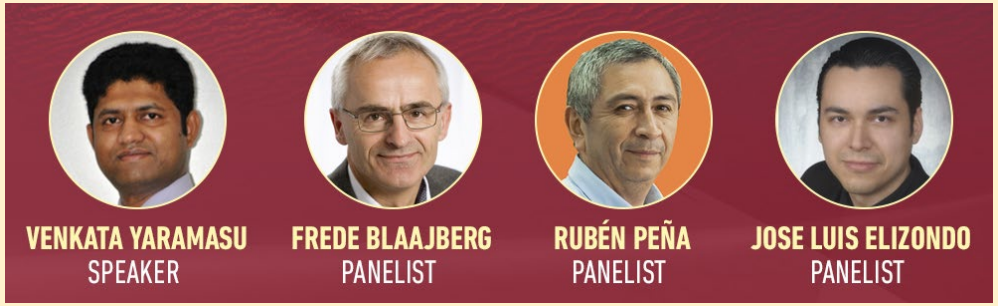
Permanent Magnet Synchronous Generator-Based Wind Energy Systems

Dr. Venkata Yaramasu

School of Informatic, Computing and Cyber Systems

Northern Arizona University, Flagstaff, AZ, USA



NAU NORTHERN ARIZONA UNIVERSITY

School of Informatics, Computing, and Cyber Systems

AMPERE

Advanced Motors, Power Electronics, and Renewable Energy Laboratory

CENTRO TECNOLÓGICO DE CONVERSIÓN DE ENERGÍA

FACULTAD DE INGENIERÍA UNIVERSIDAD DE TALCA

MacroFacultad Ingeniería - Chile

pels IEEE POWER ELECTRONICS SOCIETY Powering a Sustainable Future Chile Section Chapter

SERC CHILE SOLAR ENERGY RESEARCH CENTER

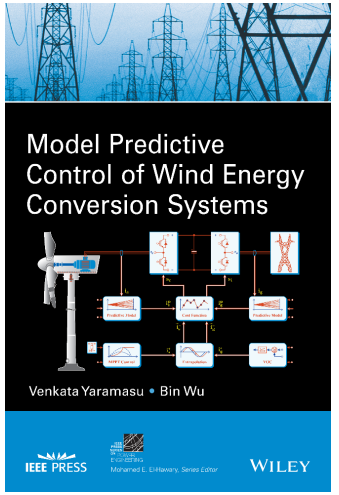
Contents of Presentation

- Introduction
- Power Converters for PMSG WECS
  - Low Voltage
  - Medium Voltage
- Control Schemes for PMSG WECS
  - Classical Control
  - Predictive Control
  - Modulated Predictive Control
- Future Trends

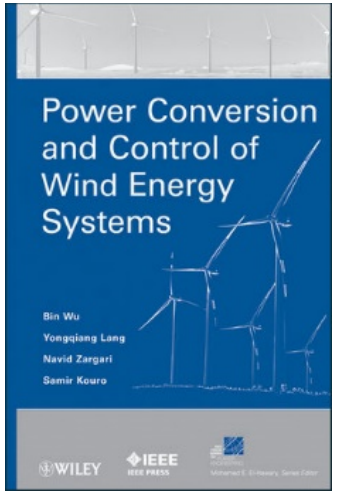
Reference Materials

V. Yaramasu, and B. Wu, "*Model Predictive Control of Wind Energy Conversion Systems*," Wiley–IEEE Press, IEEE Press Series on Power Engineering, 459 pages, 3 parts with 12 chapters, February 2017, ISBN: 9781118988589.

http://www.wiley.com/WileyCDA/WileyTitle/productCd-1118988582.html



B. Wu, K. Lang, N. Zargari and S. Kouro, *Power Conversion and Control of Wind Energy Systems*, Wiley- IEEE Press, 2011, ISBN 978-0-470-59365-3.



Introduction

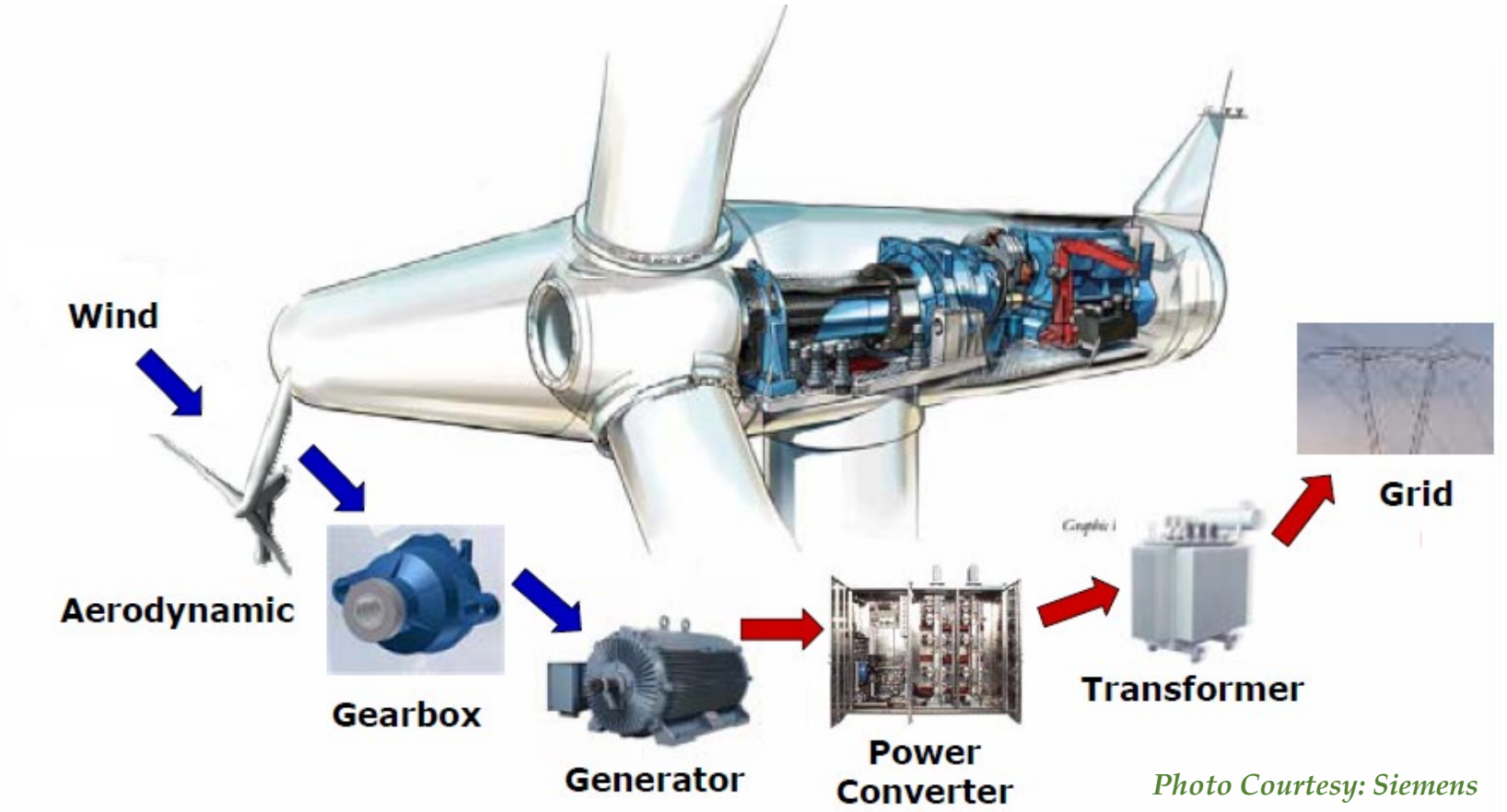


Photo Courtesy: Siemens

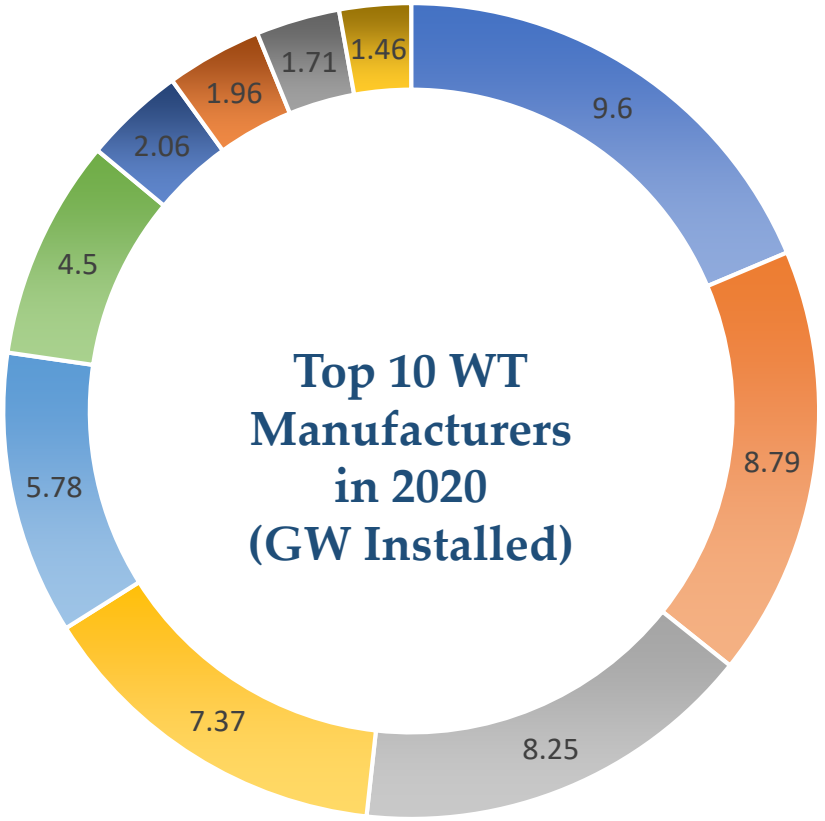
Kinetic Energy in Wind → Mechanical Energy → Electrical Energy

Wind Kinetic Energy to Electric Energy Conversion

Introduction

- Permanent magnet synchronous generator (PMSG)-based wind turbines surpassed the market share of doubly-fed induction generator (DFIG)-based turbines in 2017.
- Permanent magnet synchronous generator (PMSG) is main-stream solution for wind turbines due to efficient energy production, gearless construction, self-rotor field excitation, simple control, and increased reliability.
- Offshore wind farms are gaining attention in recent years.
- Back-to-back (BTB) connected voltage source converter (VSC) is used by many manufacturers to connect the PMSG wind turbines to the electrical network.

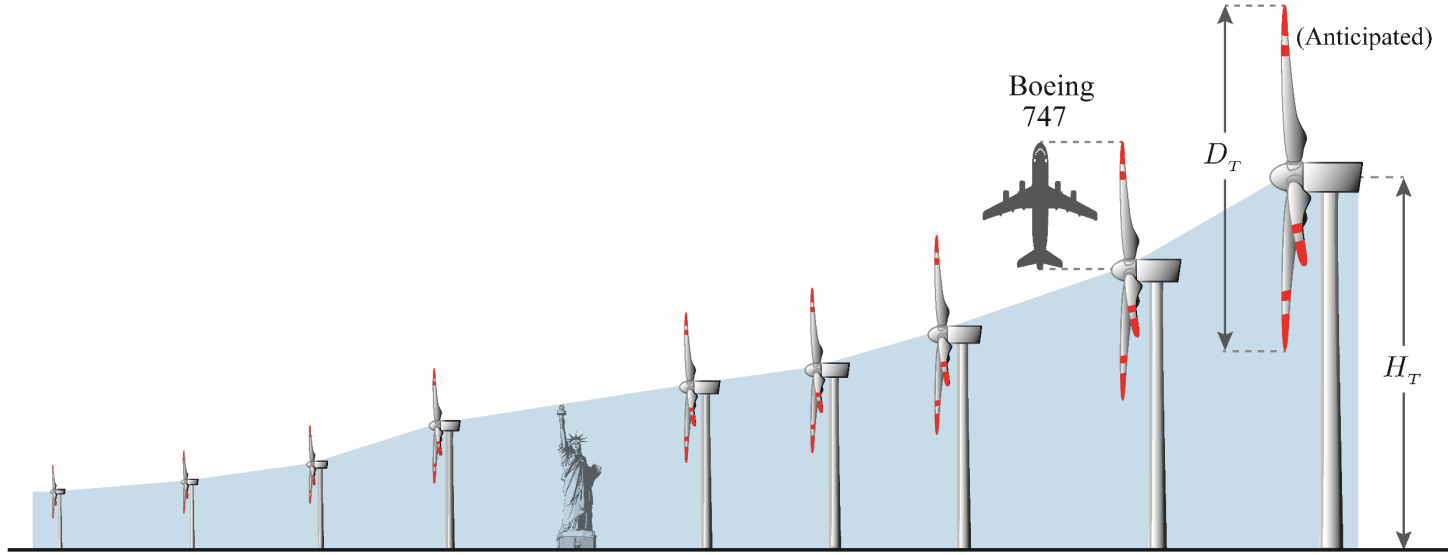
Introduction → Market Share of Turbines



- Vestas (DK) - PMSG, DFIG
- Siemens Gamesa (ES) - PMSG, SCIG
- Goldwind (PRC) - PMSG
- GE Energy (USA) - PMSG, DFIG
- Envision (PRC) - PMSG, DFIG
- Ming Yang (PRC) - PMSG, DFIG
- Windey (PRC) - PMSG
- Nordex (GE) - DFIG
- Shanghai Electric (PRC) - PMSG
- CSIC (PRC) - PMSG

PMSG is commercialized by 9 out of top 10 wind turbine manufacturers in 2020.

Introduction → Growth in the size of Turbines



	1980	1985	1990	1995	Statue	2000	2005	2010	2015	2020
P_T (MW)	0.05	0.1	0.5	0.8	of	2	5	7.5	10	15-20
D_T (m)	15	20	40	50	Liberty	124	126	127	190	200-250
H_T (m)	24	43	54	80	93	104	114	135	180	200-250

- Wind turbines above 5 MW dominate the present market
- 15-20 MW turbines will be in market by 2020 (Clipper, Sway Turbine, Sinovel, Mitsubishi, Goldwind, Mecal, MingYang, United Power, GE Energy, and Gamesa announced projects)
- Large wind turbines: Siemens Gamesa's 14-222 DD (14 MW), GE Haliade-X (12 MW), Vestas V164 (10 MW)

Introduction → Large Turbines

MHI Vestas V164-9.5MW

Siemens Gamesa SG 8.0-167 DD

Goldwind GW154 6.7MW

GE Haliade 150-6MW

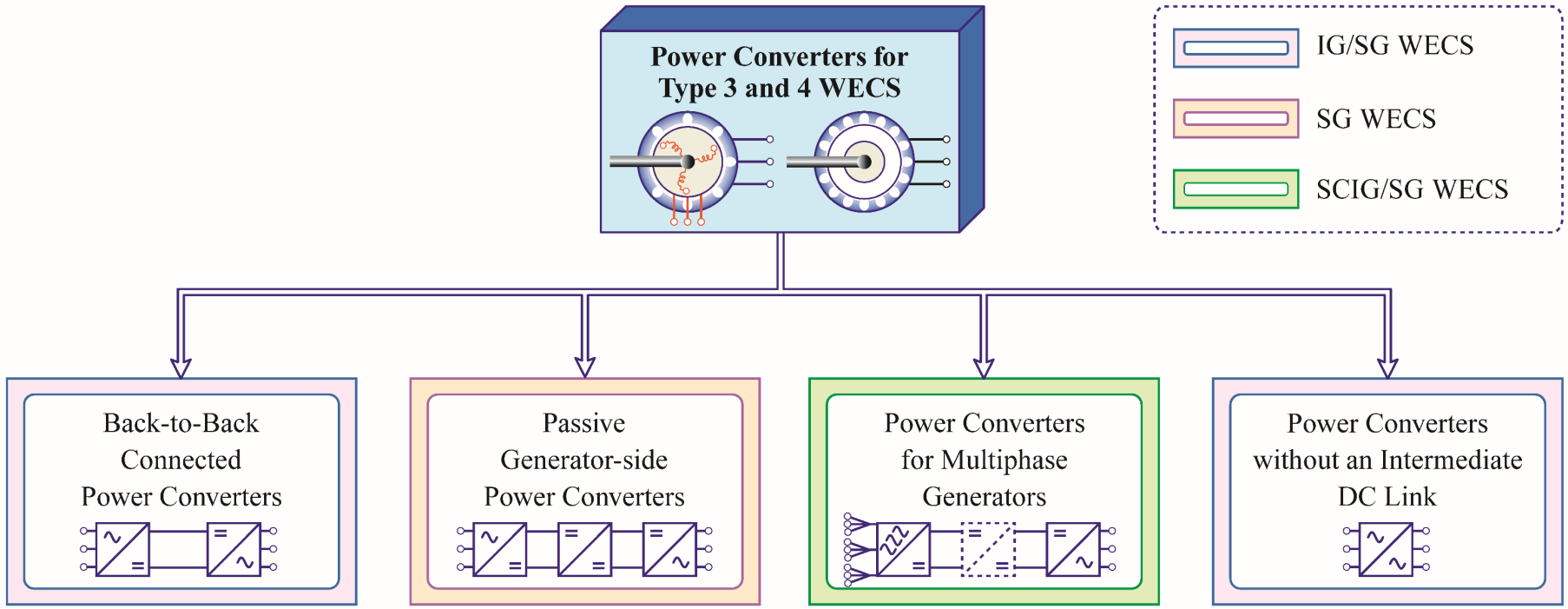
Ming Yang SCD 6.0

Adwen AD 5-135

Introduction → Powerful Turbine in the Market

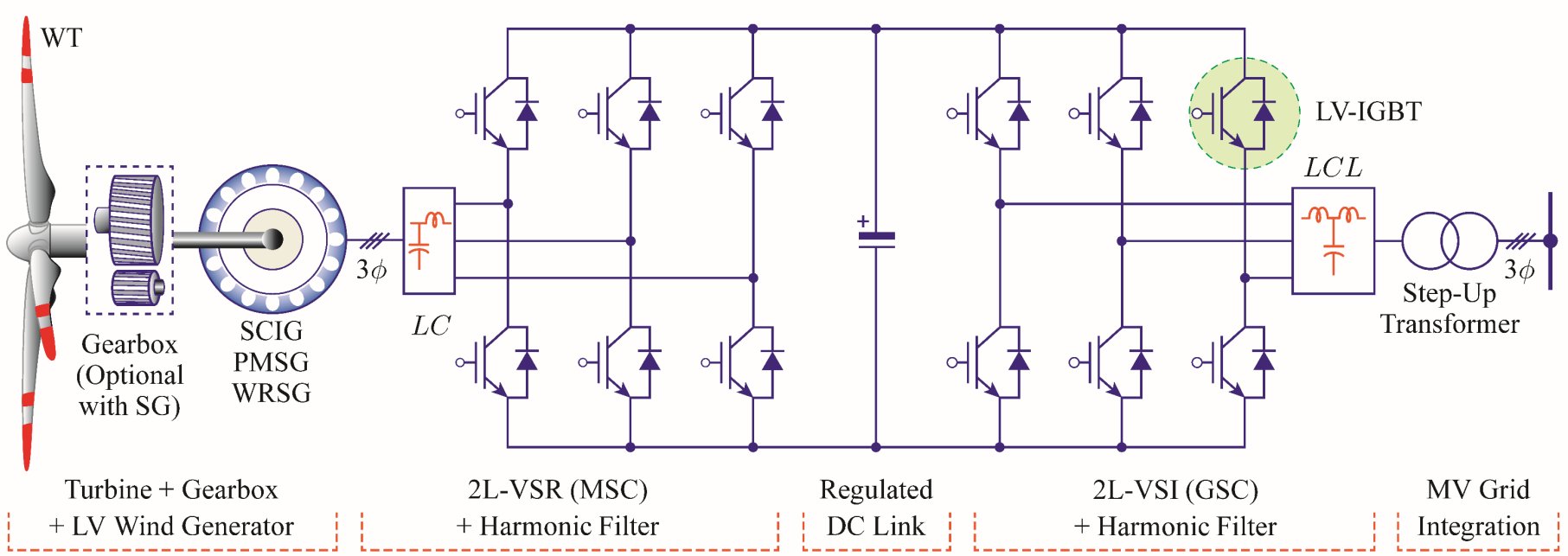
Source: GE

Power Converters for PMSG WECS



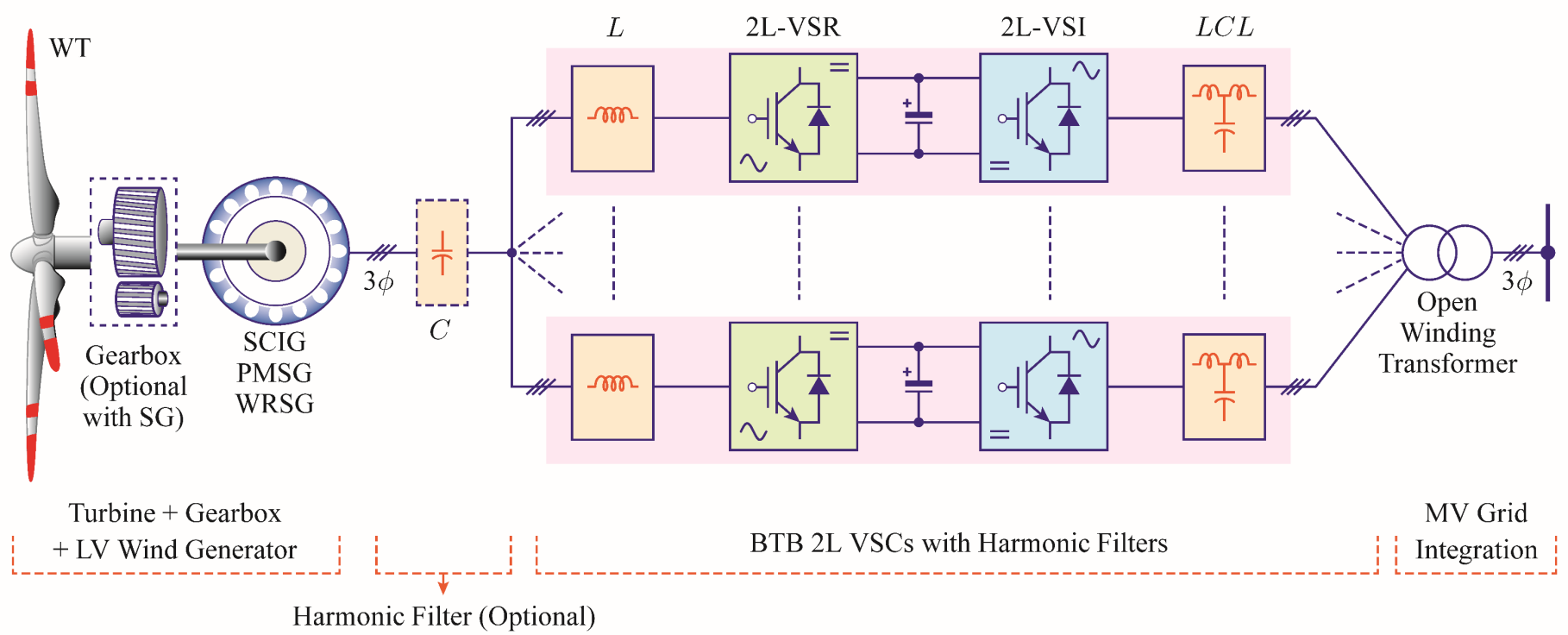
- PMSG is popular in the present wind energy market.
- Back-to-back (BTB) connected converters have highest market share.
- Passive Generator-side (PGS) and Multi-Phase (MP) converters have limited market share.
- MV matrix converters are offered by Yaskawa, but not operational yet.

Power Converters for PMSG WECS → BTB 2L-VSC



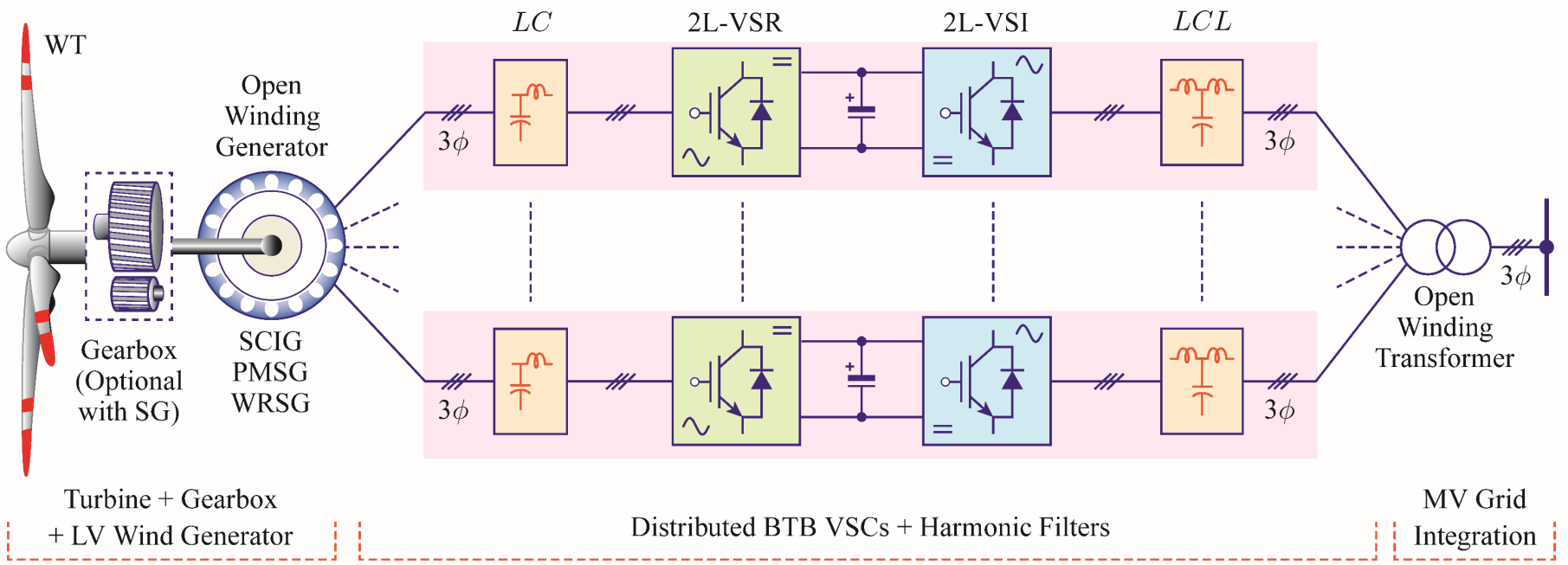
- **Topology:** Back-to-back connected two-level voltage source converters.
- **Power and voltage rating:** Up to 750 kW and 1000 V (line-to-line).
- **Used with:** SCIG, PMSG, and WRSG.
- **Features:** Bidirectional power flow, and decoupling between generator and grid.
- **Commercial products:** Employed by over 50 WT manufacturers.

Power Converters for PMSG WECS → Parallel BTB 2L-VSCs



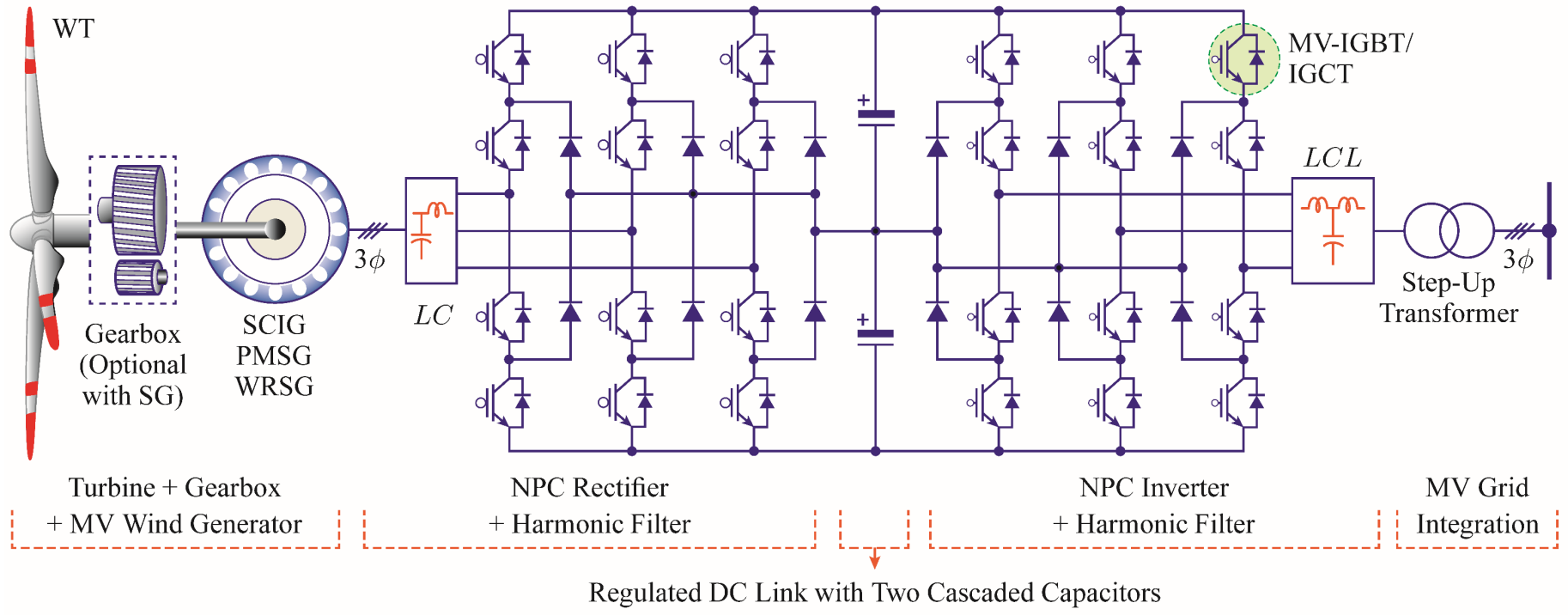
- **Topology:** Parallel connected BTB 2L-VSCs.
- **Power and voltage rating:** Up to 10 MW and 1000 V (line-to-line).
- **Used with:** SCIG, PMSG, and WRSG.
- **Features:** Modular, redundant, and reliable.
- **Commercial products:** Employed by over 40 WT manufacturers.

Power Converters for PMSG WECS → Multiphase BTB 2L-VSCs



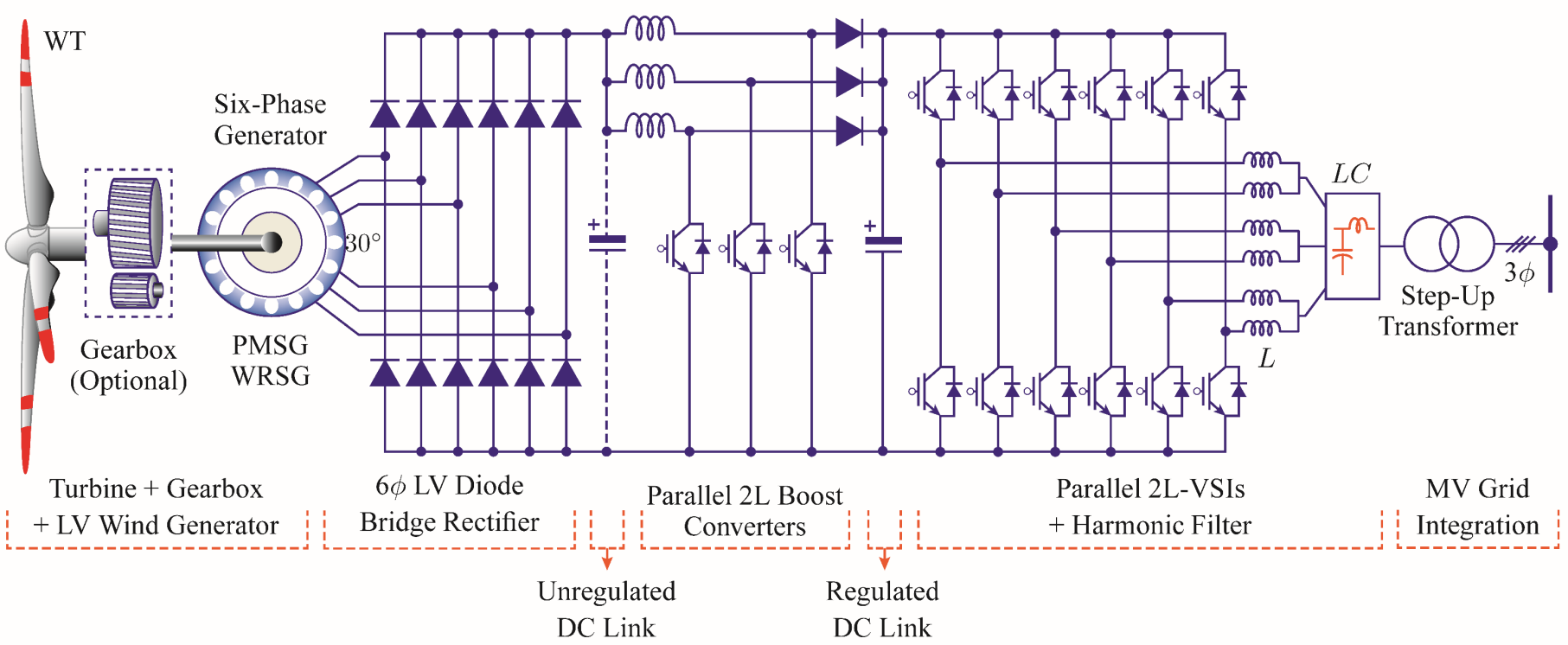
- **Topology:** Multiphase generator + BTB 2L-VSCs.
- **Power and voltage rating:** Up to 4.5 MW and 1000 V (line-to-line).
- **Used with:** SCIG, PMSG, and WRSG.
- **Features:** Modular, redundant, and reliable.
- **Commercial products:** Gamesa G10X, 4.5 MW with 6 modules.

Power Converters for PMSG WECS → BTB NPC Converter



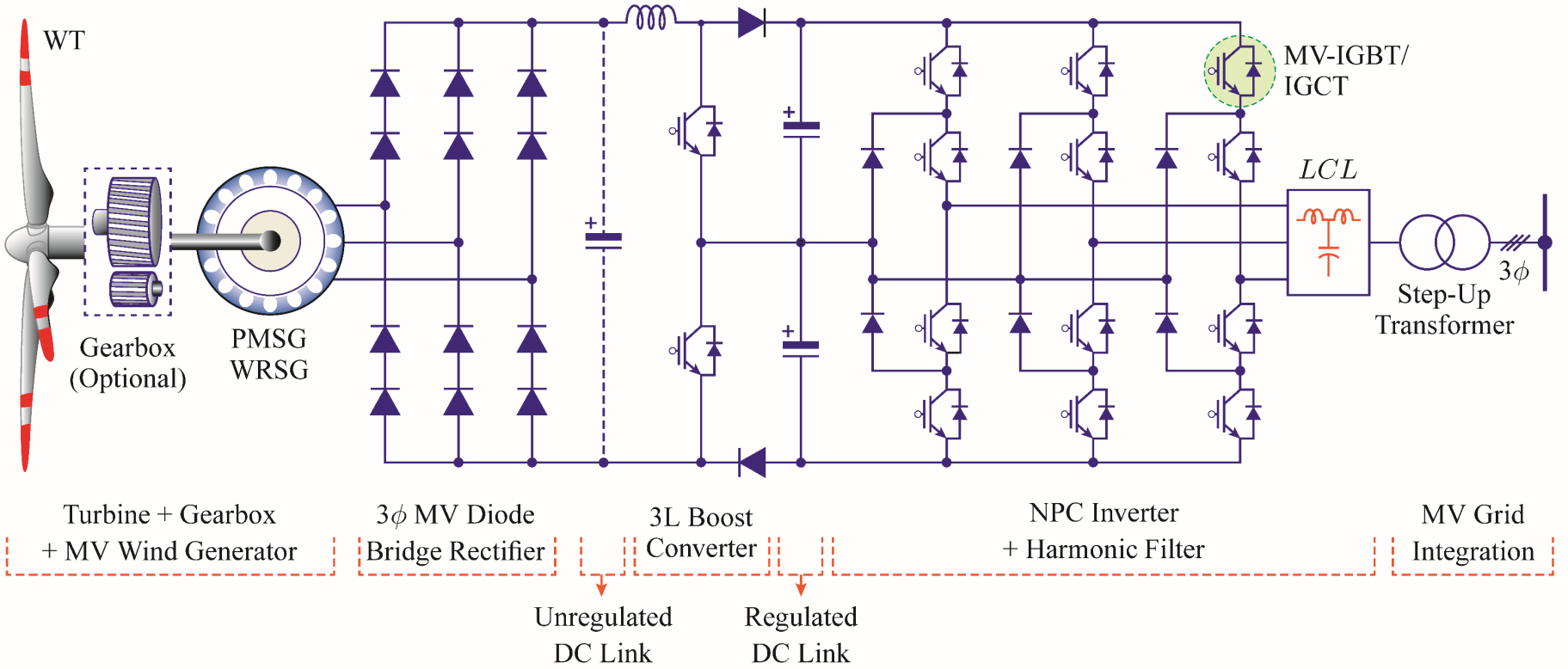
- **Topology:** Back-to-back connected neutral-point clamped (NPC) converters.
- **Power and voltage rating:** Up to 6 MW and 4000 V (line-to-line).
- **Used with:** SCIG, PMSG, and WRSG.
- **Features:** MV operation, low COE, better power quality, and low cable size.
- **Manufacturers:** ABB, Ingeteam, Converteam, Areva, Shandong, XEMC-Darwind, and Zephyros.

Power Converters for PMSG WECS → Parallel LV PGS Converters



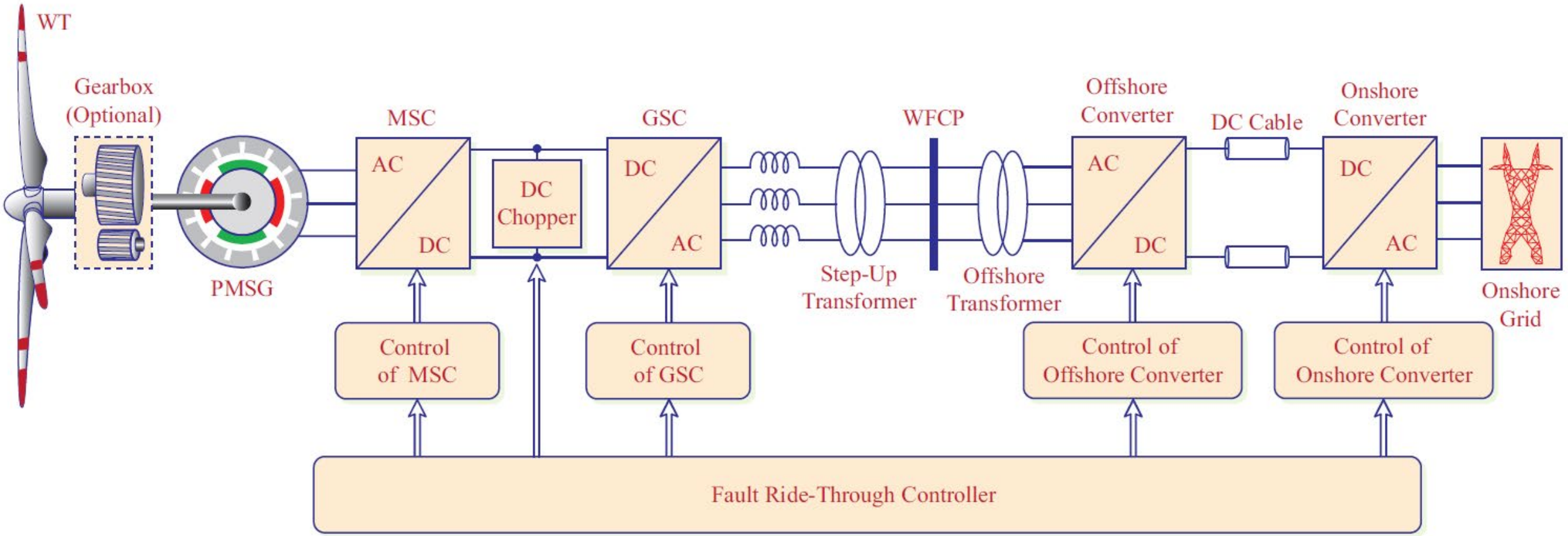
- **Topology:** Six-phase diode bridge + parallel boost converters + parallel 2L-VSIs.
- **Power and voltage rating:** Up to 1.5 MW and 1000 V (line-to-line).
- **Used with:** PMSG and WRSG.
- **Features:** Low generator current ripple and modular.
- **Manufacturers:** Vensys and Goldwind.

Power Converters for PMSG WECS → MV PGS Converter



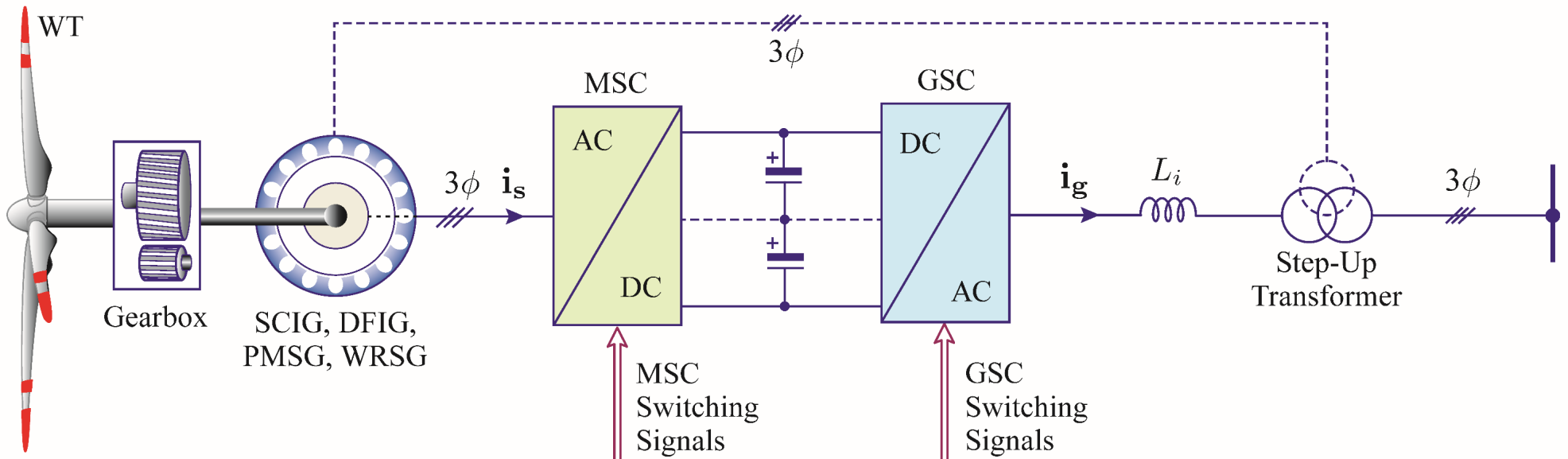
- **Topology:** Three-phase diode bridge + 3L boost converters + NPC inverter.
- **Power and voltage rating:** Up to 6 MW and 4000 V (line-to-line).
- **Used with:** PMSG and WRSG.
- **Features:** Combines low-cost diode bridge with efficient NPC converter.
- **Manufacturers:** None.

Control of PMSG WECS



Offshore PMSG WECS with HVDC Transmission

Control of PMSG WECS



Primary Control Objectives

MPPT Through Generator Speed/ Torque/Power Control

Secondary Control Objectives

Switching Frequency Minimization

Conrol of DC-link Neutral-Point Voltage

Primary Control Objectives

Net DC-bus Voltage Control

Grid Synchronization

Grid Reactive Power Control

FRT Operation

Secondary Control Objectives

Switching Frequency Minimization

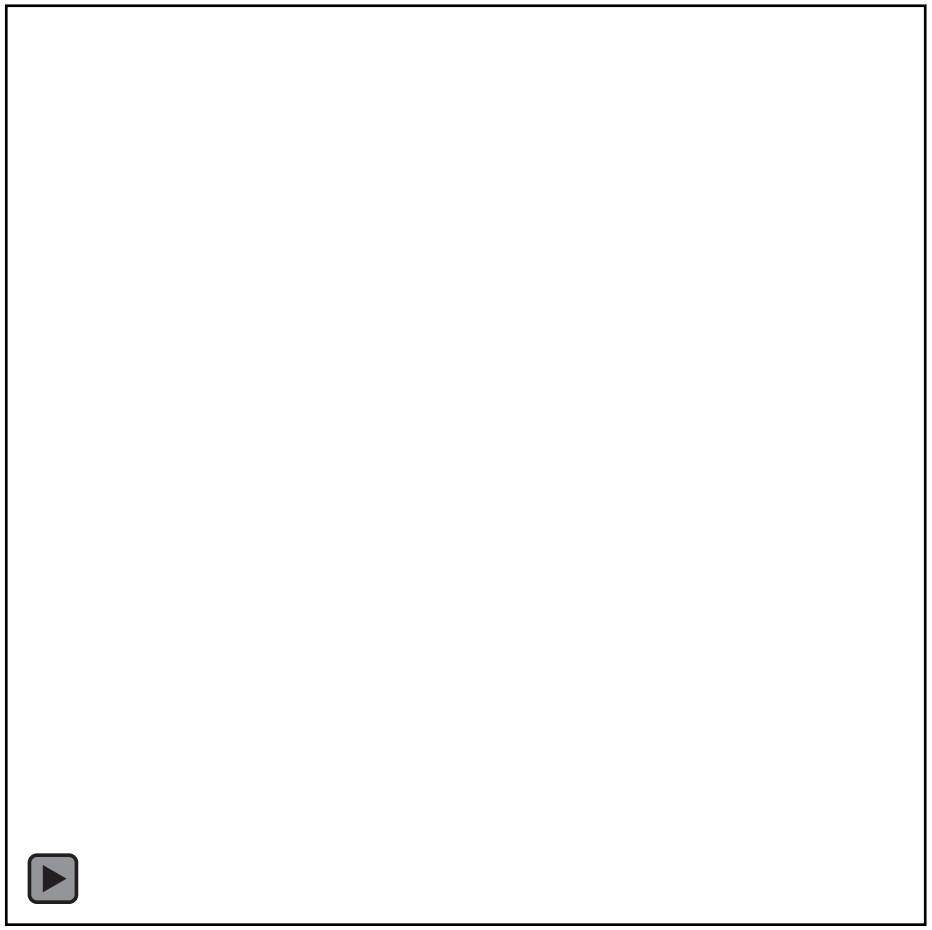
Conrol of DC-link Neutral-Point Voltage

Overall Digital Control System

Control of PMSG WECS → Overview of Control Schemes

	Linear Control	Predictive Control	Modulated Predictive Control
Model	Linear Load Model for PI and Converter Model for SVM	Discrete-Time Model of Complete System	Discrete-Time Model of Complete System
Controller Design	PI Adjustment + Modulator Design	Cost Function Definition	Cost Function + Modulator
Nature of Controller	Linear	Nonlinear	Nonlinear
Implementation Platform	Analog or Digital	Digital	Digital
Modulation	PWM/SVM	Not Required	SVM
Switching Frequency	Fixed	Variable (but controllable)	Fixed
Multivariable Control	Coupled Control	Decoupled Control	Decoupled Control
Constraints Inclusion	Not Possible	Easy to Include	Easy to Include
Complexity of Concept	Medium with SVM	Simple and Intuitive	Bit More Complex than MPC
Steady-State Performance	Excellent in dq frame	Good in abc, αβ and dq frames	Excellent in all frames
Transient Performance	Moderate	Excellent	Excellent
Computational Burden	Medium	High	High

Control of PMSG WECS → Overview of Control Schemes



Model Predictive Control (MPC) is like playing chess!!

- **Prediction**
- **Optimization**
- **Receding Horizon Strategy**

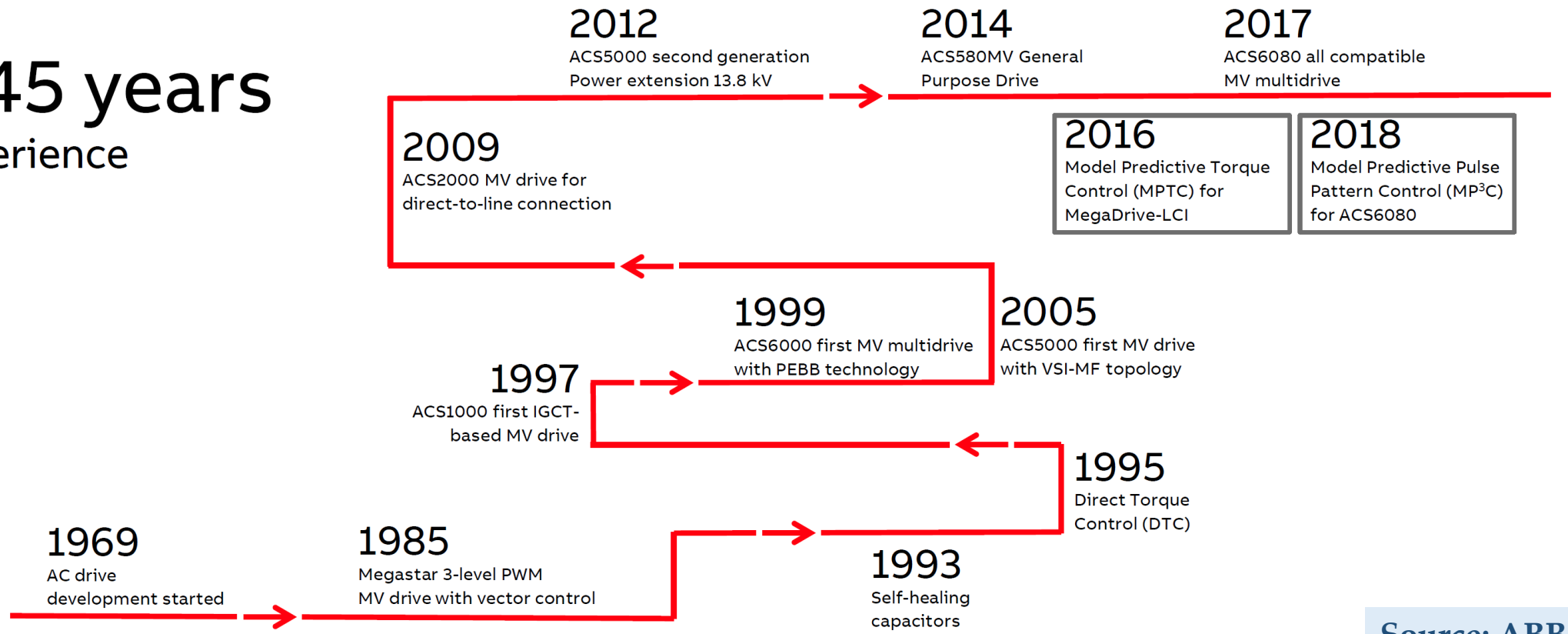
By Karophyr at English Wikipedia - Transferred from en.wikipedia to Commons., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2160498

Control of PMSG WECS → Commercial MPC Products

Medium Voltage Drives

Technology – the cornerstone of success

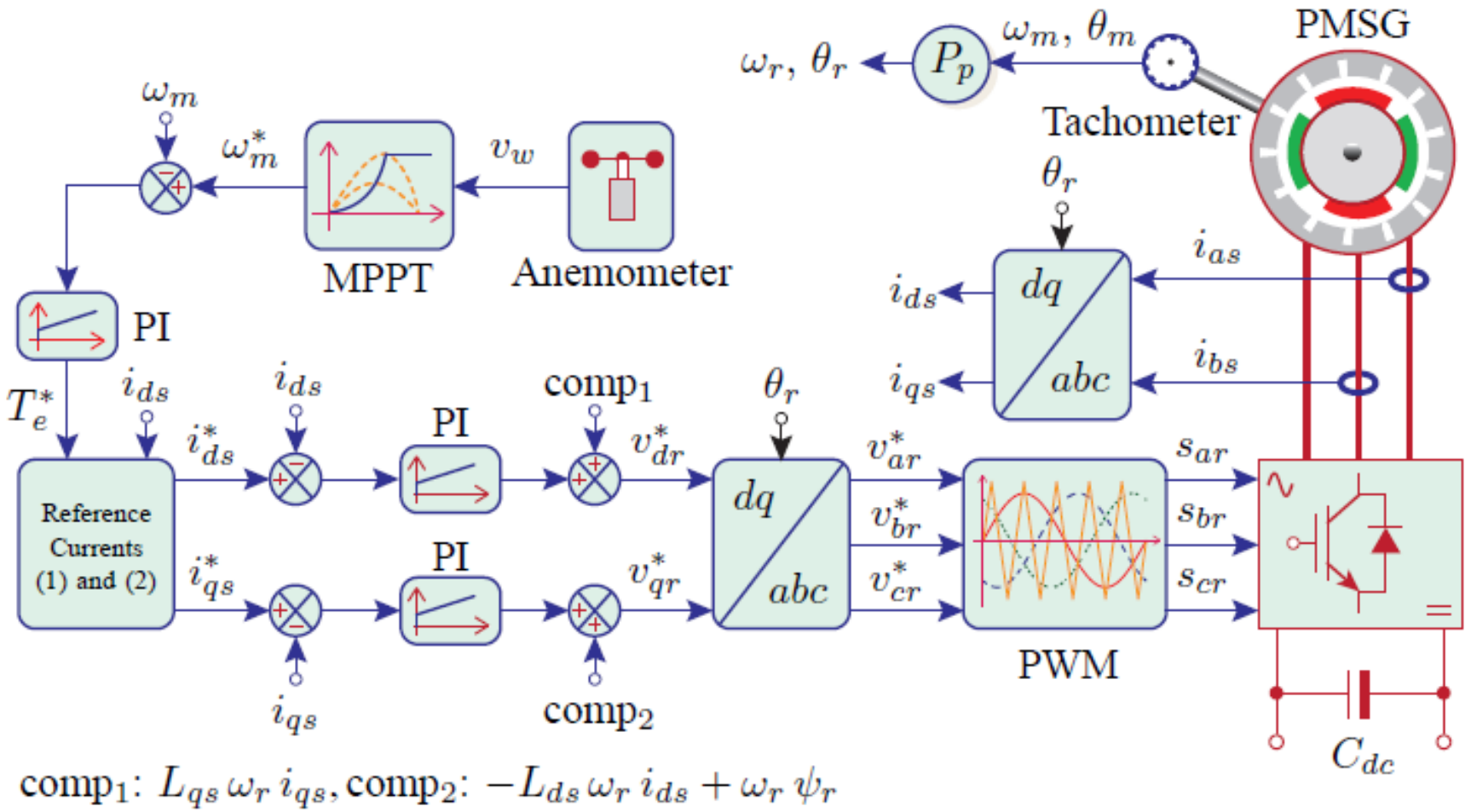
> 45 years
experience



Source: ABB

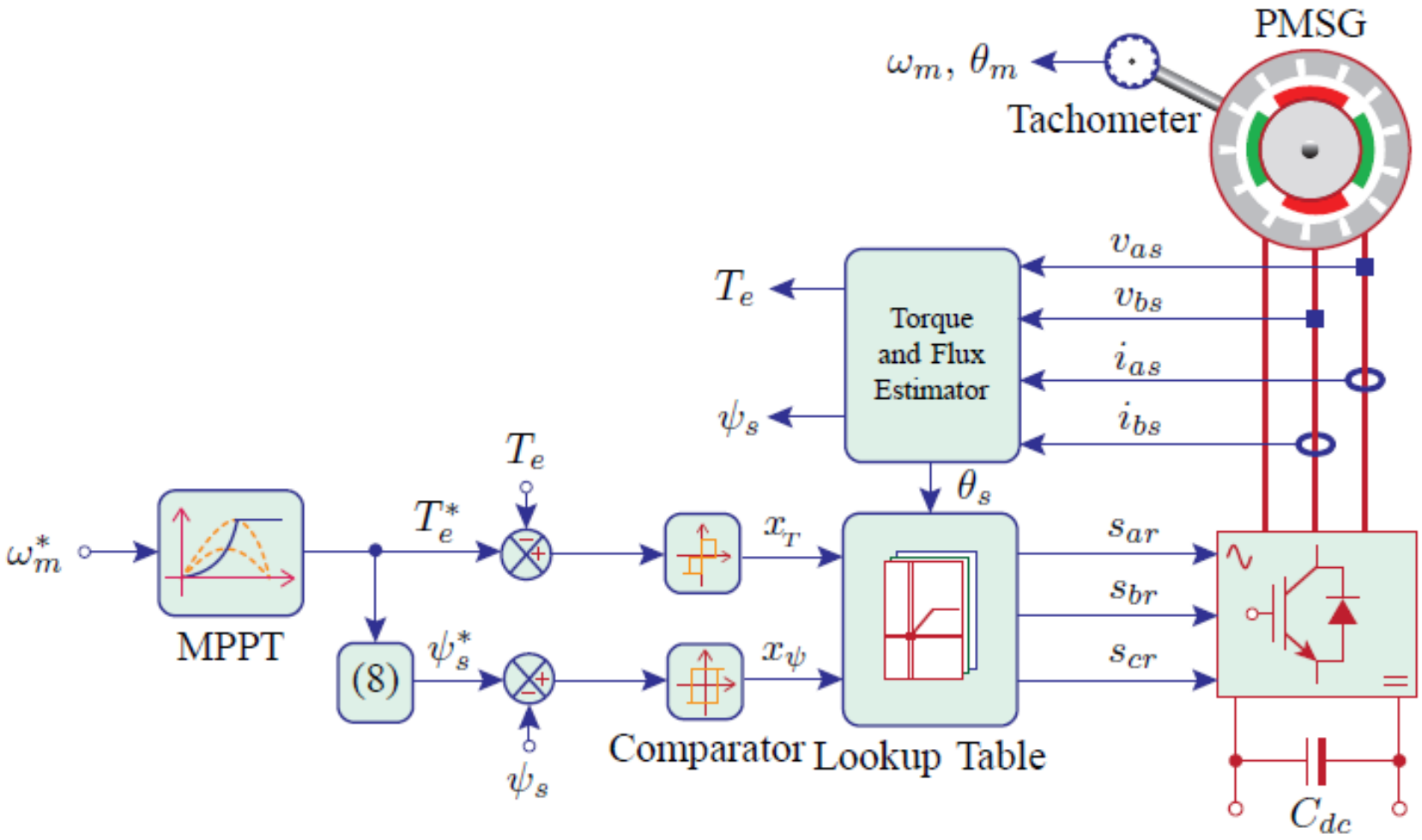
ABB MV Drives Products at Glance

Control of PMSG WECS → Classical Control



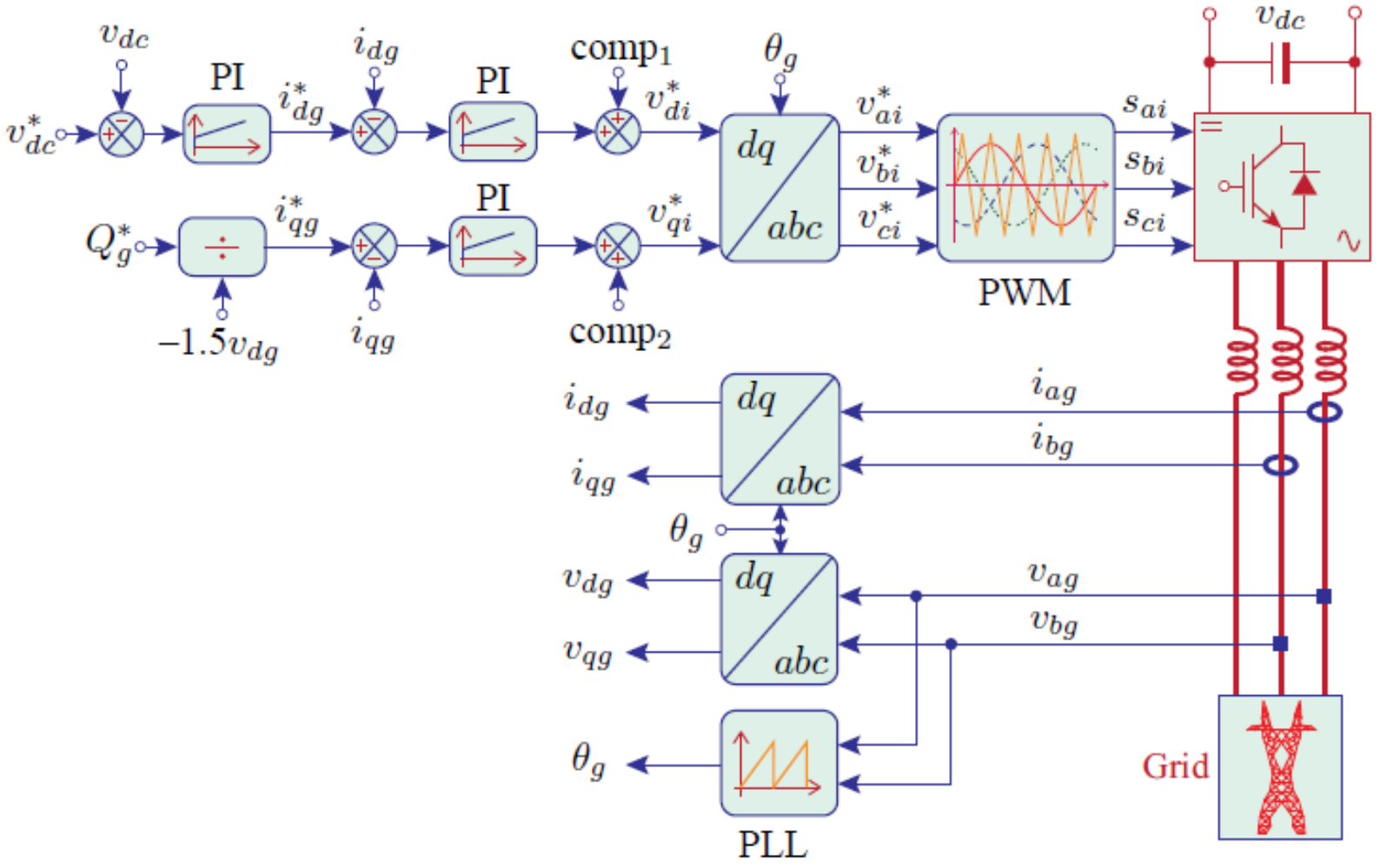
Block diagram of ZDC/MTPA control for MSC in PMSG WECS

Control of PMSG WECS → Classical Control



Block diagram of DTC for MSC in PMSG WECS

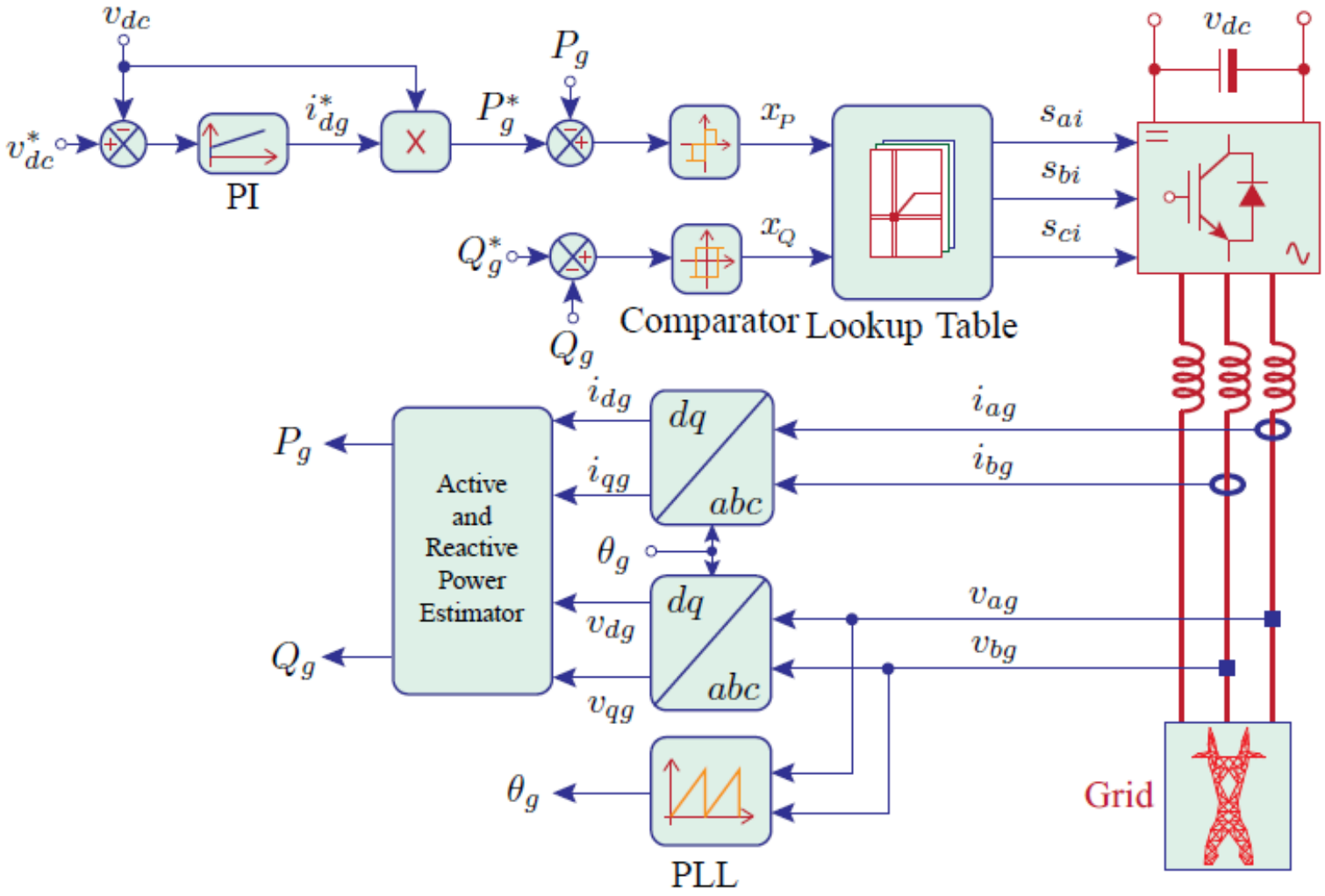
Control of PMSG WECS → Classical Control



comp$_1$: $-L_i\,\omega_g\,i_{qg} + v_{dg}$, comp$_2$: $L_i\,\omega_g\,i_{dg} + v_{qg}$

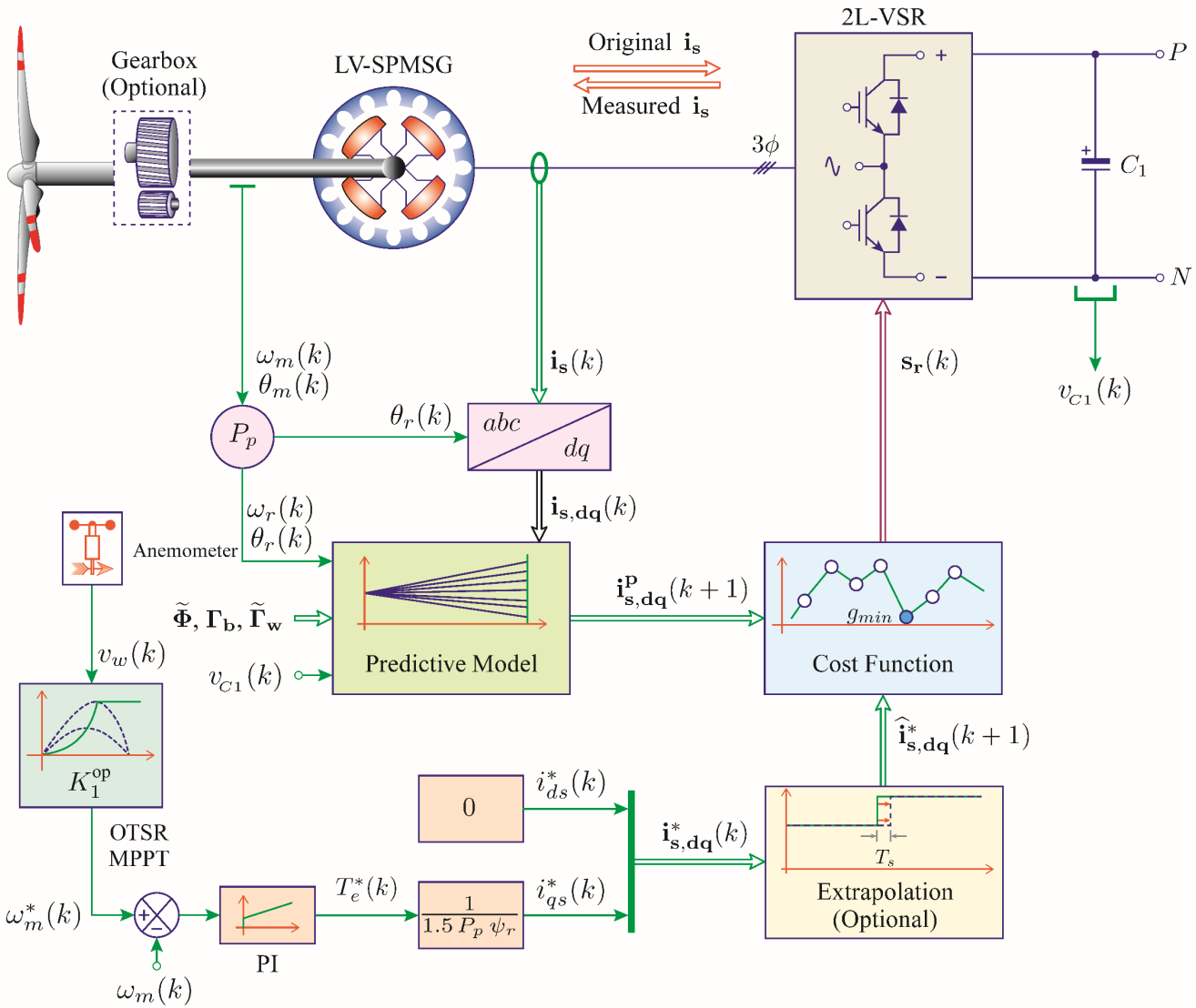
Block diagram of VOC for GSC in PMSG WECS

Control of PMSG WECS → Classical Control



Block diagram of DPC for GSC in PMSG WECS

Control of PMSG WECS → Predictive Control

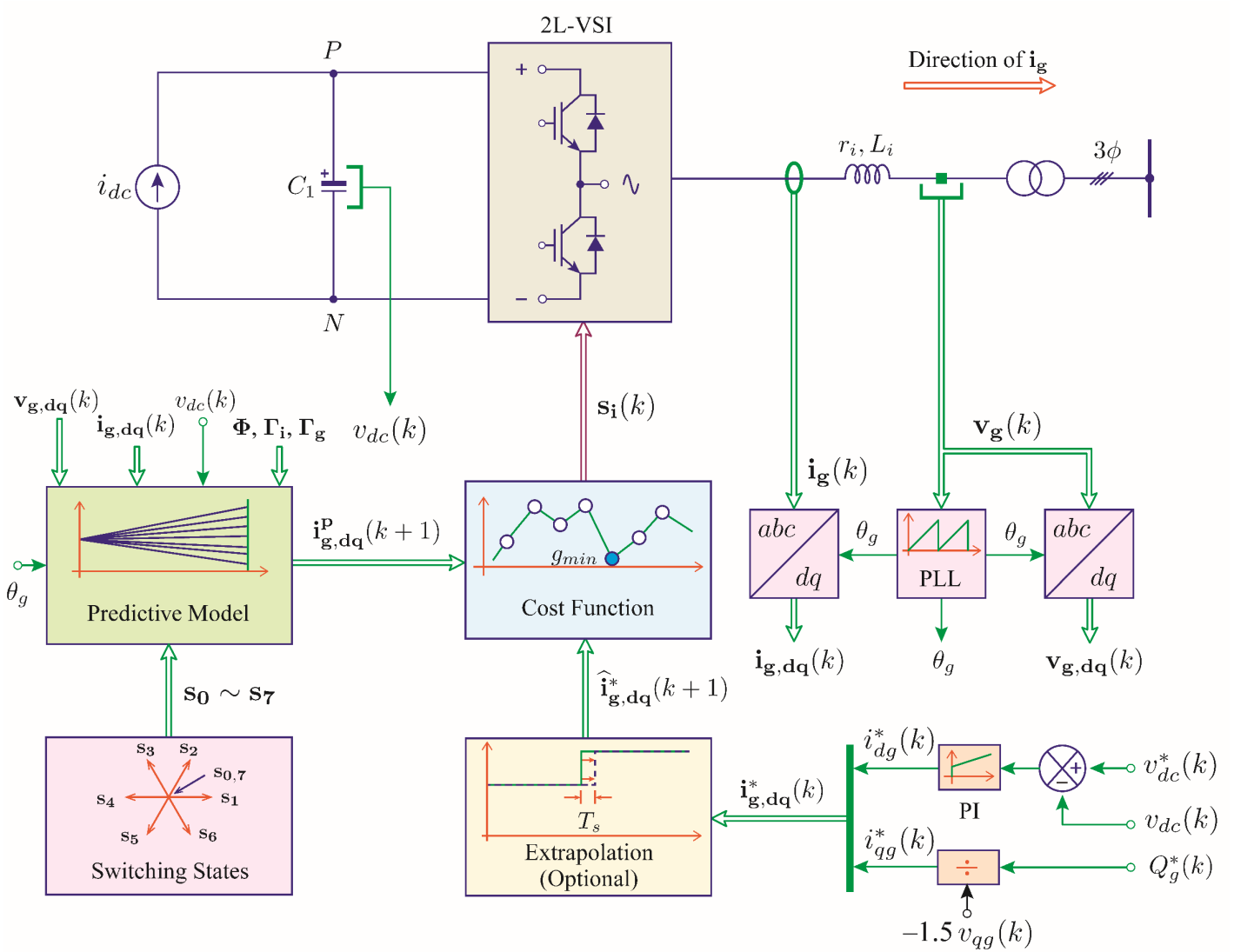


Block diagram of PCC for MSC in PMSG WECS

Design Procedure:

1. Measurement of Stator Currents, DC Voltage, Wind Speed, and Gen. Speed/Position
2. Estimation of Rotor Angle
3. Calculation of Reference Stator Currents
4. Extrapolation of Reference Stator Currents
5. Prediction of Future Behavior of Stator Currents
6. Generation of Optimal Switching Signals Through Cost Function Minimization

Control of PMSG WECS → Predictive Control

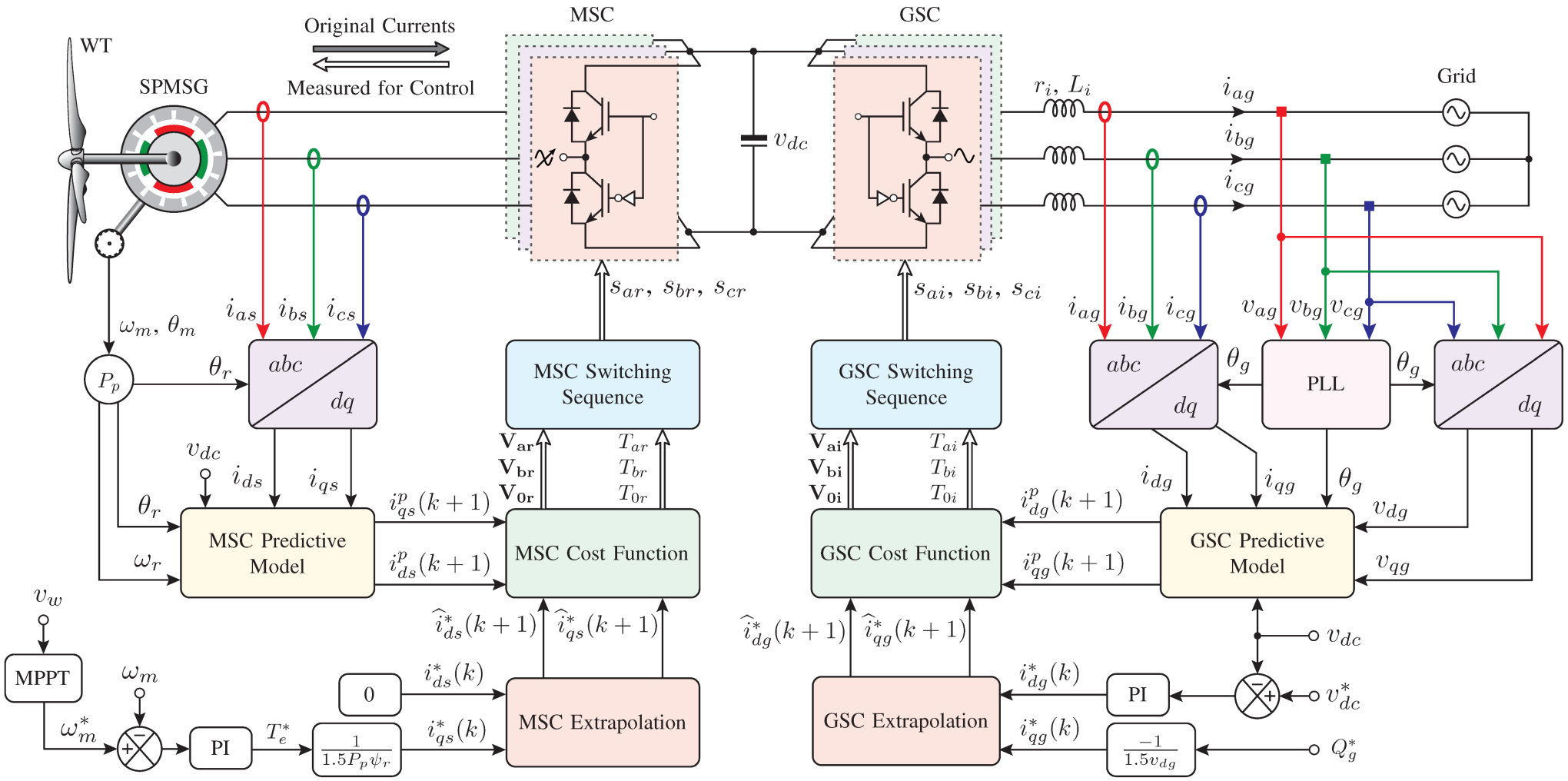


Block diagram of PCC for GSC in PMSG WECS

Design Procedure:

1. Measurement of Grid Voltages and Currents
2. Estimation of Grid Angle
3. Convert Grid Voltages and Currents to *dq*-Frame
4. Calculation of Reference Grid Currents
5. Extrapolation of Reference Grid Currents
6. Prediction of Future Behavior of Grid Currents
7. Generation of Optimal Switching Signals Through Cost Function Minimization

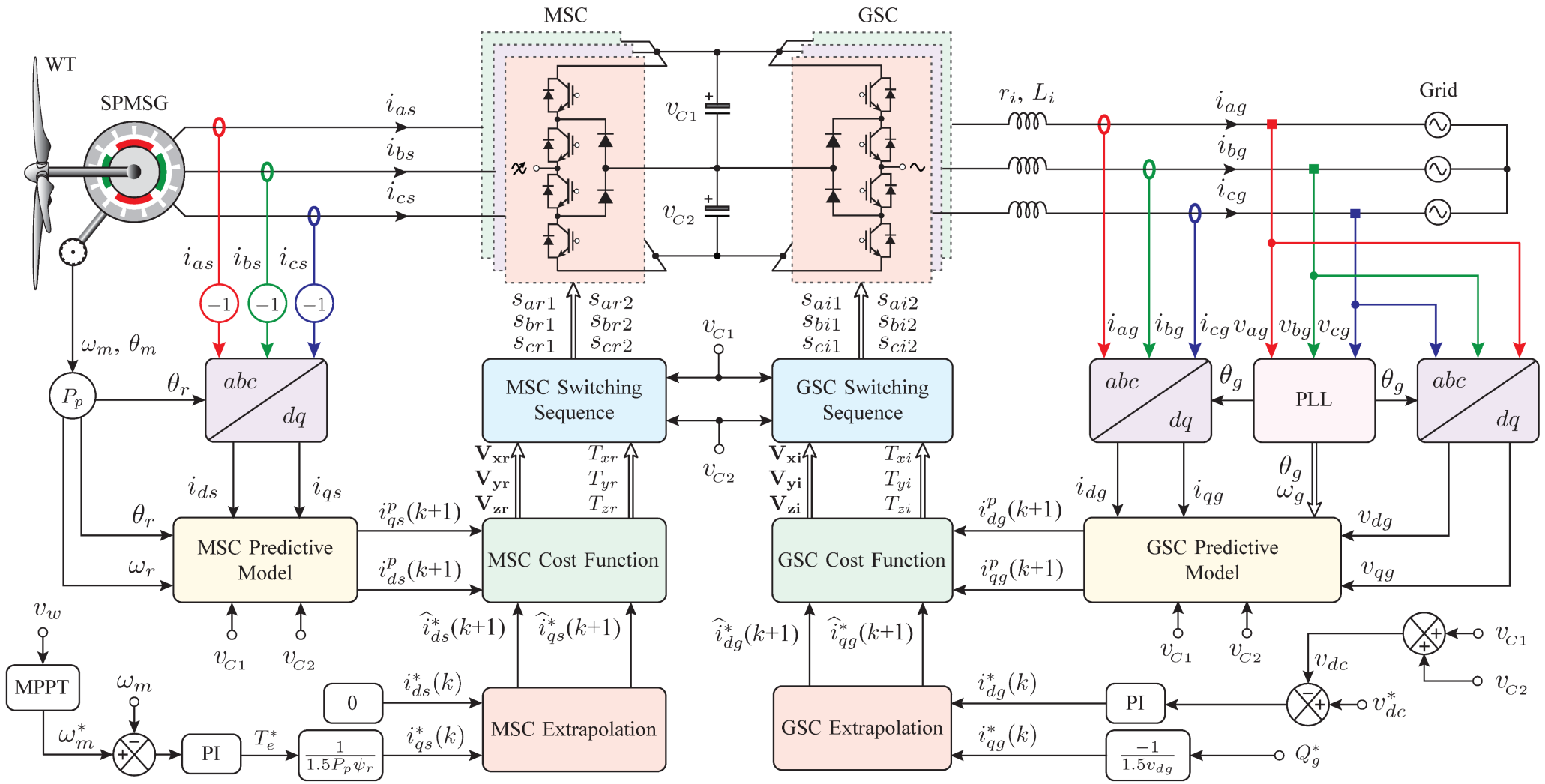
Control of PMSG WECS → Modulated Predictive Control



Block diagram of modulated PCC of BTB 2L-VSC in PMSG WECS

K. Milev, V. Yaramasu, A. Dekka and S. Kouro, "Modulated Predictive Current Control of PMSG-Based Wind Energy Systems," 2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), Tehran, Iran, 2020, pp. 1-6.

Control of PMSG WECS → Modulated Predictive Control



Block diagram of modulated PCC of BTB NPC converter in PMSG WECS

V. Yaramasu, K. Milev, A. Dekka and J. Rodriguez, "Modulated Predictive Current Control of NPC Converter-Based PMSG Wind Energy System," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 75-80.

Future Trends

- More bigger wind turbines (20 MW turbines are already announced)
- Gearless wind turbines
- High temperature superconducting generators
- More efficient medium voltage power converters (ANPC, MMC, etc.)
- Wide band-gap semiconductor devices
- Multiterminal HVDC transmission
- Fault-ride through and advanced grid codes
- Advanced control schemes at wind turbine and wind farm levels

Thanks

V. Yaramasu: venkata.yaramasu@nau.edu