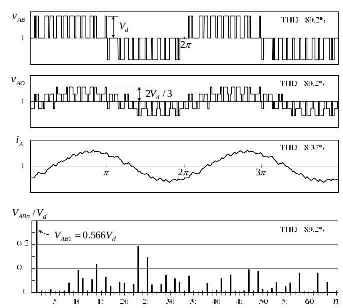


Space Vector Diagram

Topic 3 High-Power VSI

Two-Level Voltage Source Inverter

- **Space Vector Modulation**

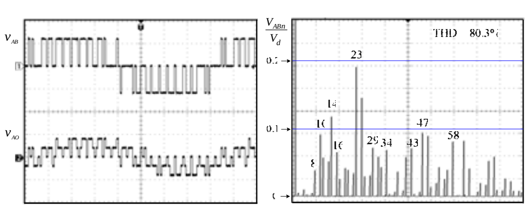


Simulated Waveforms and FFT

Topic 3 High-Power VSI

Two-Level Voltage Source Inverter

- **Space Vector Modulation**



(a) Waveforms 2ms div (b) Spectrum (500Hz div)

Measured Waveforms and FFT

Topic 3 High-Power VSI

Multilevel Cascaded H-Bridge (CHB) Inverters

Why Use Multilevel Inverters?

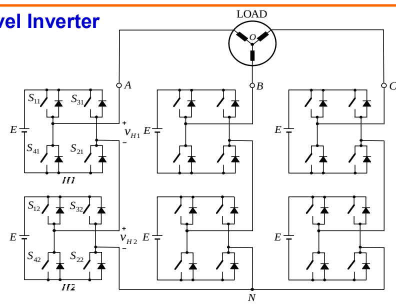
- To increase operating voltage without devices in series
- To minimize THD with low switching frequencies f_{sw}
- To reduce *dv/dt* and EMI

Device Switching Frequency:

f_{sw} < 1000Hz

Multilevel CHB Inverters

• **Five-Level Inverter**

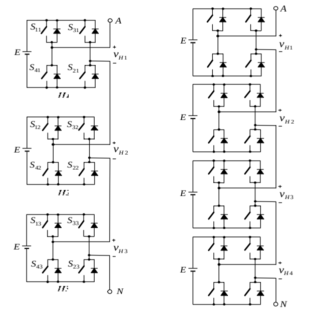


• **Waveform of v_{AN} has five voltage levels:** *2E*, *E*, 0, *-E*, and *-2E*

• **Converters in cascade, but no switching devices in series**

Multilevel CHB Inverters

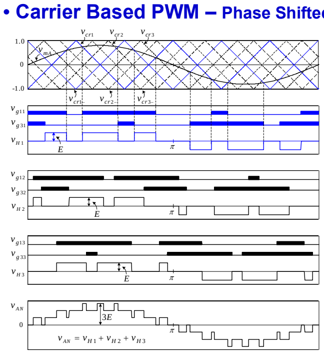
• **Seven- and Nine-Level Inverters (Per phase diagram)**



(a) Seven-level inverter (b) Nine-level inverter

Multilevel CHB Inverters

• **Carrier Based PWM – Phase Shifted**



• **# of voltage levels:** $m = 7$

• **# of carriers:** $m_c = m - 1 = 6$

• **Phase shift:** $360° / m_c = 60°$

Carriers for *H1* bridge: v_{cr1} and v_{cr1-}

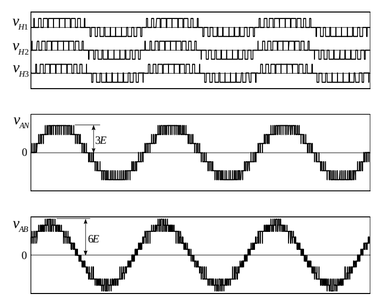
Carriers for *H2* bridge: v_{cr2} and v_{cr2-}

Carriers for *H3* bridge: v_{cr3} and v_{cr3-}

$m = 7$

Multilevel CHB Inverters

• **Carrier Based PWM – Phase Shifted**



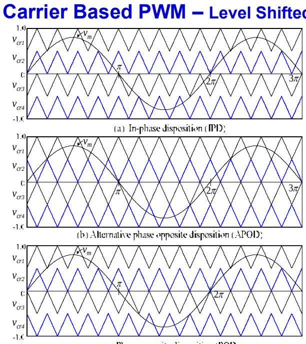
• **Switching occurs at different times**

• **Small voltage steps**
• **Low EMI**
• **Low THD**

Waveforms of a 7- level CHB inverter

Multilevel CHB Inverters

• **Carrier Based PWM – Level Shifted**



(a) In-phase disposition (IPD)

IPD

(b) Alternative phase opposite disposition (APOD)

APOD

(c) Phase opposite disposition (POD)

POD

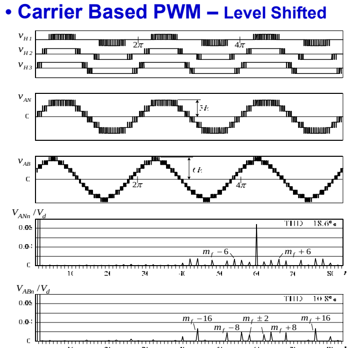
• **# of voltage levels:** $m = 5$

• **# of carriers:** $m_c = m - 1 = 4$

• **IPD provides the best harmonic profile.**

Multilevel CHB Inverters

• **Carrier Based PWM – Level Shifted**



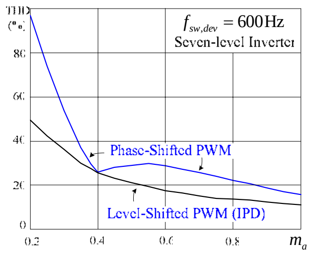
• **Switching occurs at different times**

• **Small voltage steps**
• **Low EMI**
• **Low THD**

Waveforms and FFT of a 7- level CHB inverter with IPD modulation

Multilevel CHB Inverters

• **Modulation Scheme Comparison**

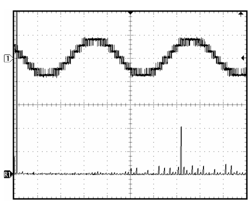


Multilevel CHB Inverters

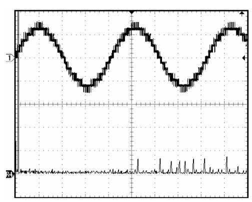
• **Prototype at Ryerson**

Multilevel CHB Inverters

• **Prototype at Ryerson**



Inverter phase voltage v_{AZ}

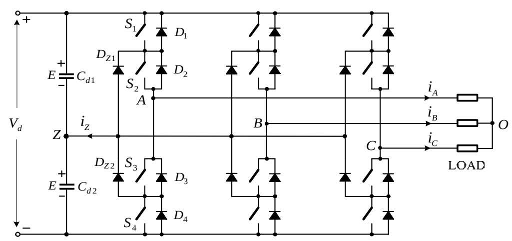


Line-to-line voltage v_{AB}

Measured Waveforms (IPD, 7-level)

Multilevel Neutral Point Clamped (NPC) Inverters

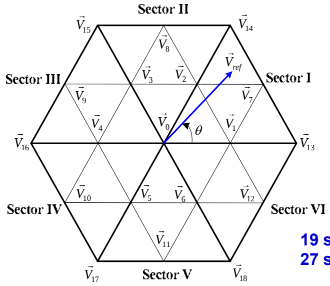
• **Three Level NPC Inverter**



Clamping diodes: D_{Z1} and D_{Z2}

Multilevel NPC Inverters

• **Three Level NPC Inverter**

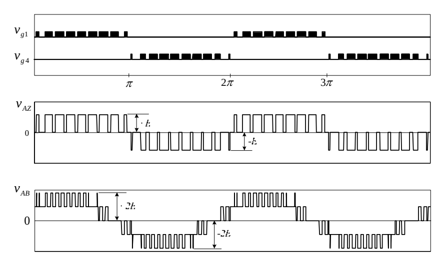


19 space vectors
27 switching states

Space Vectors Diagram

Multilevel NPC Inverters

• **Three Level NPC Inverter**

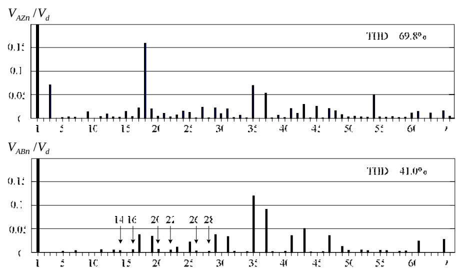


f_1 = 60Hz, T_s = 1/1080 sec, m_a = 0.8, f_{sw} = 570Hz

Simulated Waveforms

Multilevel NPC Inverters

• **Three Level NPC Inverter**



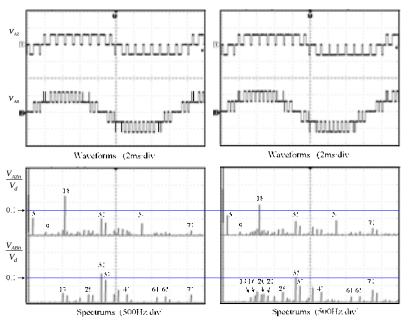
Harmonic Spectrum

Multilevel NPC Inverters

• **Laboratory Prototype at Ryerson**

Multilevel NPC Inverters

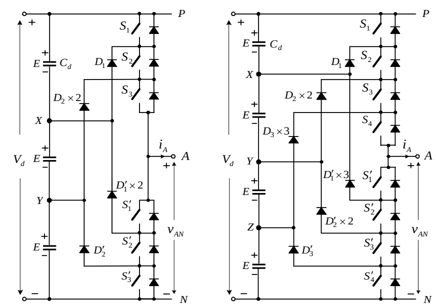
• **Measured Waveforms**



(a) $m_a = 0.8$ (b) $m_a = 0.9$

Multilevel NPC Inverters

• **High-level Topologies** (per phase diagram)



(a) Four-level ($m = 4$) (b) Five-level ($m = 5$)

Multilevel NPC Inverters

• **Component Count**

Voltage Level	Switches	Clamping Diodes*	dc capacitors
m	6(m-1)	3(m-1)(m-2)	(m-1)
3	12	6	2
4	18	18	3
5	24	36	4
6	30	60	5

* The clamping diodes have the same voltage rating as other switches.

Note:
The number of clamping diodes increases substantially with the voltage level.

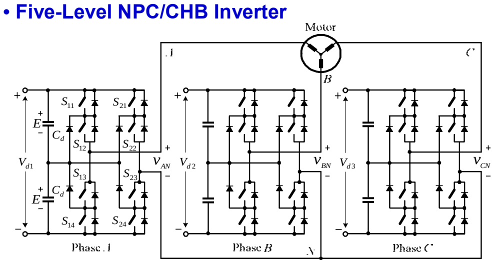
Other Multilevel Voltage Source Inverters

• **NPC/H-Bridge Inverters**

• **Flying-Capacitor Multilevel Inverters**

Other Multilevel Voltage Source Inverters

• **Five-Level NPC/CHB Inverter**



Compared with three-level NPC Topology:
- Voltage levels increases from three to five
- Inverter output voltage and power are doubled
- Device count is doubled19

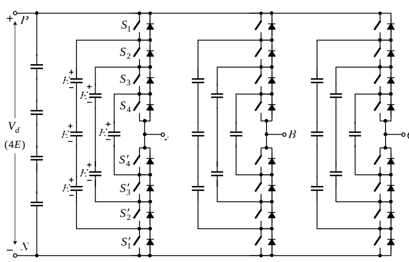
Other Multilevel Voltage Source Inverters

• **Laboratory Prototype at Ryerson**

Five-Level NPC/CHB Inverter

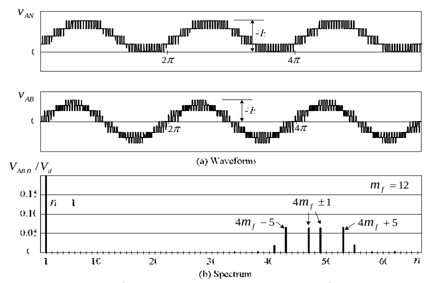
Other Multilevel Voltage Source Inverters

• **Seven-Level Flying Capacitor Inverter**



Other Multilevel Voltage Source Inverters

• **Seven-Level Flying Capacitor Inverter**



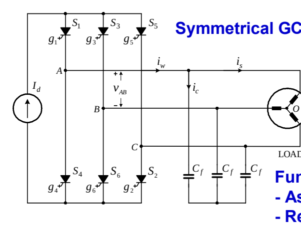
Waveforms and FFT (Phase shifted PWM)

Topic 4
PWM Current Source Converters

- Current Source Inverter (CSI)
- Dual-bridge CSI
- Current Source Rectifier (CSR)
- Dual-bridge CSR

Current Source Inverter

• **Inverter Topology**



Symmetrical GCTs

Function of C_f:
- Assist GCT commutation
- Reduce harmonic distortion

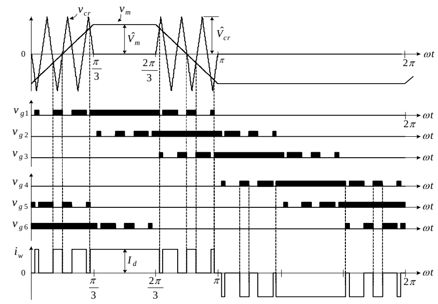
Features:
- Simple topology – no antiparallel diodes
- Reliable short circuit protection – constant dc current
- Very low *dv/dt* on motor terminals

Current Source Inverter

- **PWM Schemes**
  - Trapezoidal PWM (TPWM)
  - Selective Harmonic Elimination (SHE)
  - Space Vector Modulation (SVM)

Current Source Inverter

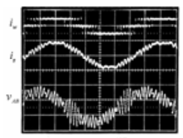
- **Trapezoidal PWM (TPWM)**



Number of pulses per half cycle: $N_p = 7$

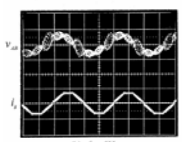
Current Source Inverter

- **Trapezoidal PWM (TPWM)**



(a) $f_1 = 13.8$Hz

$f_1 = 13.8\text{Hz}, N_p = 13,$
$f_{sw} = 180\text{Hz}$

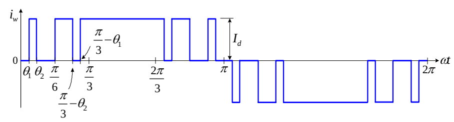


(b) $f_1 = 5$Hz

$f_5 = 5\text{Hz}, N_p = 31,$
$f_{sw} = 155\text{Hz}$

Current Source Inverter

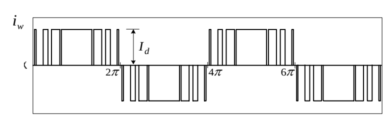
- **Selective Harmonic Elimination (SHE)**

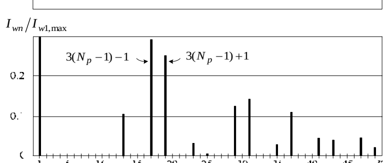


- Switching angles are selected to eliminate low-order Harmonics such as 5th and 7th
- Off-line calculation

Current Source Inverter

- **Selective Harmonic Elimination (SHE)**

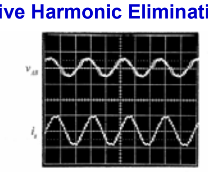




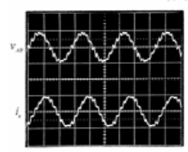
Harmonic eliminated: 5th, 7th and 11th; f_{sw} = 420Hz

Current Source Inverter

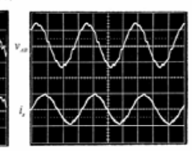
- **Selective Harmonic Elimination (SHE)**



(a) $f_1 = 20$Hz



(b) $f_1 = 35$Hz



(c) $f_1 = 60$Hz

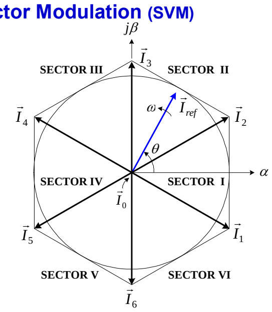
(a)
$f_1 = 20Hz, N_p = 7$
$I_{w5} = I_{w7} = I_{w11} = 0$

(b)
$f_1 = 35Hz, N_p = 5$
$I_{w5} = I_{w7} = 0$

(c)
$f_1 = 60Hz, N_p = 3$
$I_{w5} = 0$

Current Source Inverter

- **Space Vector Modulation** (SVM)

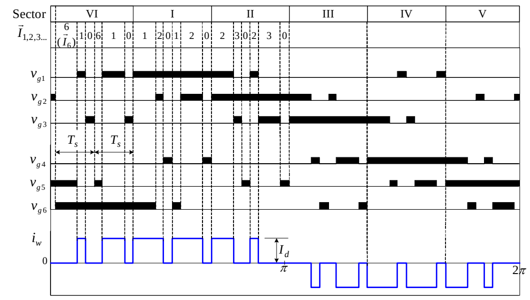


Seven current space vectors

Topic 4 PWM Current Source Converters

Current Source Inverter

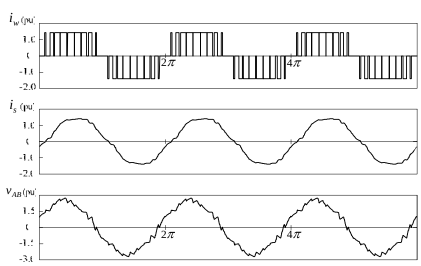
- **Space Vector Modulation** (SVM)



Topic 4 PWM Current Source Converters

Current Source Inverter

- **Inverter Output Waveforms** (SVM)



(a) Waveforms

f_1 = 60Hz, f_{sw} = 540Hz, N_p = 9 and m_a = 1

Topic 4 PWM Current Source Converters

Current Source Inverter

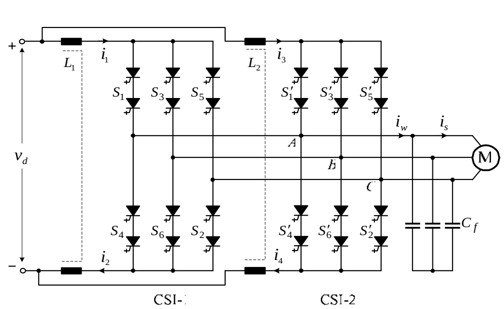
- **PWM Scheme Comparison**

Item	SVM	TPWM	SHE
DC Current Utilization $I_{w1,\max}/I_d$	0.707	0.74	0.73 to 0.78
Dynamic performance	High	Medium	Low
Digital Implementation	Real time	Real time or look-up table	Look-up table
Harmonic Performance	Adequate	Good	Best
dc Current Bypass Operation	Yes	No	Optional

Topic 4 PWM Current Source Converters

Dual-Bridge CSI

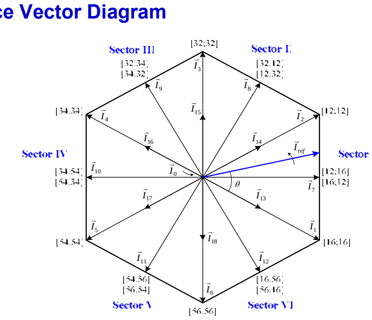
- **Inverter Topology**



Topic 4 PWM Current Source Converters

Dual-Bridge CSI

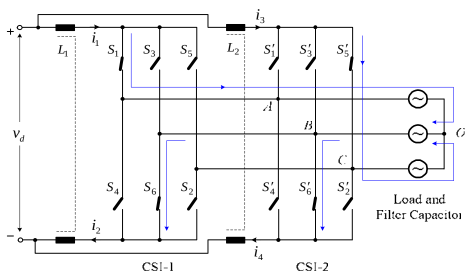
- **Space Vector Diagram**



19 vectors and 51 switching states

Dual-Bridge CSI

- **DC Current Balance Control**



Current paths with switching state [16;56]

Dual-Bridge CSI

- **DC Current Balance Control**

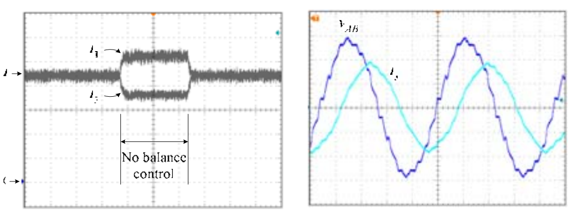
Switching State	Load Voltage	i_1	i_2	i_3	i_4
[16;56] and [16;56]	$v_{AO} = v_{CO}$	×	×	×	×
[16;56]	$v_{AO} > v_{CO}$	↓	×	↑	×
	$v_{AO} < v_{CO}$	↑	×	↓	×
[56;16]	$v_{AO} > v_{CO}$	↑	×	↓	×
	$v_{AO} < v_{CO}$	↓	×	↑	×

Symbol '×': dc currents not affected.

Dc current change with redundant switching states

Dual-Bridge CSI

- **DC Current Balance Control**

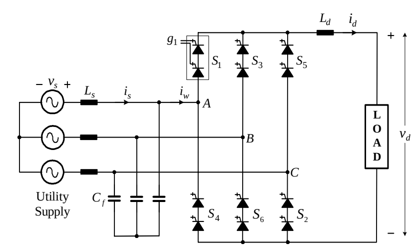


Timebase: 1.0sec/div
(a) dc current transient response

Timebase: 4ms/div
(b) Steady state ac waveforms

Current Source Rectifier

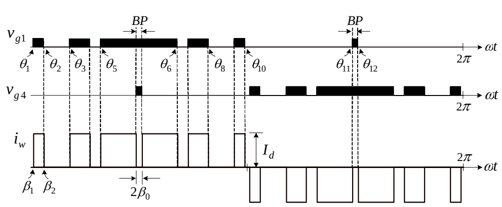
- **Rectifier Topology**



- **Switching devices: Symmetrical GCT**
- **Function of C_f : To assist GCT commutation; To reduce line current THD.**

Current Source Rectifier

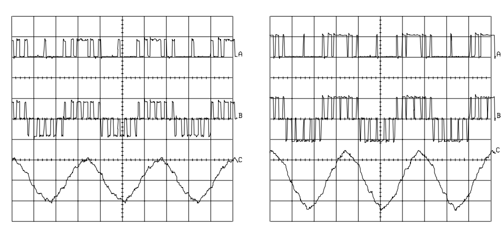
- **Selective Harmonic Elimination (SHE)**



- **Bypass pulse (BP) - make i_w adjustable**

Current Source Rectifier

- **Experiments**



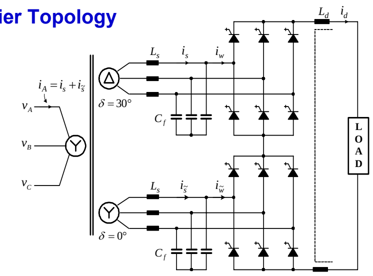
m_a = 0.7

m_a = 0.95

Trace A: current in switch S_1
Trace B: Rectifier input current i_w
Trace C: Line current i_s

Dual-Bridge CSR

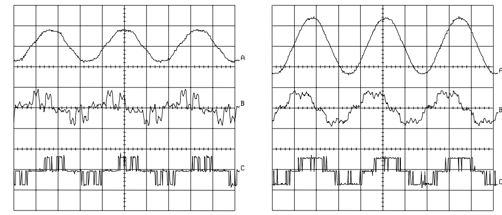
• **Rectifier Topology**



- Use 12-pulse transformer to cancel the 5th and 7th harmonics
- Use PWM to eliminate the 11th and 13th harmonics
- The lowest harmonic in the line current is the 17th
- Very low line current harmonic distortion

Dual-Bridge CSR

• **Experimental Waveforms**



Modulation index: 0.5 Modulation index: 0.9

Trace A: i_A - line current on transformer primary side
Trace B: i_s - line current on transformer secondary side
Trace C: i_w - rectifier input current

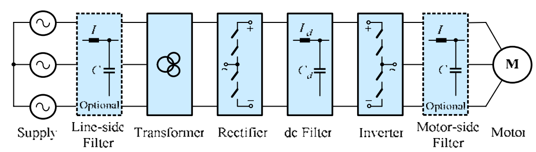
Topic 5
Applications in Motor Drive Industry

- VSI Fed Medium Voltage (MV) Drives
- CSI Fed MV Drives
- Application Examples

Medium Voltage: 2.3KV to 13.8KV

VSI Fed MV Drives

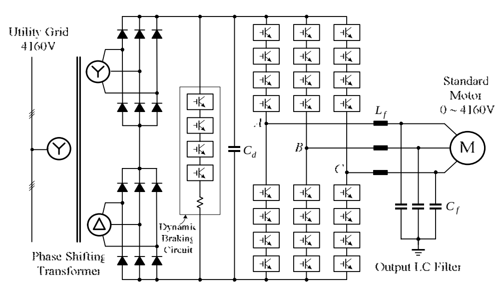
• **Drive Block Diagram**



Line- and motor-side filters:
Optional, depending on converter topologies and harmonic requirements

VSI Fed MV Drives

• **Two-Level VSI Drive**



VSI Fed MV Drives

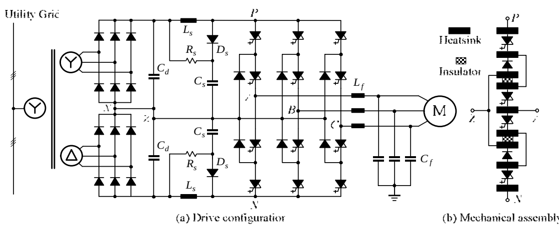
• **Two-Level VSI Drive**

Features
- Modular structure using PCBB
- Simple PWM Scheme
- Active voltage clamping for series connected IGBTs
- N+1 Provision
- Ease of dc capacitor precharging
- Provision for four-quadrant operation and regenerative braking

Drawbacks
- High *dv/dt* in the inverter output voltage
- Large size output LC filter

VSI Fed MV Drives

- **NPC Inverter Fed Drives**



Three-Level GCT Inverter

VSI Fed MV Drives

- **NPC Inverter Fed Drives**

Three-Level GCT Inverter Source: ABB

VSI Fed MV Drives

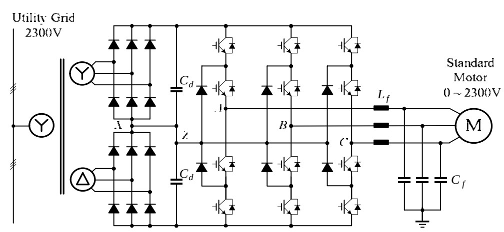
- **NPC Inverter Fed Drives**

Main Specifications (with GCT Inverter)

Nominal input voltage	2300V, 3300V, 4160V
Output power rating	400 ~ 6700HP (0.3 ~ 5 MW)
Output voltage rating	0 ~ 2300V, 0 ~ 3300V, 0 ~ 4160V
Output frequency	0 ~ 66Hz (up to 200Hz optional)
Drive system efficiency	Typically > 98.0% (including output filter losses but excluding transformer losses)
Input power factor	> 0.95% (Displacement power factor > 0.97)
Output waveform	Sinusoidal (with output filter)
Motor type	Induction or synchronous
Overload capability	Standard: 10% for one minute every 10 minutes Optional: 150% for one minute every 10 minutes
Cooling	Forced air or liquid
Mean time between failure (MTBF)	> 6 years
Regenerative braking capability	No

VSI Fed MV Drives

- **NPC Inverter Fed Drives**



Drive Configuration (with IGBT Inverter)

VSI Fed MV Drives

- **NPC Inverter Fed Drives**

SIMOVERT MV Courtesy of Siemens

IGBT based three-level NPC inverter fed drive

VSI Fed MV Drives

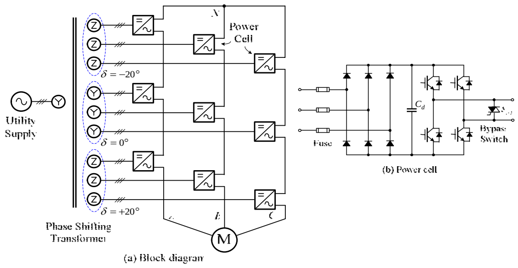
- **NPC Inverter Fed Drives**

Main Specifications (With IGBT Inverter)

Rectifier	Standard: 12-pulse diode rectifier Optional: 24-pulse diode rectifier or active front end (PWM IGBT rectifier)
Displacement power factor ($\cos\varphi$)	> 0.96 (12-pulse diode rectifier)
Nominal utility/motor voltage	2300V, 3300V, 4160V, 6600V
Output power rating	0.8 ~ 2.4MW @2300V 1.0 ~ 3.1MW @3300V 1.3 ~ 4.0MW @4160V 4.7 ~ 7.2MW @4160V (Parallel converter configuration) 0.6 ~ 2.0MW @6600V
Output voltage range	0 ~ 2300V, 0 ~ 3300V, 0 ~ 4160V, 0 ~ 6600V
Output frequency	0 ~100Hz (standard)
Motor speed range	1:1000 (with encoder)
Drive system efficiency	Typically > 98.5% (at rated operating point, excluding transformer losses)

VSI Fed MV Drives

- **CHB Inverter Fed Drives**



Seven-Level CHB Inverter Fed Drive

VSI Fed MV Drives

- **CHB Inverter Fed Drives**

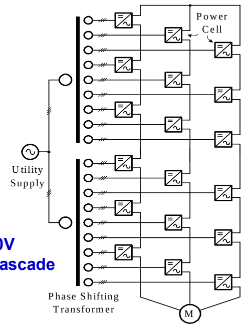
Drive Configuration

Rated Utility/Motor Voltage	Multipulse Diode Rectifier: Rectifier Pulses	Secondary Windings	Transformer Secondary Cables	Multilevel CHB Inverter: Power Cells	IGBTs	Voltage Levels	Rated H-Bridge Output	$f_{sw,IGBT}$	$f_{sw,inv}$
2300V	18	9	27	9	36	7	480V	600Hz	3600Hz
3300V	24	12	36	12	48	9	480V	600Hz	4800Hz
4160V	30	15	45	15	60	11	480V	600Hz	6000Hz

Typical power range: 0.3 ~ 10MW (400 ~ 14000HP)

VSI Fed MV Drives

- **CHB Inverter Fed Drives**



Two units of 3300V CHB inverter in cascade

VSI Fed MV Drives

- **CHB Inverter Fed Drives**

Perfect Harmony, Courtesy of ASI Robicon

IGBT based cascaded H-bridge inverter fed MV drive (4.16KV / 7.5MW)

VSI Fed MV Drives

- **CHB Inverter Fed Drives**

Features
- **Modular design for cost reduction**
- **Nearly sinusoidal inputs and output currents without LC filters**
- **Provision for N+1 design for high reliability**

Drawbacks
- **Costly phase shifting transformers**
- **Large number of cables between transformer secondaries and power converters**
- **The transformer normally installed inside cabinet – larger footprint, more cooling requirement**

CSI Fed MV Drives

- **PWM CSI Fed Drive**

PowerFlex 7000 Frame A, Rockwell Automation Canada

CSI GCT Drive System

CSI Fed MV Drives

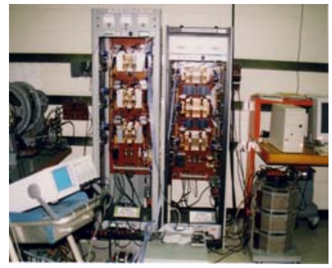
• **PWM CSI Fed Drive**

PowerFlex 7000 Frame C, Rockwell Automation Canada

4160V / 7MW GCT Drive System

CSI Fed MV Drives

• **Prototype of CSI Drive at Ryerson**



Successful research collaboration with Rockwell Automation for over 13 years

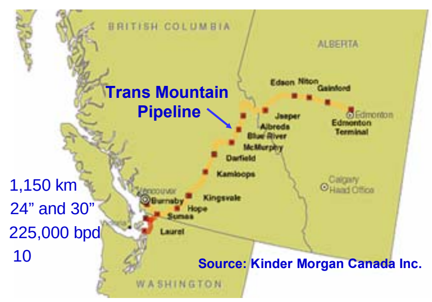
Drive Application Examples

Mining / cement, Petrochemical, Metals, Paper / pulp, Marine, Oil / gas, Power generation, Water / waste water

Source: Robicon

Drive Application Examples

• **Megawatt Drive for Pipeline Pumps**



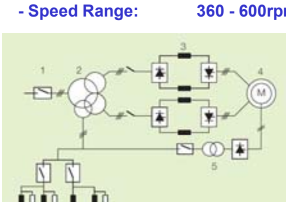
Length: 1,150 km
Pipe Size: 24" and 30"
Capacity: 225,000 bpd
Pump stations: 10

Source: Kinder Morgan Canada Inc.

Drive Application Examples

• **100MW Wind Tunnel Drive**

- Application: NASA wind tunnel
- Motor: Synchronous, 100MW, 12.5KV
- Load: High power fan
- Speed Range: 360 - 600rpm

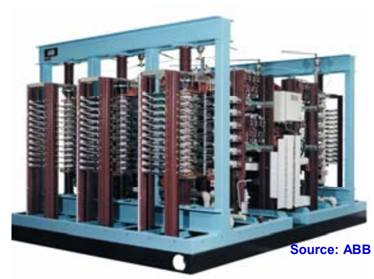


Source: ABB

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

Drive Application Examples

• **100MW Wind Tunnel Drive**



Source: ABB

Load Commutated Current Source Inverter

Topic 5 Applications in Drive Industry

Drive Application Examples

• **100MW Wind Tunnel Drive**

Source: ABB

Six-phase synchronous motor
(100MW, 12.5KV, 2.8KA)

Topic 5 Applications in Drive Industry

Drive Application Examples

• **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)
	IGBT	0.5MVA – 6MVA	Toshiba (TOSVERT-MV)
	IGBT	0.45MVA – 7.5MVA	General Electric (Innovation MV-GP Type H)

Topic 5 Applications in Drive Industry

Drive Application Examples

• **Summary**

Inverter Configuration	Switching Device	Power Range	Manufacturer
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)
	SCR	>10MVA	ABB (LCI)
	SCR	>10MVA	Alstom (ALSPA SD7000)

Topic 5 Applications in Drive Industry

Ryerson LEDAR Research Lab

Laboratory for Electric Drive Applications and Research (LEDAR)

The best research facility in high-power converters
and AC drives in a Canadian university

CFI Rockwell Automation NSERC CRSNG Honeywell Ontario Innovation Trust

Topic 6
Applications in Wind Energy Industry

• **Introduction**

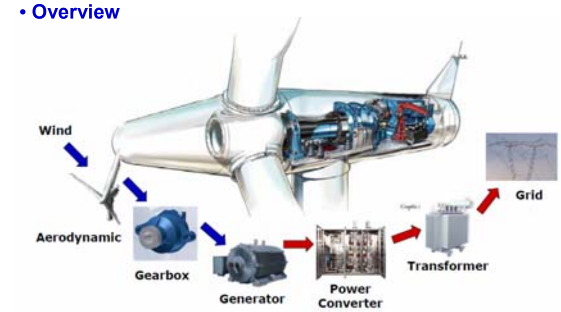
• **Doubly Fed Induction Generator**

• **Direct-Drive Synchronous Generator**

Topic 6 Applications in Wind Energy Industry

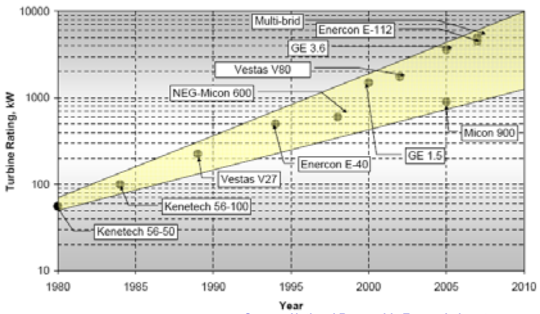
Introduction

• **Overview**



Topic 6 Applications in Wind Energy Industry
Introduction

• **Wind Generator Power Rating**

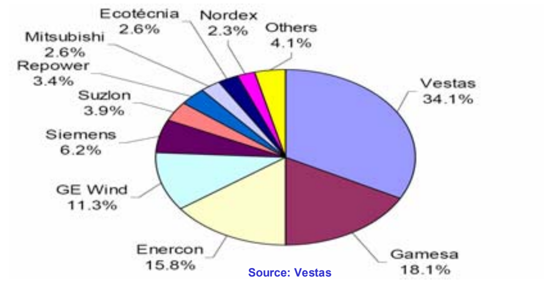


Source: National Renewable Energy Laboratory

Topic 6 Applications in Wind Energy Industry
Introduction

• **Market Survey**

World Market Share in 2004



Source: Vestas

Topic 6 Applications in Wind Energy Industry
Introduction

• **Market Survey**

Wind Energy Installation as of December 2005

	Country/ Region	Additional capacity in 2005 (MW)	Rate of growth 2005 (%)	Total capacity installed end 2005 (MW)
1	Germany	1798,8	10,8	18.427,5
2	Spain	1764,0	21,3	10.027,0
3	USA	2424,0	36,0	9.149,0
4	India	1430,0	47,7	4.430,0
5	Denmark	4,0	0,1	3.128,0
6	Italy	452,4	35,8	1.717,4
7	United Kingdom	465,0	52,4	1.353,0
8	China	496,0	64,9	1.260,0

Source: http://www.wwindea.org

Topic 6 Applications in Wind Energy Industry
Introduction

• **Market Survey**

Wind Energy Installation as of December 2005

	Country/ Region	Additional capacity in 2005 (MW)	Rate of growth 2005 (%)	Total capacity installed end 2005 (MW)
8	China	496,0	64,9	1.260,0
9	The Netherlands	141,0	13,1	1.219,0
10	Japan	143,8	16,0	1.040,0
11	Portugal	500,0	95,8	1.022,0
12	Austria	213,0	35,1	819,0
13	France	371,2	96,2	757,2
14	Canada	239,0	53,8	683,0
15	Greece	100,3	21,2	573,3

Source: http://www.wwindea.org

By June 2006, the installed capacity in Canada reaches 1049MW

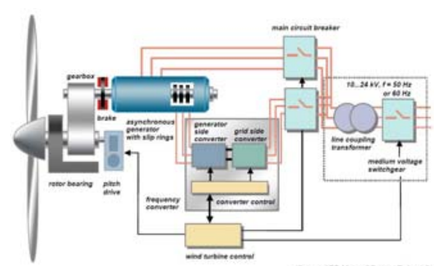
Topic 6 Applications in Wind Energy Industry
Introduction

• **Products Overview**

	Zephyros	GE Energy	Siemens	Vestas	REpower	Multibrid	Enercon
Type	Z72	3.6s	3.6 MW	V120	5M	M5000	E112
Rated Power	2MW	3.6MW	3.6MW	4.5MW	5MW	5MW	4.5-6MW
Gearbox	Gearless	3-Stage	3-Stage	3-Stage	3-Stage	1-Stage	Gearless
Generator	PMSG	DFIG	Squirrel Cage IG	High Voltage DFIG	DFIG	PMSG	Electrical Excited SG
Converter	4-quadrant IGCT Converter	4-quadrant IGBT Converter	Fully Automated Converter	Frequency Converter	4-quadrant IGBT Converter	4-quadrant GTO Converter	Intermediate Circuit Converter
Rotor Diameter	70m	104m	107m	120m	126m	116m	114m

Source: OffshoreWind.de

Topic 6 Applications in Wind Energy Industry
Doubly Fed Induction Generator



(Source ABB Motors&Drives, Finland ©)

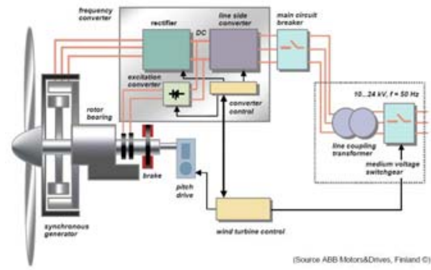
✓ Variable speed
✓ Low converter rating
✓ Active and reactive power control

• Brushes, high maintenance
• Large gearbox, high cost and maintenance
• Limited grid connection performance

Topic 6 Applications in Wind Energy Industry

Direct Drive Synchronous Generator (SG)

• Conventional SG



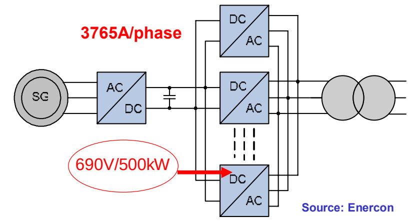
✓Direct driven, no gear box.
✓Completely decoupled from grid.

• Full power converter
• Excitation circuit
• Brushes

Topic 6 Applications in Wind Energy Industry

Direct Drive Synchronous Generator (SG)

• Examples: Enercon E112 (4.5-6MW)

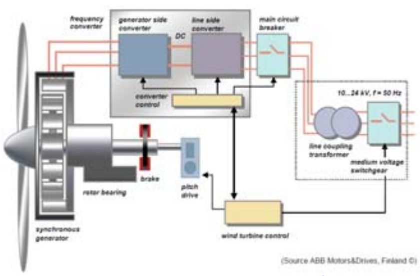


E112

Topic 6 Applications in Wind Energy Industry

Direct Drive Synchronous Generator (SG)

• Permanent Magnet SG



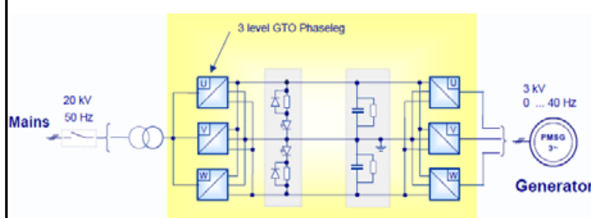
✓ Direct driven, no gear box
✓ Completely decoupled from grid

• Full power Converter
• Possible de-magnetization
• No flux control capability

Topic 6 Applications in Wind Energy Industry

Direct Drive Synchronous Generator (SG)

• Examples - Multibrid M5000 (5MW PMSG)



Source: Alstom

Converter: ALSPA VDM7000

Topic 6 Applications in Wind Energy Industry

Ryerson LEDAR – WindTech

An application has been submitted to CFI to establish an advanced Wind Technology research facility at Ryerson

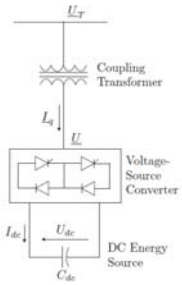
Topic 7
Applications in Power/Utility Industry

- **FACTS - Flexible AC Transmission Systems**
  - Static Synchronous Compensator (STATCOM)
  - Static Synchronous Series Compensator (SSSC)
  - Unified Power Flow Controller (UPFC)
- **Custom Power Devices**
  - Dynamic Voltage Restorer (DVR)
  - Distribution Static Synchronous Compensator (D-STATCOM)
  - Active Power Filter (APF)
- **HVDC – High Voltage DC Transmission**

Topic 7 Applications in Power/Utility Industry

FACTS - STATCOM

• **Configuration**



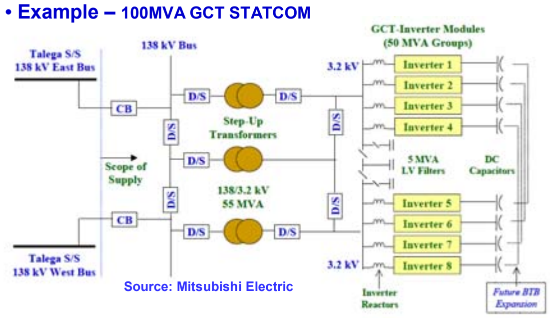
Source: Toshiba Electric

Purpose: To provide reactive power for voltage regulation

Topic 7 Applications in Power/Utility Industry

FACTS - STATCOM

• **Example – 100MVA GCT STATCOM**



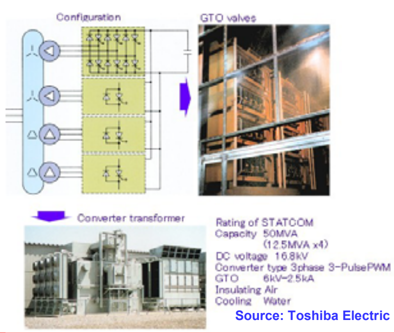
Source: Mitsubishi Electric

Talega ±100 MVA, 138 kV STATCOM system

Topic 7 Applications in Power/Utility Industry

FACTS - STATCOM

• **Example – 50MVA GTO STATCOM**



Source: Toshiba Electric

Topic 7 Applications in Power/Utility Industry

FACTS - STATCOM

• **STATCOM Installation in USA**

Year	Customer	Location	Voltage	Control range	Remarks	Supplier
1995	Tennessee Valley Authority (TVA)	Sullivan Substation (Johnson City, Tennessee)	161kV	±100MVar	GTO thyristor valves	Westinghouse Electric Corporation
2000	American Electric Power (AEP)	Eagle Pass Station (Texas)	138kV	±36MVar	Back to Back scheme	ABB
2001	Vermont Electric Power	Essex station (Burlington, Vermont)	115kV	-41 to +133MVar	GCT based STATCOM	Mitsubishi
–	Central & South West Services	Laredo and Brownsville stations (Texas)	–	±150MVar	–	W-Siemens

Source: Oak Ridge National Laboratory

Topic 7 Applications in Power/Utility Industry

FACTS - STATCOM

• **STATCOM Installation in USA**

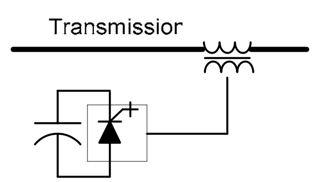
Year	Customer	Location	Voltage	Control range	Remarks	Supplier
2003	San Diego Gas & Electric (SDG&E)	Talega station (Southern California)	138kV	±100MVar	GCT based STATCOM	Mitsubishi
2003	Northeast Utilities (NU)	Glenbrook station (Hartford, Connecticut)	115kV	±150MVar	–	Areva (Alstom)
2004	Austin Energy	Holly (Texas)	138kV	-80 to +110MVar	IGBT based STATCOM	ABB

Source: Oak Ridge National Laboratory

Topic 7 Applications in Power/Utility Industry

FACTS – SSSC

• **Operating Principle**

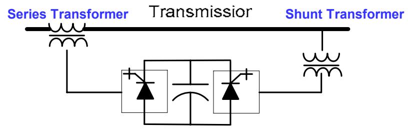


➤ Emulate a variable inductor or a capacitor in ***series*** with the transmission line by generating a voltage in quadrature with the line current

➤ The emulated inductive or capacitive reactance regulates the effective line reactance between its two ends

FACTS – UPFC

- **Operating Principle**



- Combines STATCOM and SSSC which are coupled via a common DC link
- Allows bi-directional flow of real power between the STATCOM and SSSC without external energy source
- Controls power flow, voltage and power factor, allowing optimal use of existing lines

FACTS – UPFC

- **Example – 160MVA 138kV UPFC (GTO Based)**

UPFC Equipment

GTO valve hall

Source: AEP Inez UPFC Project

FACTS - UPFC

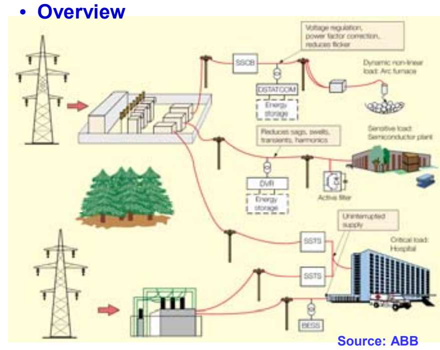
- **List of UPFC in operation**

Year Installed	Country	Capacity	Voltage level	Place
1998	USA	±320MVA	138KV	AEP Inez substation
2003	South Korea	80MVA	154KV	Gangjin substation

Source: Asian Institute of Technology

Custom Power Devices

- **Overview**



Source: ABB

D-STATCOM: Distribution Static Synchronous Compensator

DVR: Dynamic Voltage Restorer

Active Filters

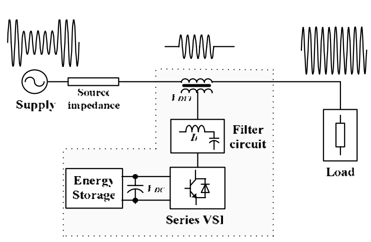
SSTS: Solid-State Transfer Switch

SSCB: Solid-State Circuit Breaker

BESS: Battery Energy Storage System

Custom Power Device – DVR

- **Operating Principle**



Compensates voltage sags by injecting a voltage in ***series*** with the incoming voltage

Custom Power Device – DVR

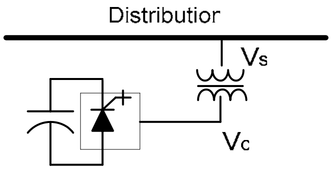
- **Example – 4MW 21kV DVR (IGCT Based)**

Compensation capacity:
3-phase: 38% voltage sag
1-phase: 50% voltage sag

Source: ABB

Custom Power Device – DSTATCOM

- **Operating Principle**



- Similar to its larger STATCOM cousin, but having greater a speed and flexibility due to faster switching devices at lower power distribution level
- Provides power quality solutions: flicker suppression, voltage and system stabilization, power factor correction etc.

Custom Power Device – DSTATCOM

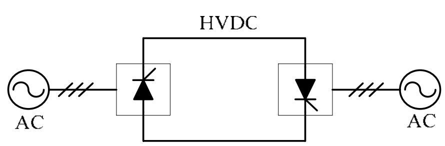
- **Example – 5MVA, 4.16kV D-STATCOM (IGBT Based)**

Project Name	Seattle Iron & Metals Corporation D-STATCOM System Project
Commissioned	January 2000
Location	Seattle, Washington, USA
Dynamic Rating	0 to +5 Mvar
System Voltage	4.16 / 26.4 kV-ac
Converter Type	2-Level Voltage Sourced Converter Design
Configuration	5 Converter Sets in Parallel
IGBT Ratings	1.2-kV / 600-A
Control	High Frequency Control for Flicker Suppression Application

Source: Mitsubishi Electric

HVDC

- **Overview**

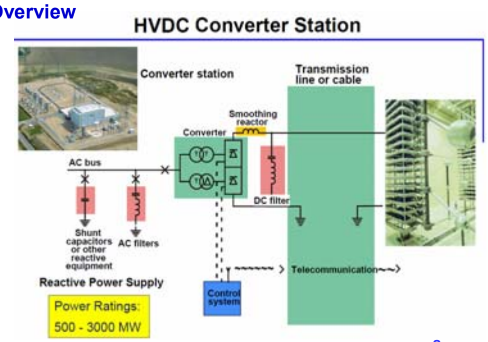


Main Benefits of HVDC

- Long distance
- Network stability
- Low losses
- Environmental concerns

HVDC

- **Overview**



Source: ABB

HVDC

- **Example 1 – HVDC Transmission Québec - New England**

Source: ABB

Main data	
Commissioning year:	1990 - 1992
Power rating:	2000 MW
DC voltage:	±450 kV
Length of overhead DC line:	1,480 km
Main reason for choosing HVDC: Long distance, asynchronous networks	

HVDC

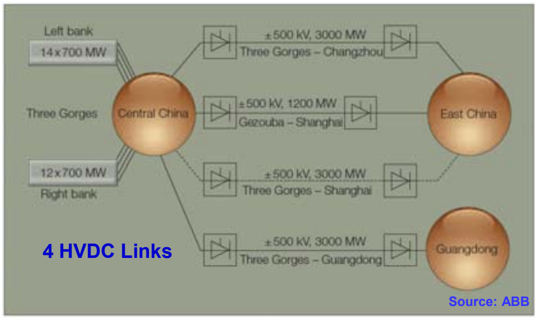
- **Example 1 – HVDC Transmission Québec - New England**

Source: ABB

Radisson Converter Station

HVDC

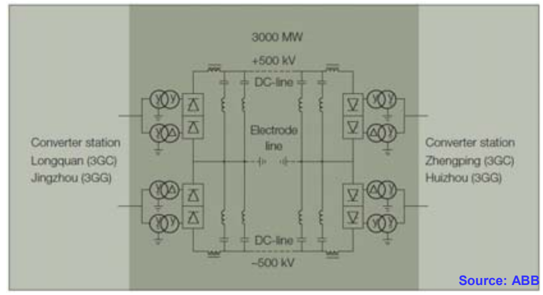
• **Example 2 – HVDC Project in China**



HVDC

• **Example 2 – HVDC Project in China**

3000MW HVDC from Three Gorges to Guangdong



HVDC

• **Example 2 – HVDC Project in China**

3000MW HVDC from Three Gorges to Guangdong


Overview

Thyristor valve hall

Length of overhead DC line: 940 km

High-Power Converters and Applications in Drive/Wind/Power Industries