



Power Systems
Engineering Research Center

Evolution of Wind Generation Systems, Medium Voltage DC (MVDC) Collector Grids, and High-Voltage DC (HVDC) Transmission Grids

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Presentation Overview

❑ Wind Turbine Systems

- History of Wind Turbines
- How Does a Wind Turbine Work
- Haliade-X: An Example of Large Offshore Wind Turbine
- Direct Drive vs. Geared Generators
- Offshore vs. Onshore Wind Farms
- Wind Turbine Connection to the Grid

❑ MVDC and HVDC Systems

- Walney Wind Farm: An Example of HVAC Systems
- HVDC Transmission
- Multilevel Modular Converters (MMC) – HVDC
- MMC-HVDC: Control & EMT Models
- MVDC Collector Grids
- Wind Turbine Conversion for All-DC Grids
- Comparison: Existing Wind Generation Systems with All-DC

History of Wind Turbines

- ❑ The first reliable information about the existence of windmills from historical sources originates from the year **644 A.D.** It tells of windmills from the **Persian-Afghan border region of Sistan**.

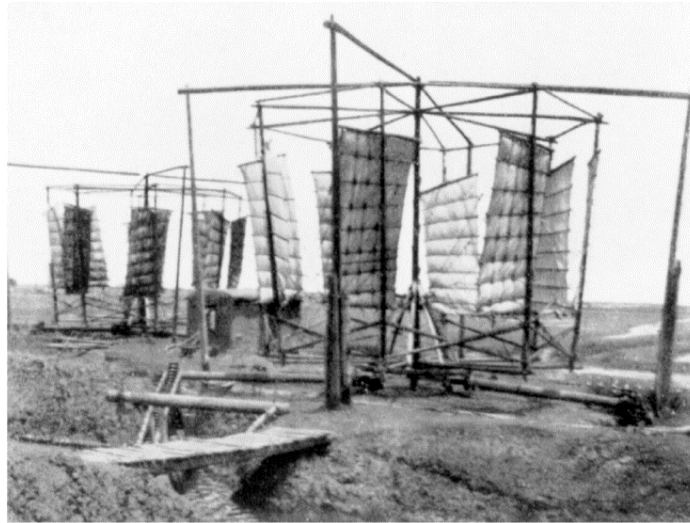


Windmill for milling grains (Persian-Afghan)



Persian-Afghan border region of Sistan
(Photo courtesy of Google Map)

History of Wind Turbines

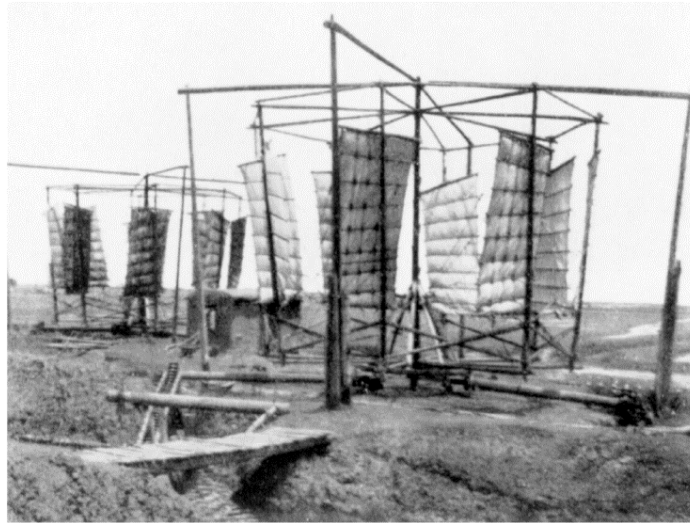


Windmill in China for pumping water

History of Wind Turbines



German windmill



Windmill in China for pumping water

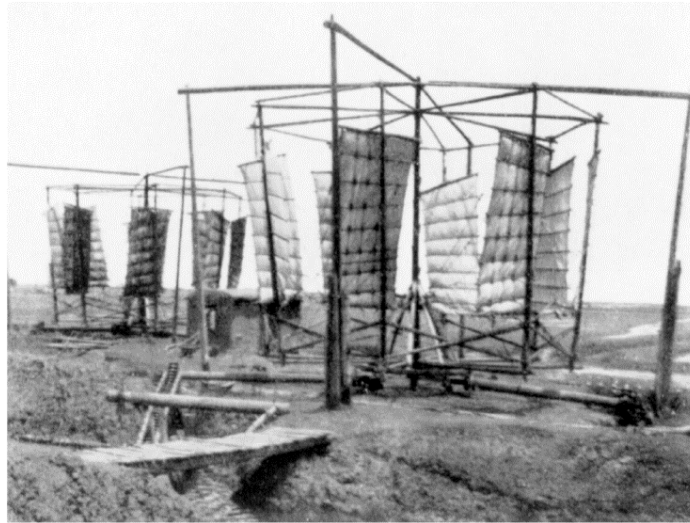


Dutch windmill

History of Wind Turbines



German windmill



Windmill in China for pumping water

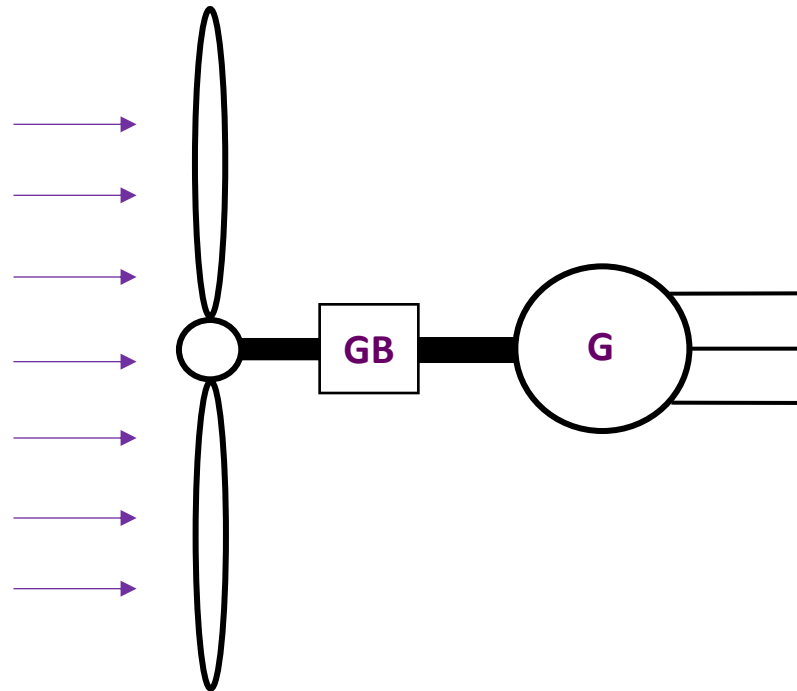


Dutch windmill

Around 1890s first wind turbine was manufactured to
produce electricity using DC generators

How Does A Wind Turbine Work

- ❑ Wind turbine converts wind kinetic energy to first mechanical and then electrical energy through a power-train.



How Does A Wind Turbine Work

- ❑ Wind turbine converts wind kinetic energy to first mechanical and then electrical energy through a power-train.

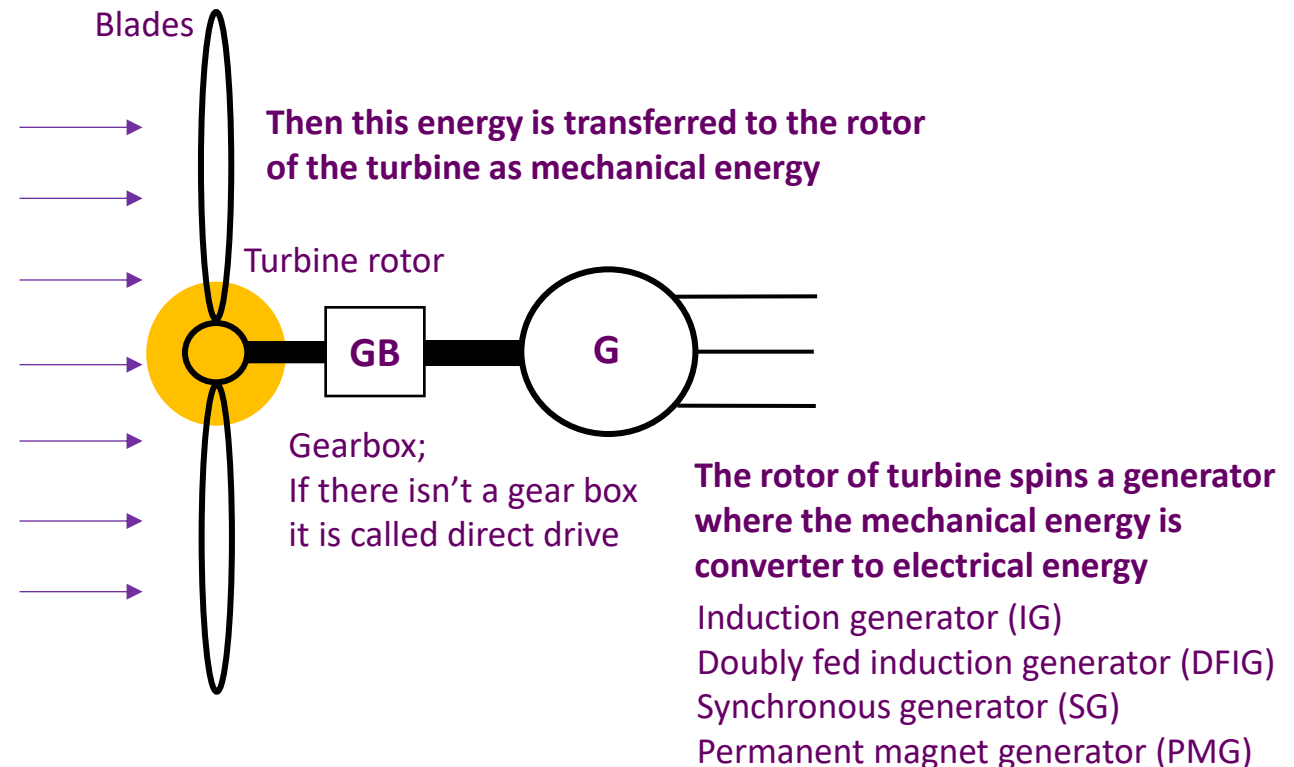
Turbine blades harvest the wind energy by slowing down the wind velocity $P_t = \frac{1}{2} \rho A v^3 C_p$ (W)

Energy in the wind is a function of wind velocity and mass of wind parcel

$$U = \frac{1}{2} m v^2 \quad (\text{Joules})$$

Power in wind (rate of energy change in time) is a function of velocity, air density and cross-sectional area of wind parcel

$$P_w = \frac{dU}{dt} = \frac{1}{2} \rho A v^3 \quad (\text{W})$$

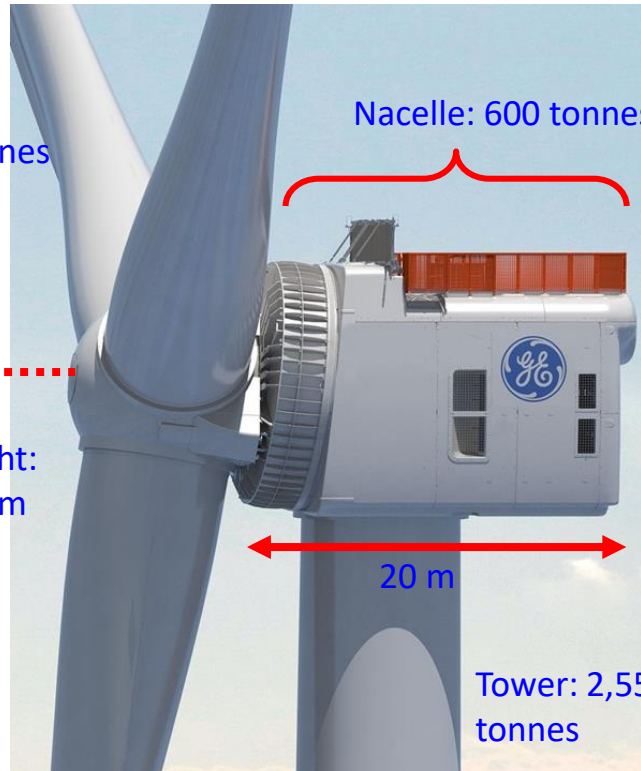


Haliade-X Offshore Wind Turbine

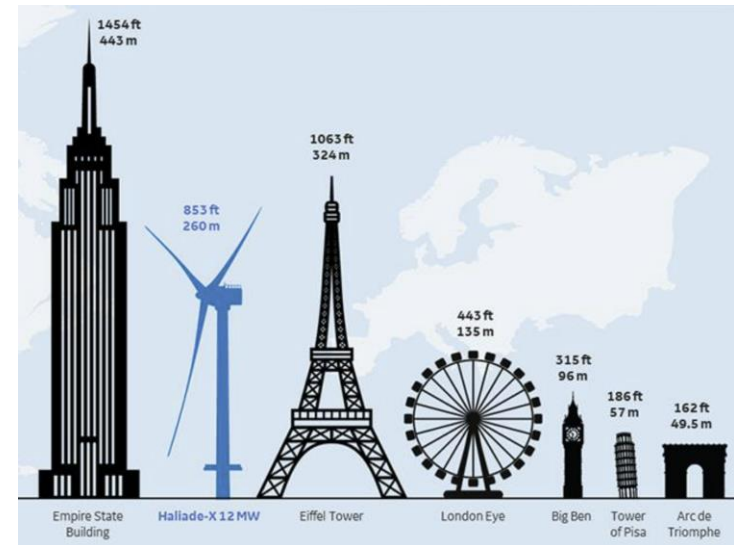
GE HALIADE-X	
Rated capacity	12-14MW
Specific power rating	321W/m ² (12MW)
IEC wind class	IB
Blade length	107m
Blade mass	55 tonnes
Rotor diameter	218.2m ¹
Cut-in wind speed	about 3.5m/s
Cut out windspeed	28m/s
Rated rotor speed	7.81RPM
Rated tip speed	89.2 m/s ²
Hub height	135.0m
Tip height	245.0m
Tip height for offshore	260.0m ³
Nacelle width	11m
Nacelle height	10.4m
Nacelle length	20.6m
Nacelle mass	600 tonnes
Conical tubular steel mast	
Base diameter	8.0m (or 10.0m ⁴)
Top diameter	5.5m
Length	129.1m
Tower mass	2,550 tonnes

¹ GE official communication 220m² Author calculation based on 218.2 m rotor diameter
³ GE infographic ⁴ Is diameter foundation top flange

Blade:
107 m
55 tonnes

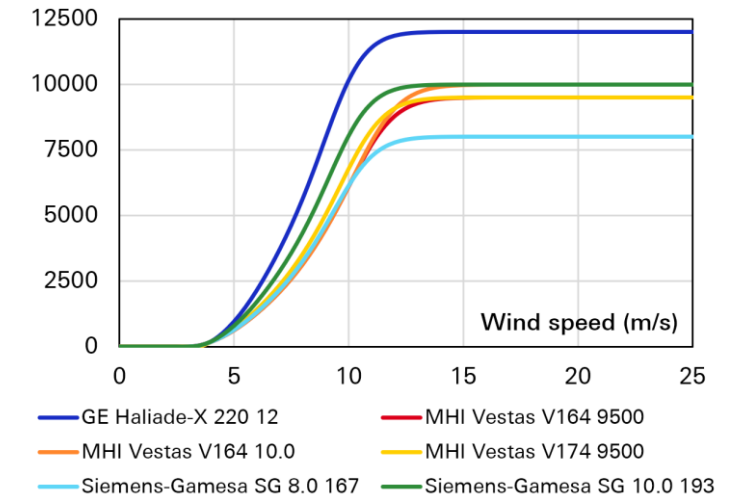


Haliade-X 14 MW
(Photo courtesy of GE)

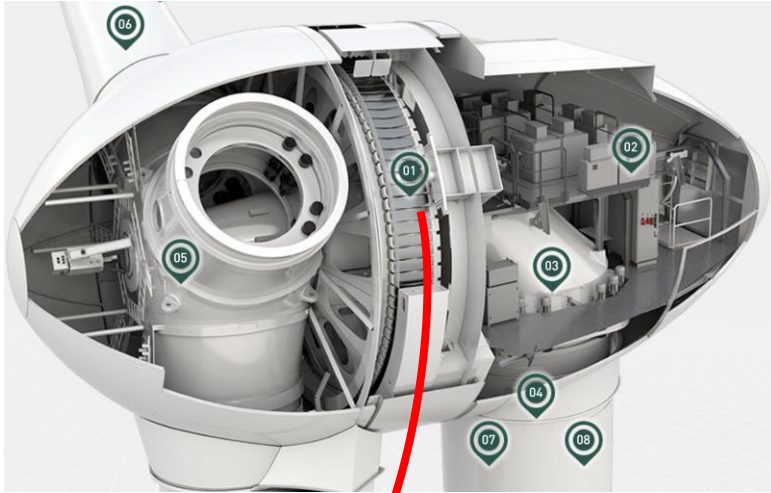


Curves from Saint-Drenan et al. <http://arxiv.org/abs/1909.13780>

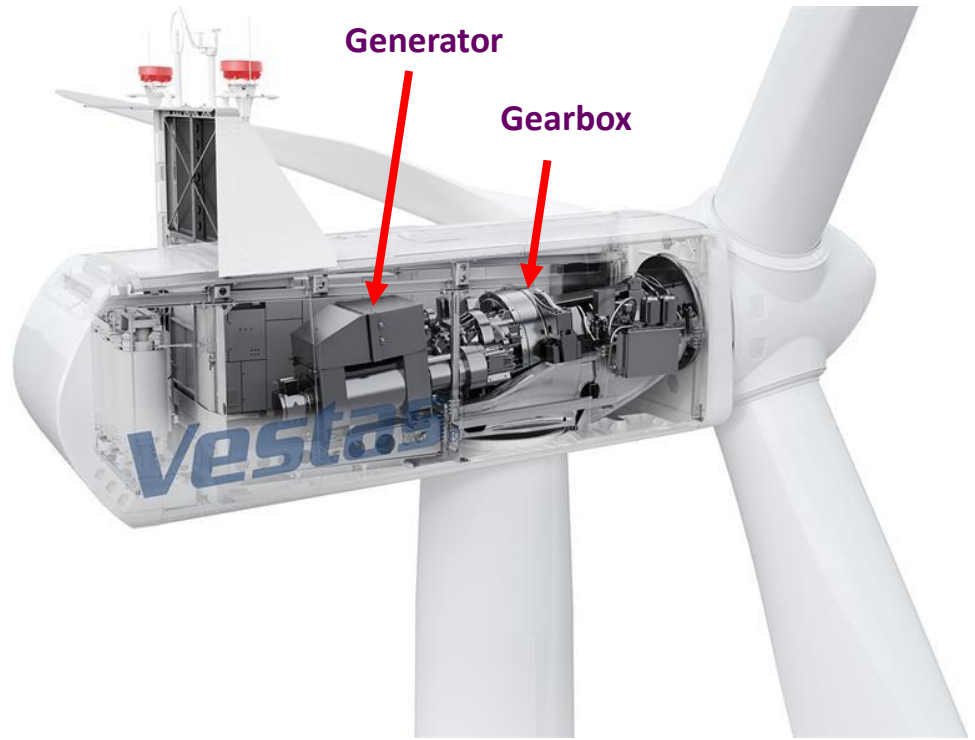
Power output (kW)



Direct Drive vs. Geared Generators

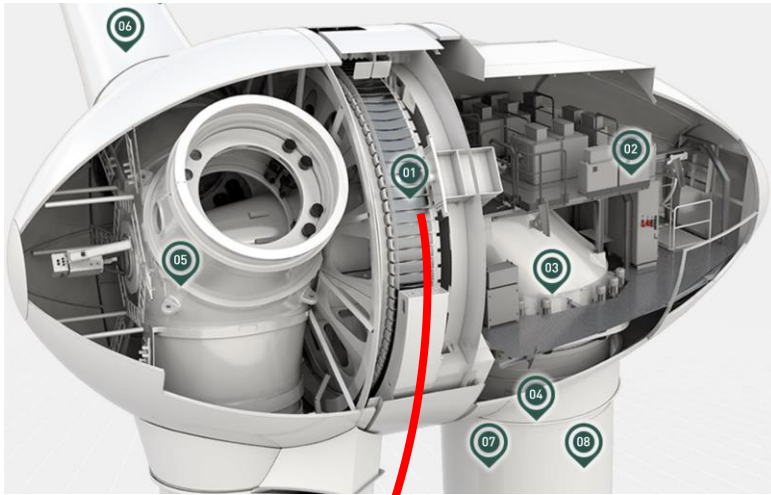


Direct drive generator
(Photo courtesy of Enercon)

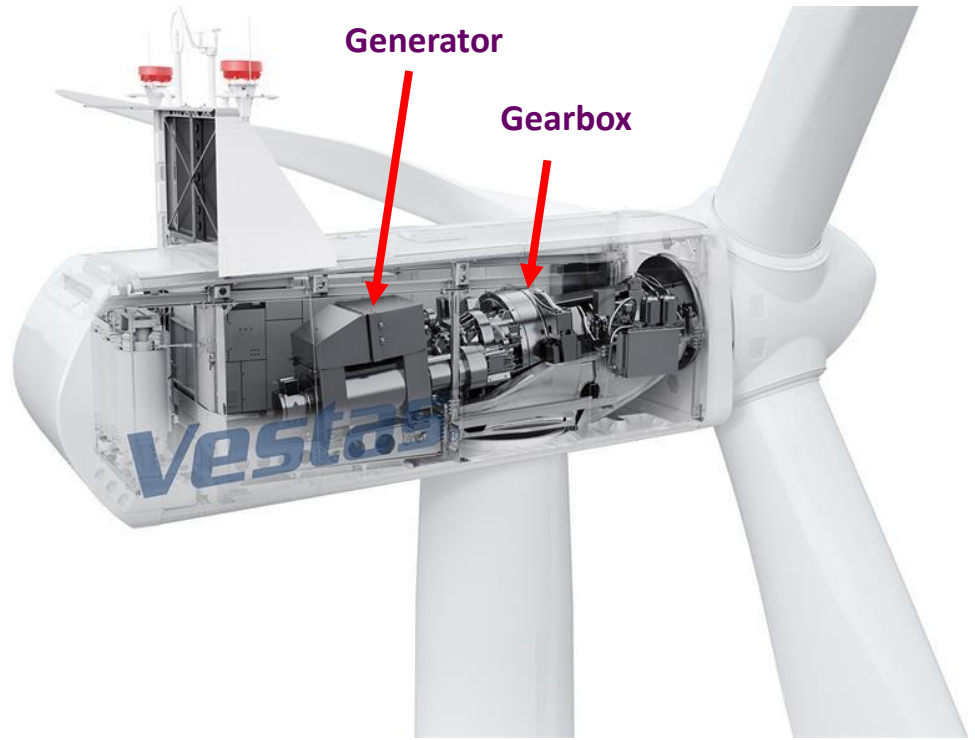


Geared generator
(Photo courtesy of Vestas)

Direct Drive vs. Geared Generators



Direct drive generator
(Photo courtesy of Enercon)

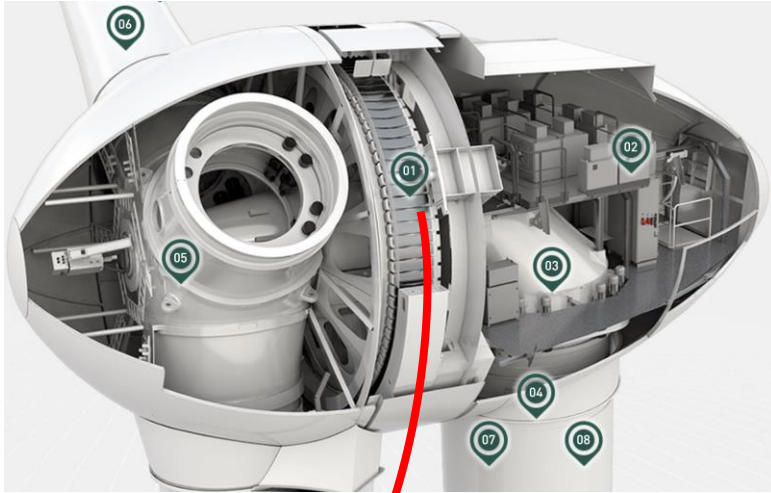


Geared generator
(Photo courtesy of Vestas)

Machine torque given by:

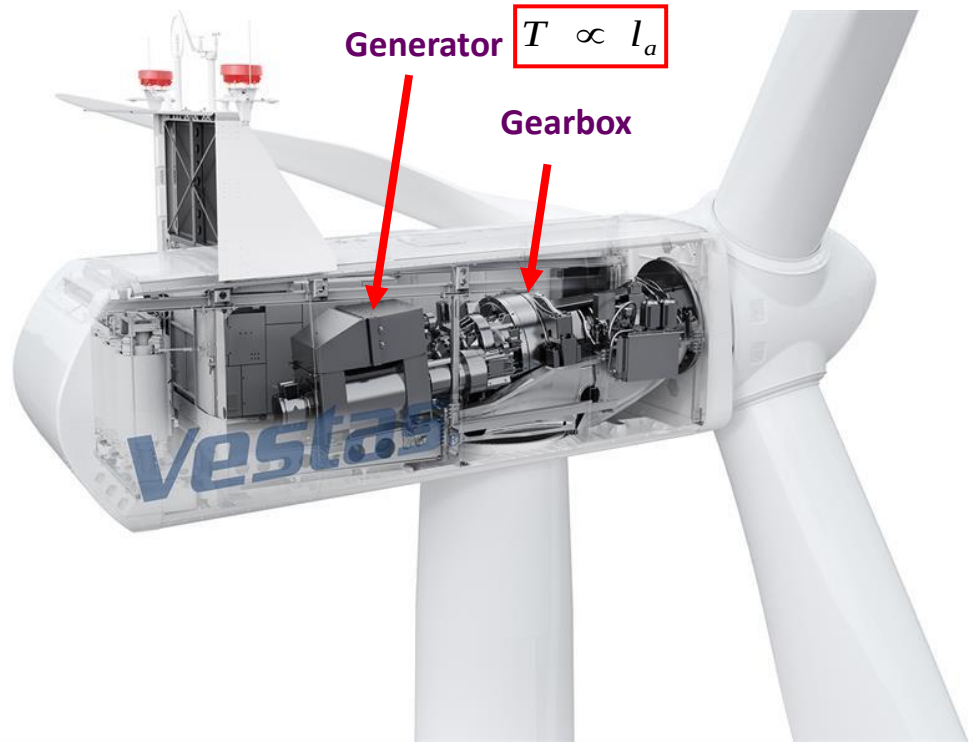
$$T = \left(\frac{\pi D^2 l_a}{2} \right) B_{ave} Q$$

Direct Drive vs. Geared Generators



Direct drive generator
(Photo courtesy of Enercon)

$$T \propto D^2$$



Geared generator
(Photo courtesy of Vestas)

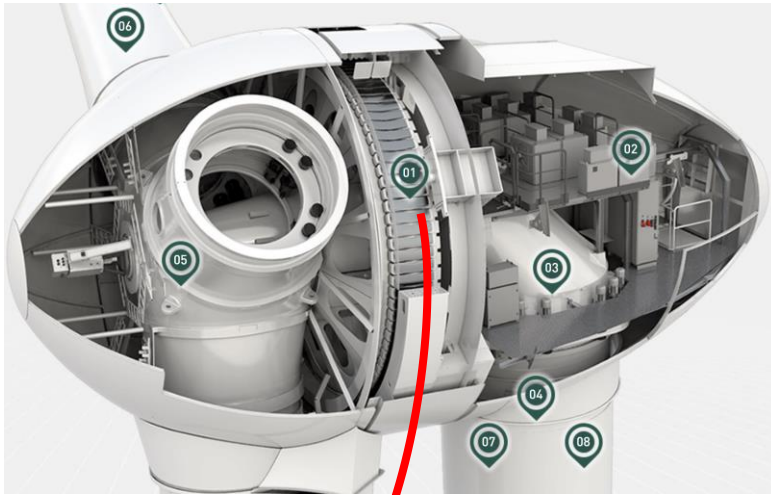
Generator $T \propto l_a$

Gearbox

Machine torque given by:

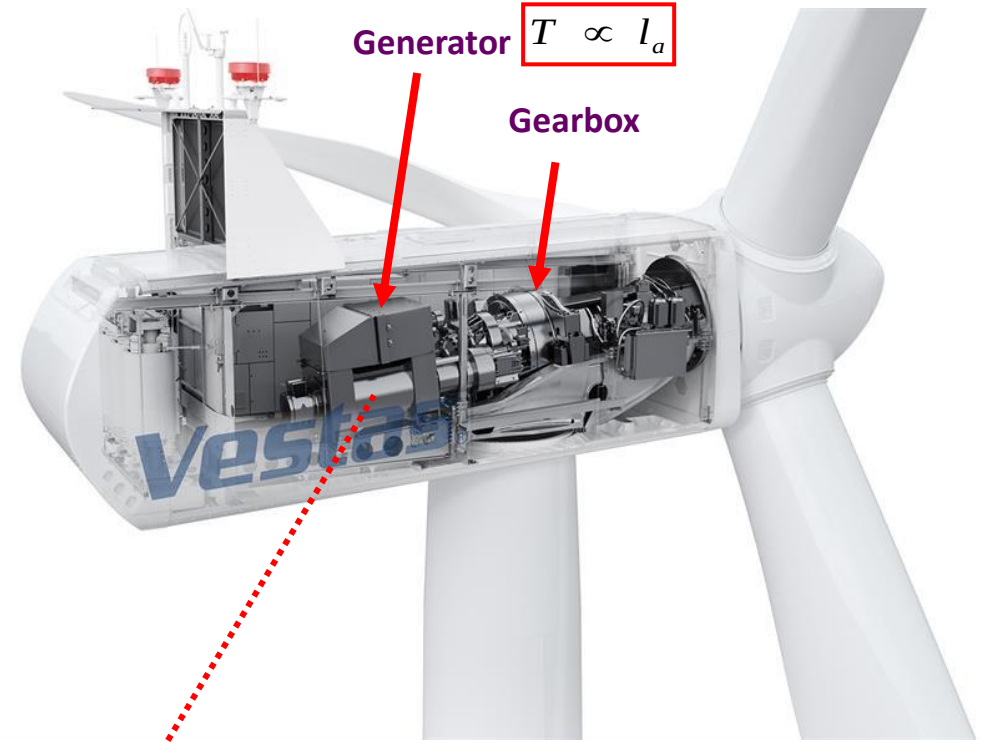
$$T = \left(\frac{\pi D^2 l_a}{2} \right) B_{ave} Q$$

Direct Drive vs. Geared Generators



Direct drive generator
(Photo courtesy of Enercon)

$$T \propto D^2$$



Generator $T \propto l_a$

Gearbox

Geared generator
(Photo courtesy of Vestas)

Machine torque given by:

$$T = \left(\frac{\pi D^2 l_a}{2} \right) B_{ave} Q$$

Offshore vs. Onshore Wind Farms

- ❑ A number of wind turbines clustered in a group constitute a wind farm, or wind park
- ❑ Offshore:
 - Stronger and steadier winds, perhaps higher transportation and installations costs (it varies case by case)
- ❑ Onshore:
 - Limited land, visual impacts, harm to birds (how much?), noise (how much?)

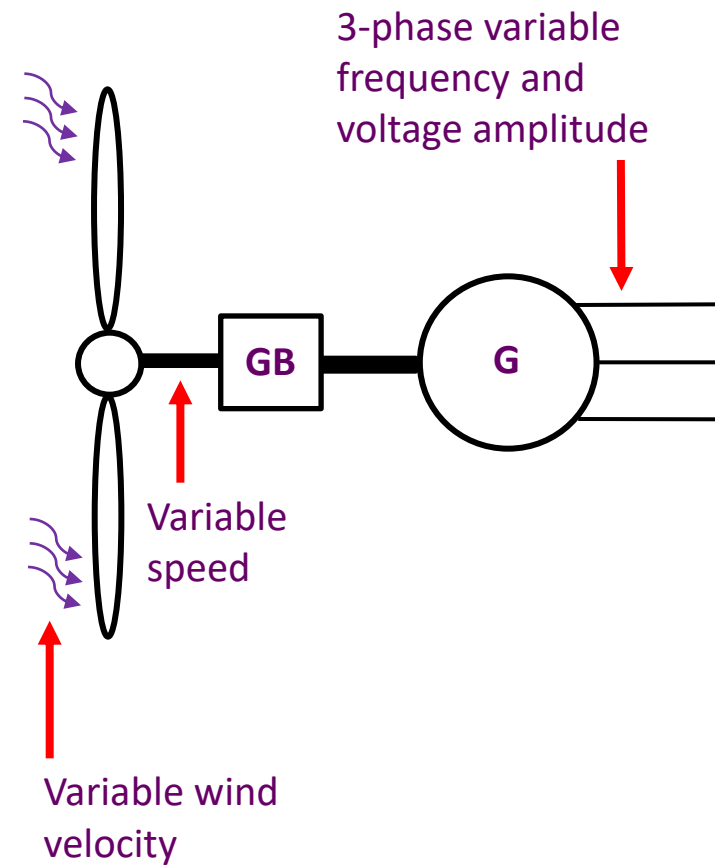


Walney offshore wind farm, UK

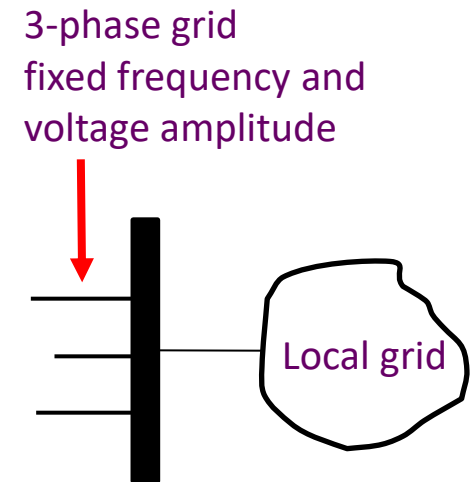
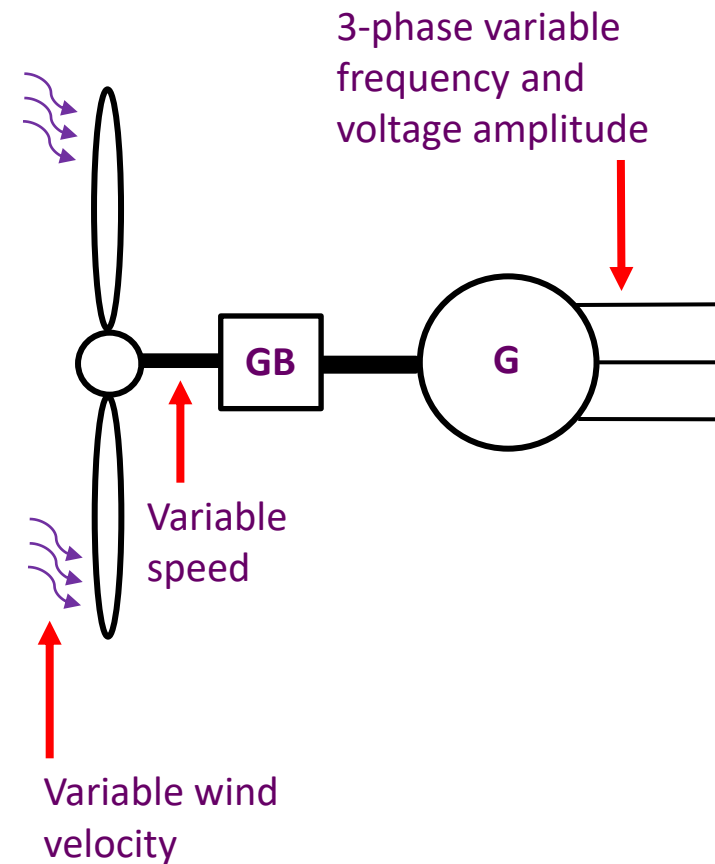


Shepherds flat wind farm, Oregon, USA

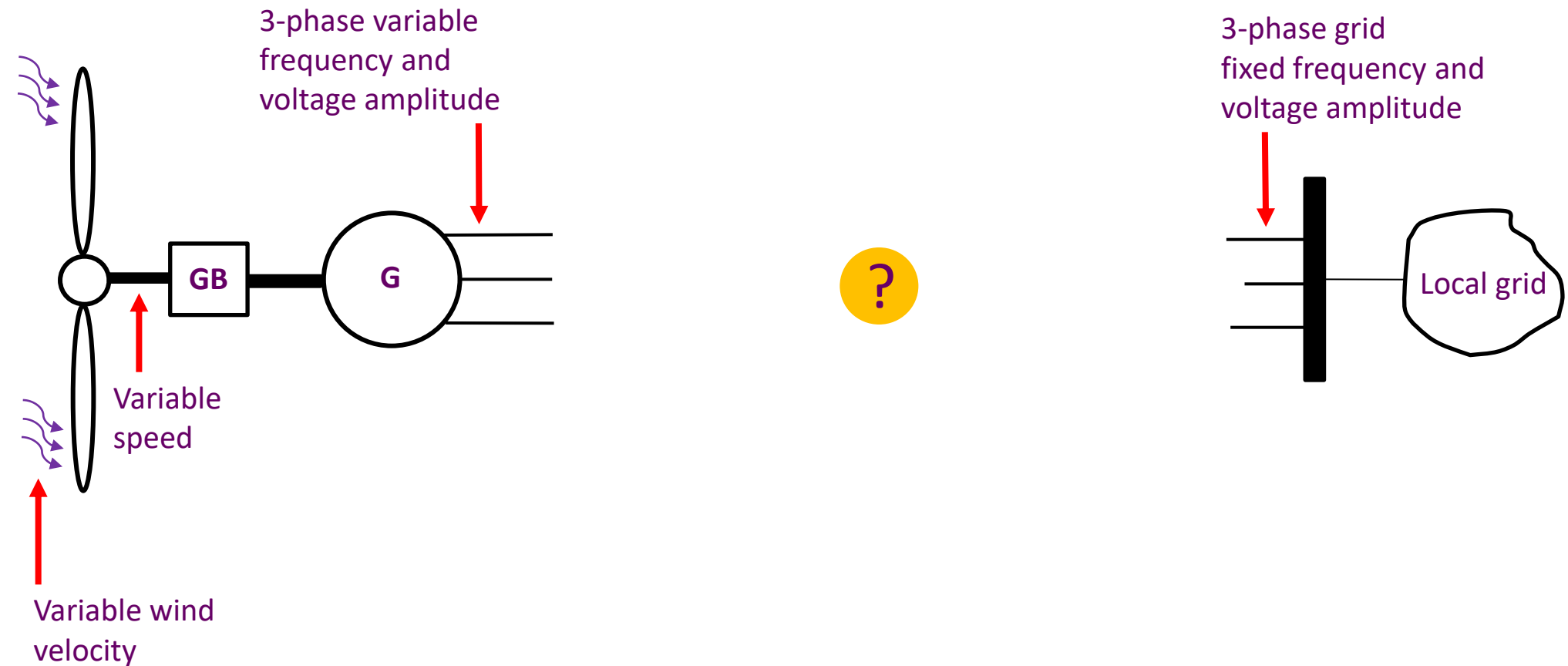
Connection of Wind Turbine to Grid



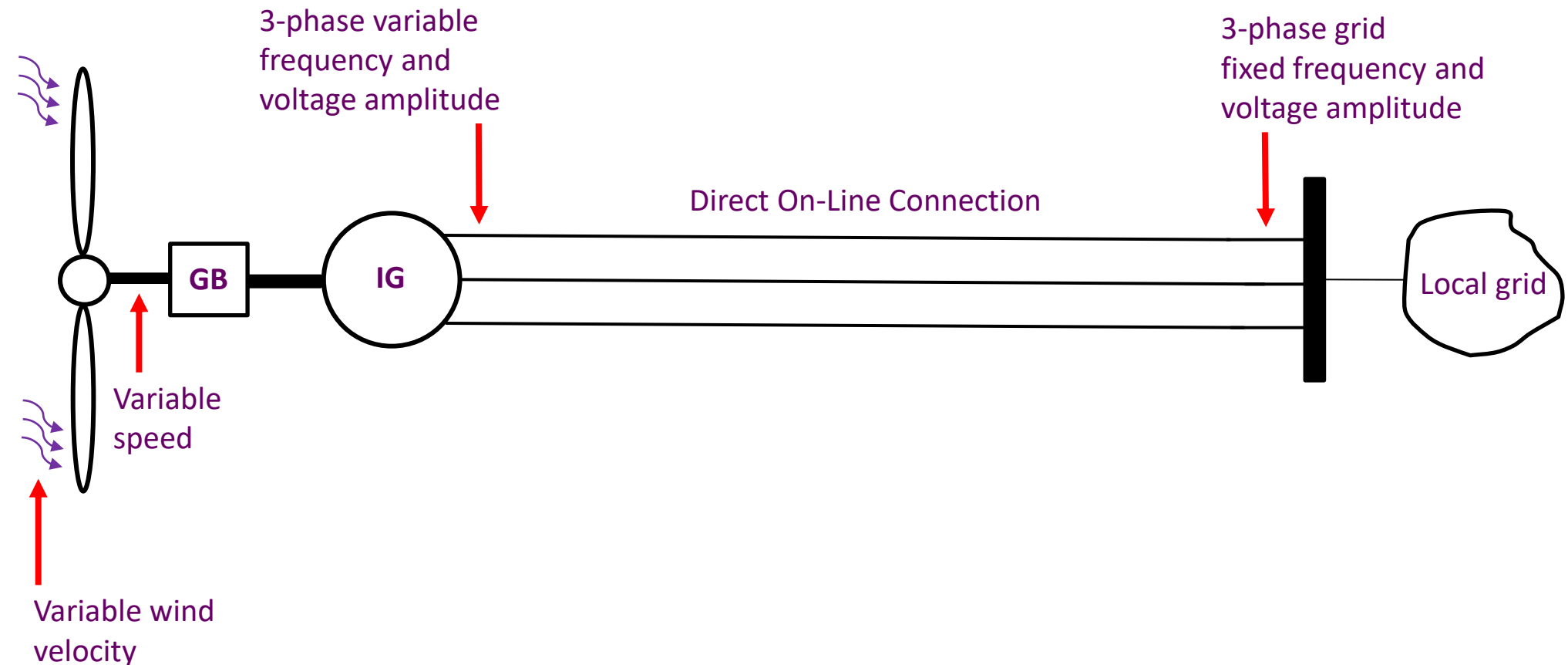
Connection of Wind Turbine to Grid



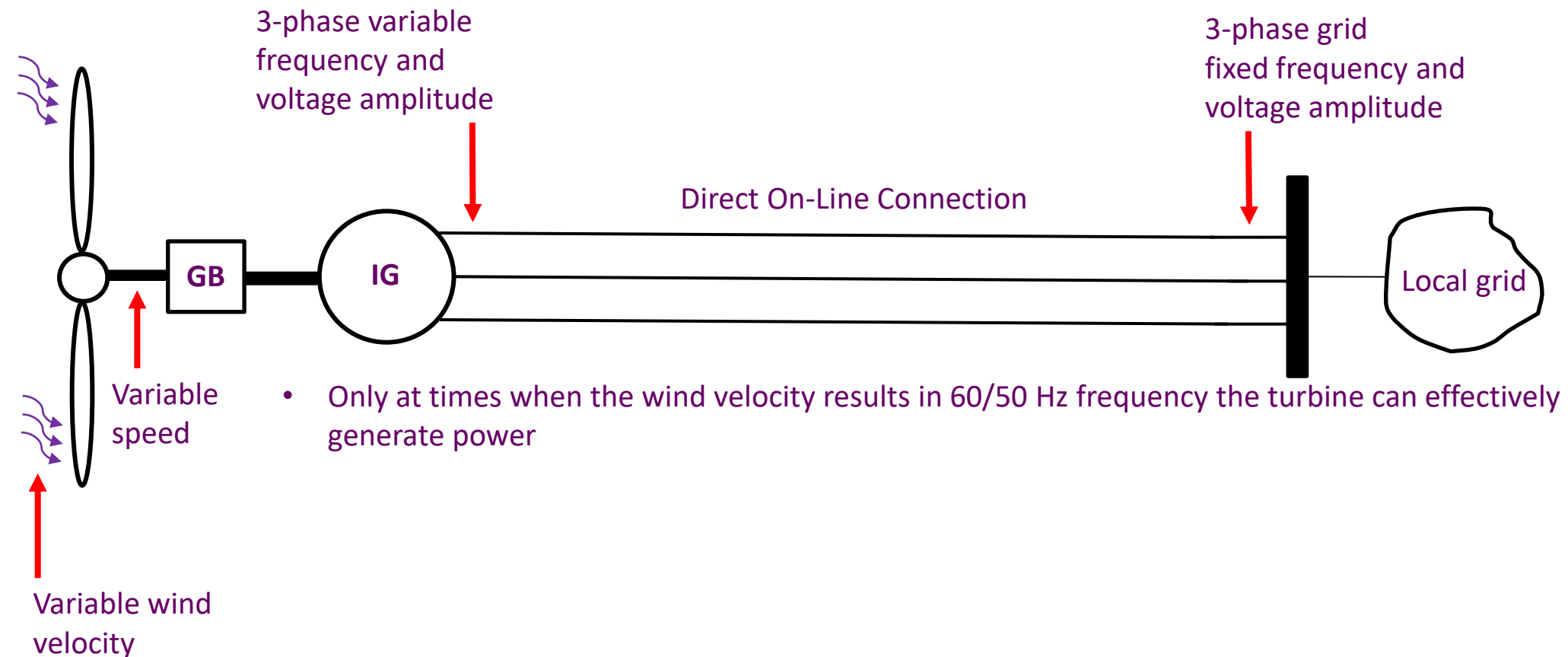
Connection of Wind Turbine to Grid



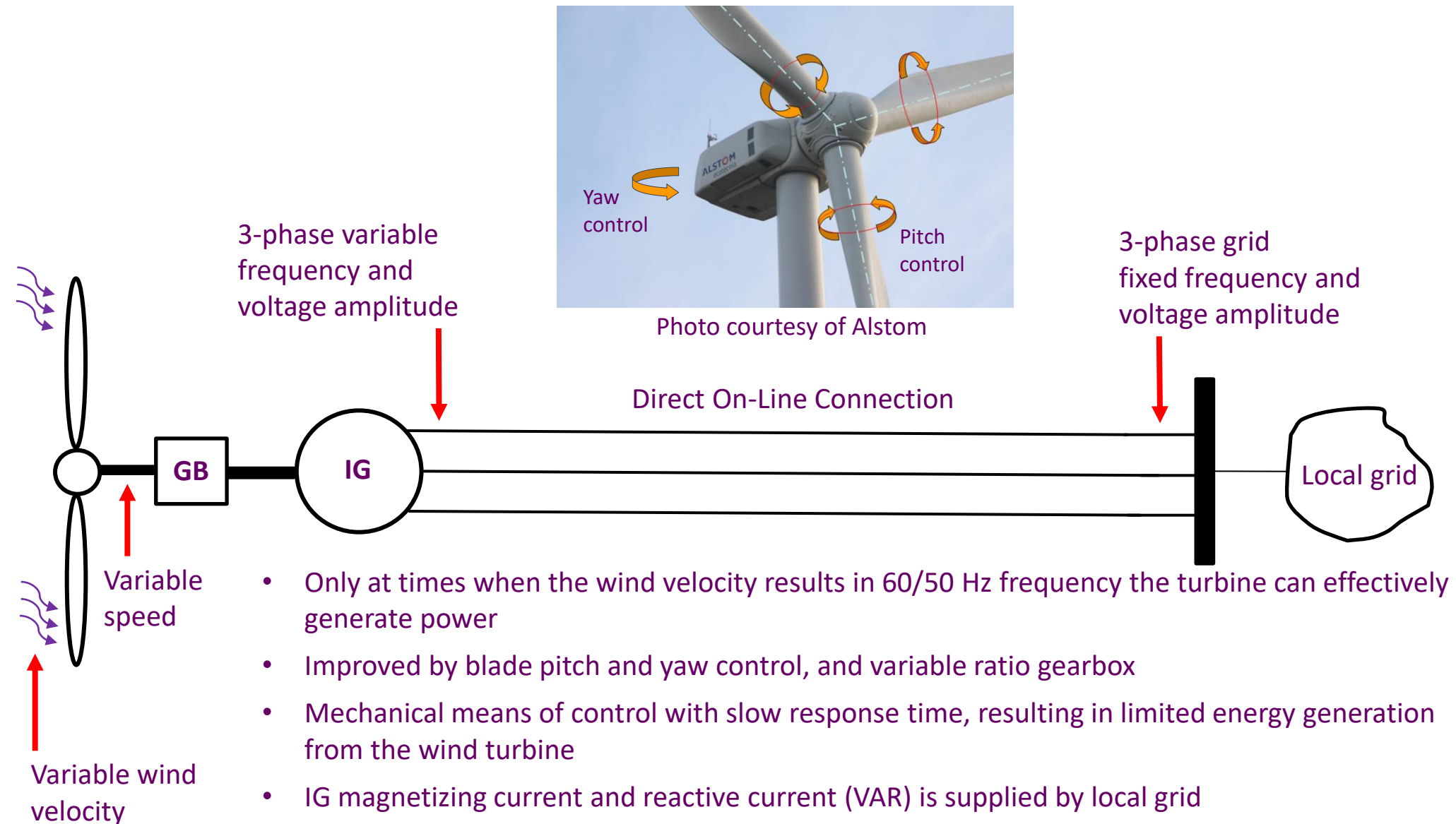
Direct On-Line (DOL) Connection to the Grid: Type-1 Wind Turbine



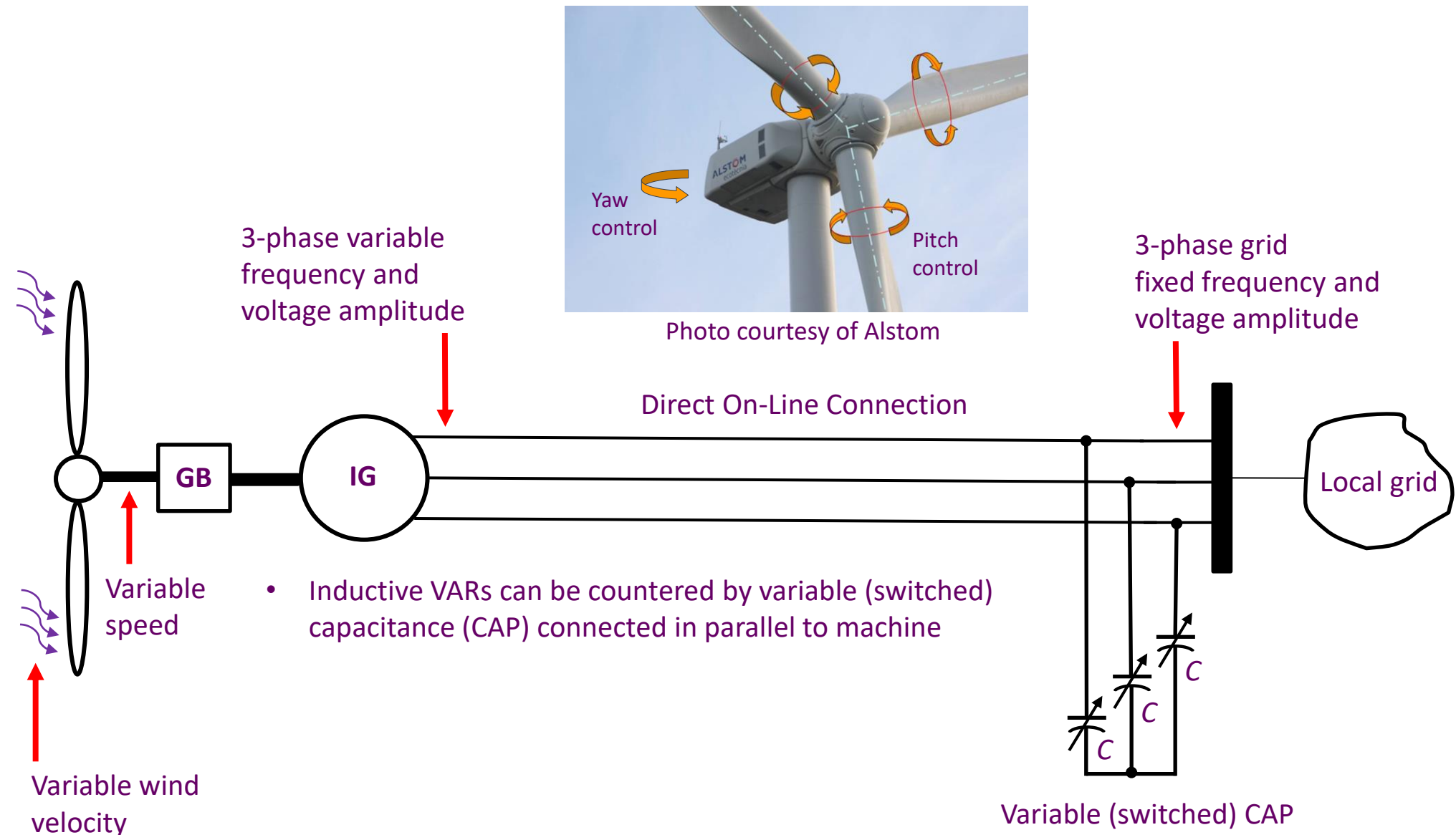
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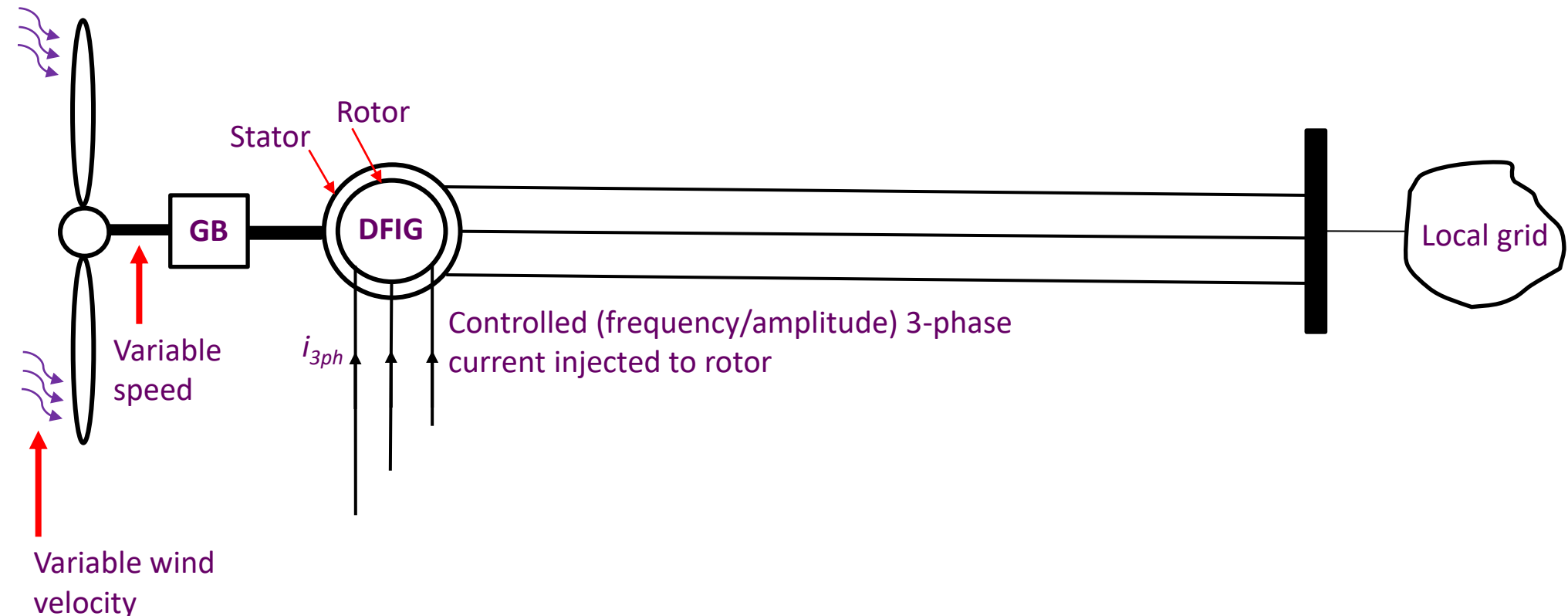


Direct On-Line (DOL) Connection to the Grid with CAP: Type-2 Wind Turbine



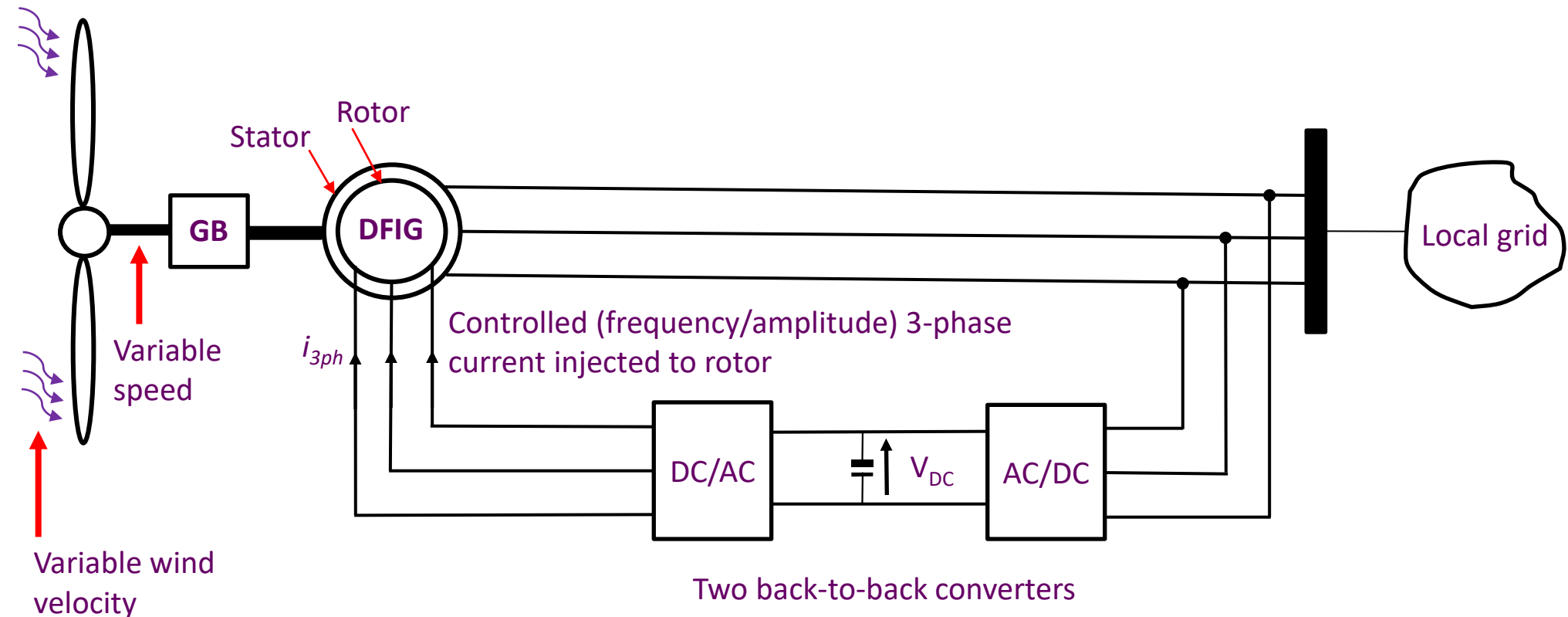
Improved DOL with Doubly Fed Induction Generation (DFIG): Type-3 Wind Turbine

- ❑ Improved DOL using Doubly Fed Induction Generator (DFIG) and two converters that are not fully rate. Typically, converters process the power as much as about 1/3 of the full power. DFIG has typical $\pm 30\%$ operational speed range around the synchronous speed
- ❑ As the wind velocity varies the output voltage and frequency change. By injecting a variable frequency and amplitude current into the rotor the machine output voltage and frequency are control to be fixed

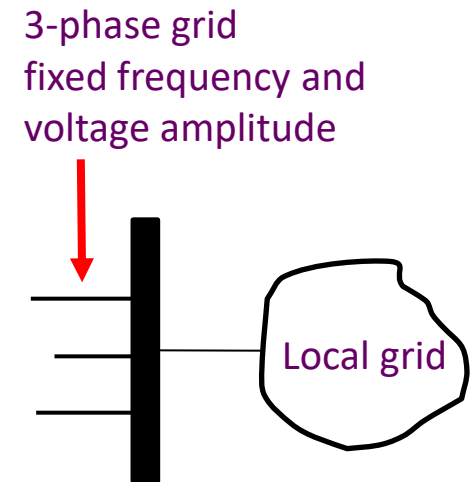
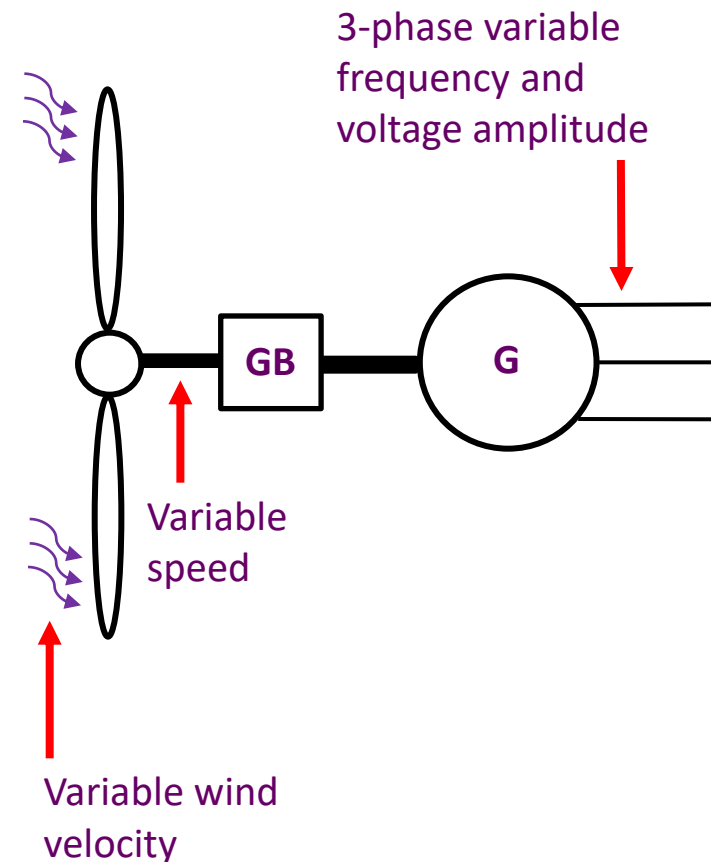


Improved DOL with Doubly Fed Induction Generation (DFIG): Type-3 Wind Turbine

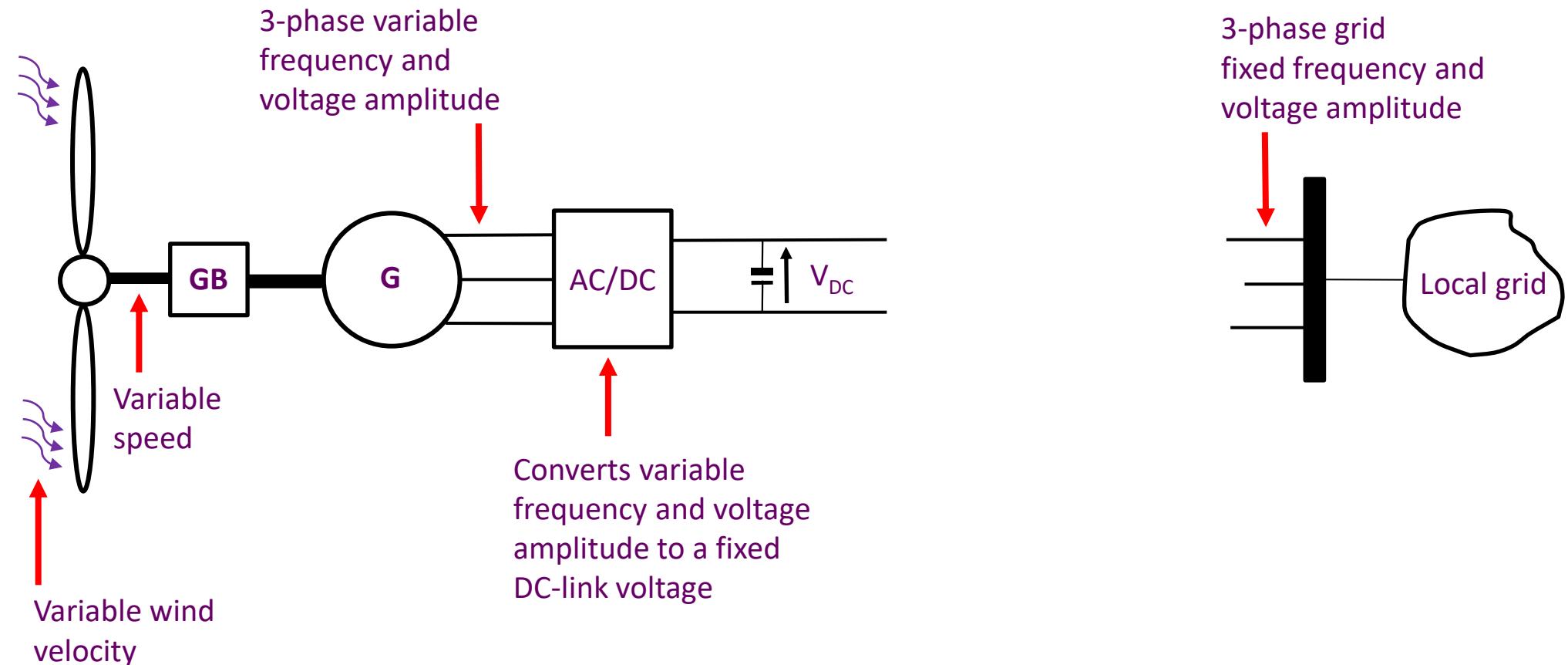
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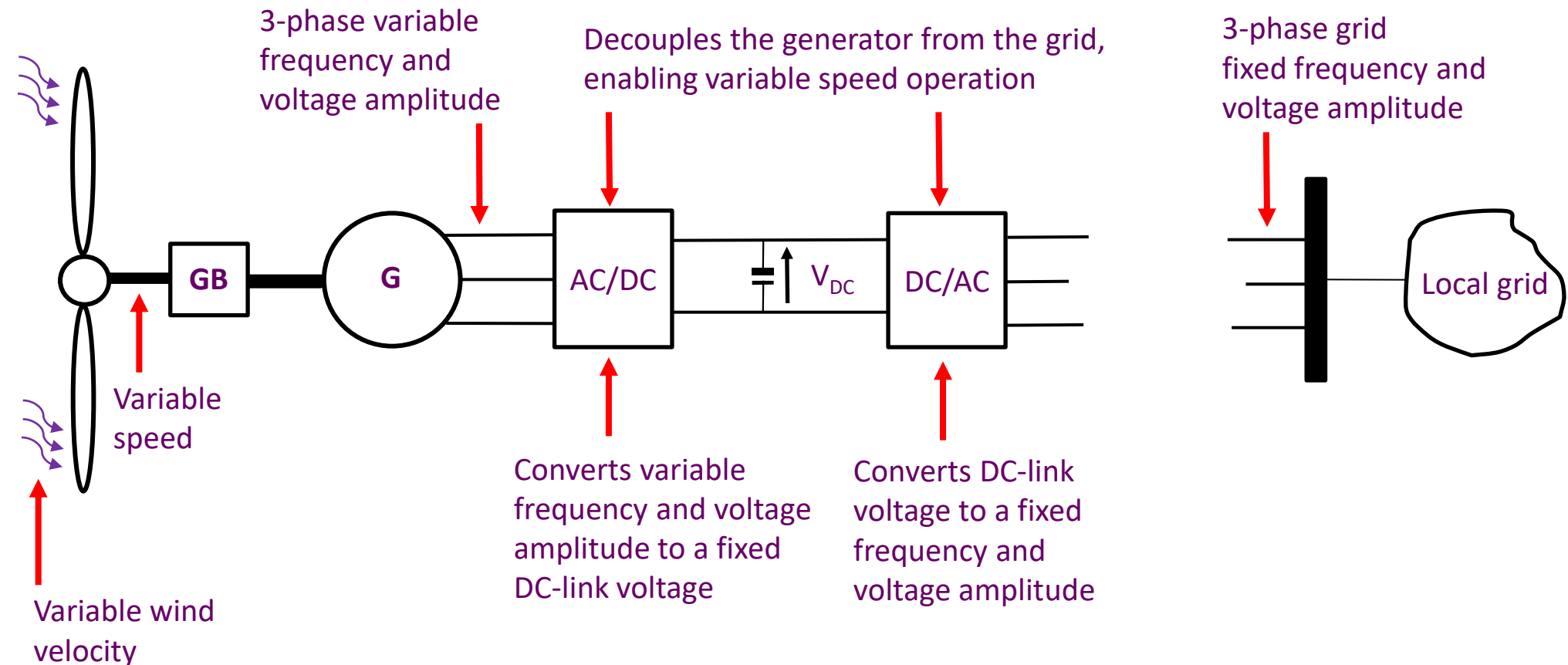
Connection to the Grid Using Power Electronics Converters: Type-4 Wind Turbine



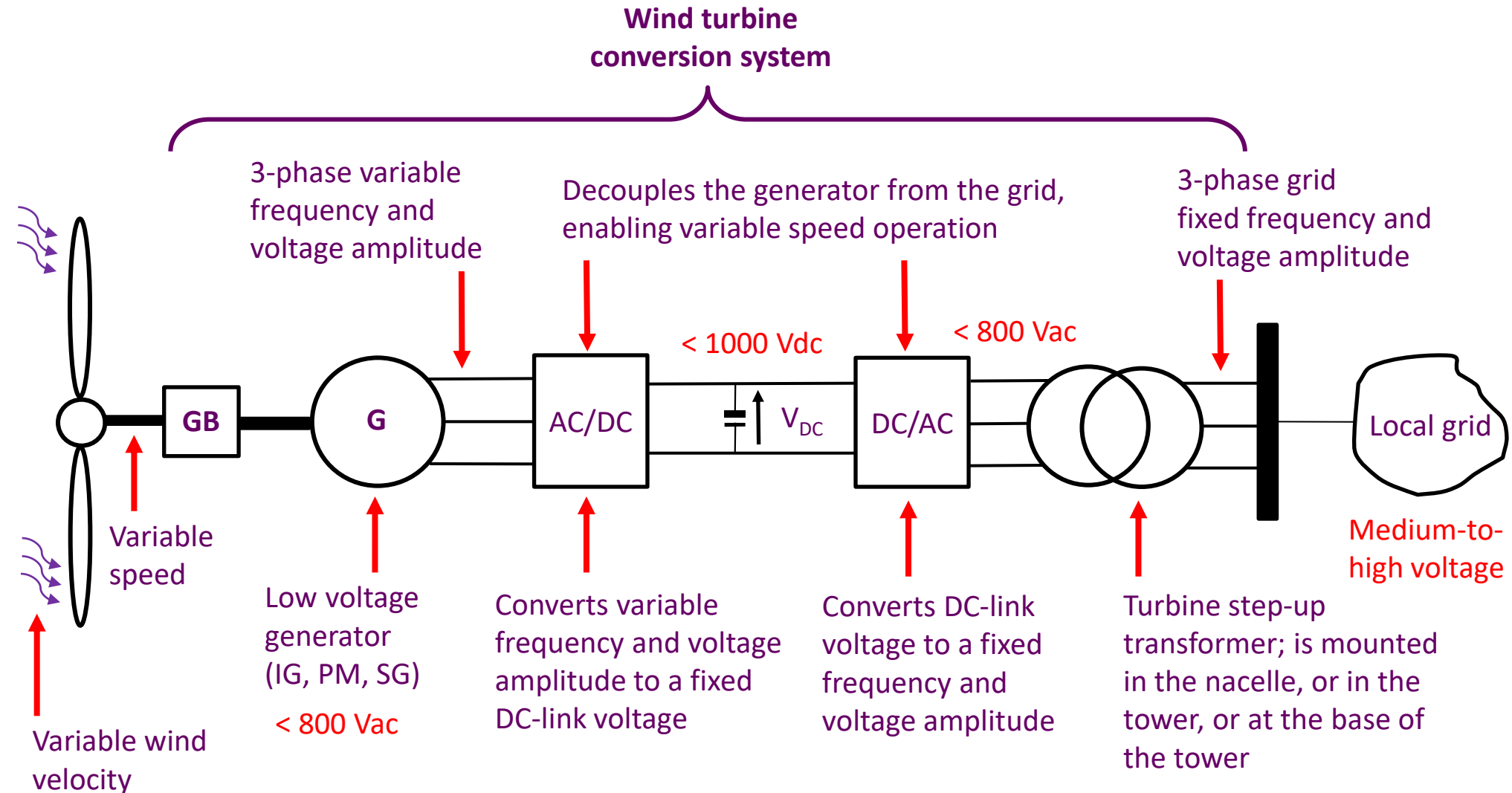
Connection to the Grid Using Power Electronics Converters: Type-4 Wind Turbine



Connection to the Grid Using Power Electronics Converters: Type-4 Wind Turbine



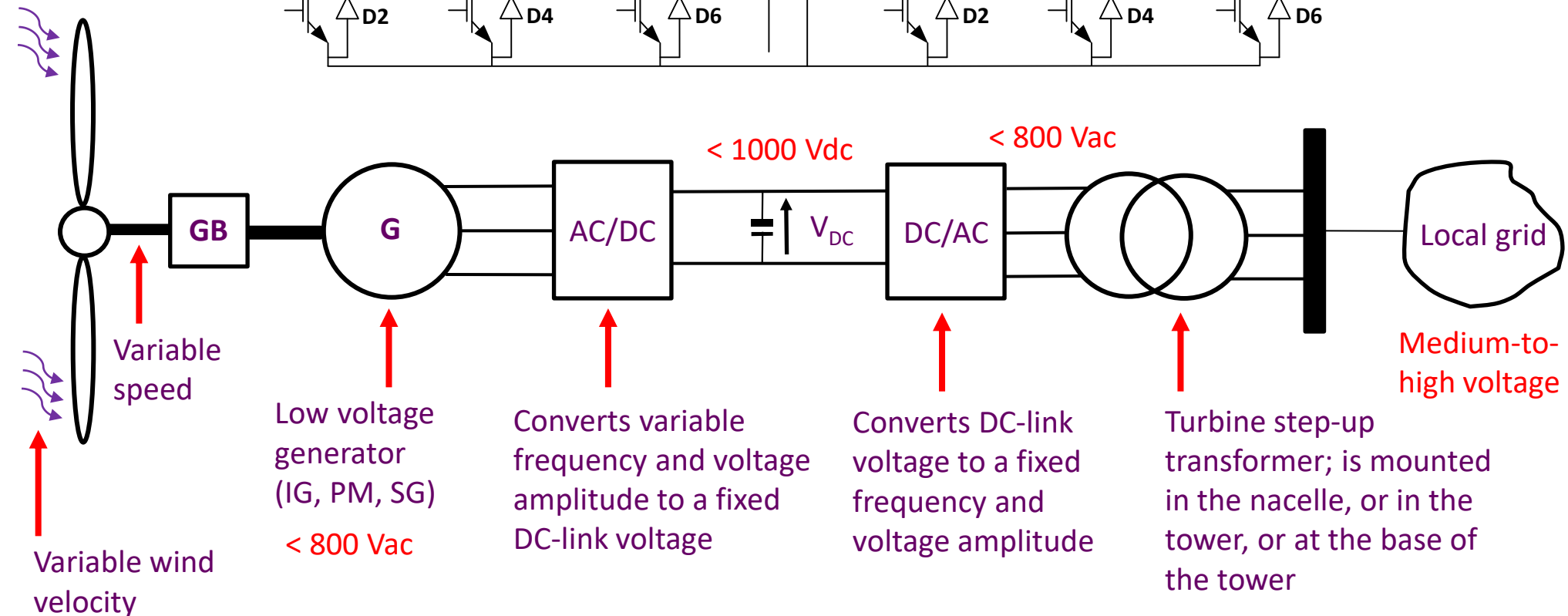
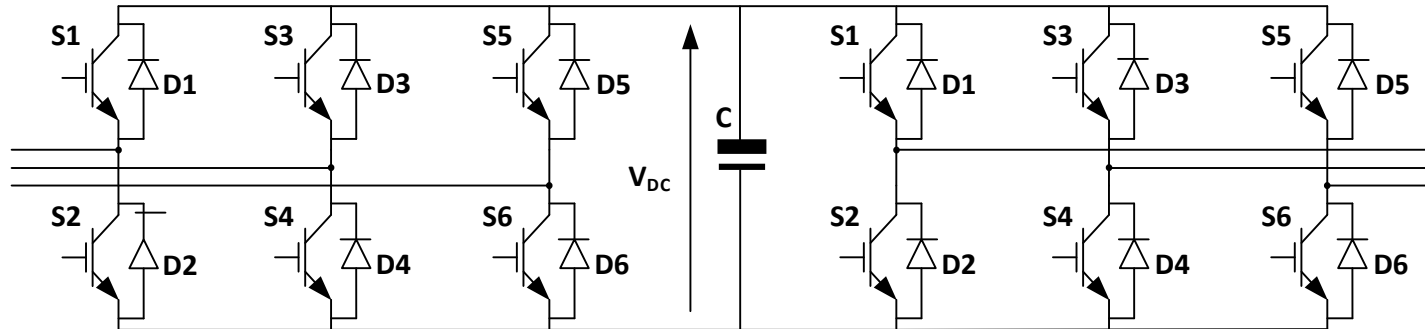
Connection to the Grid Using Power Electronics Converters: Type-4 Wind Turbine



Back-to-Back Voltage Source Converters (VSC)

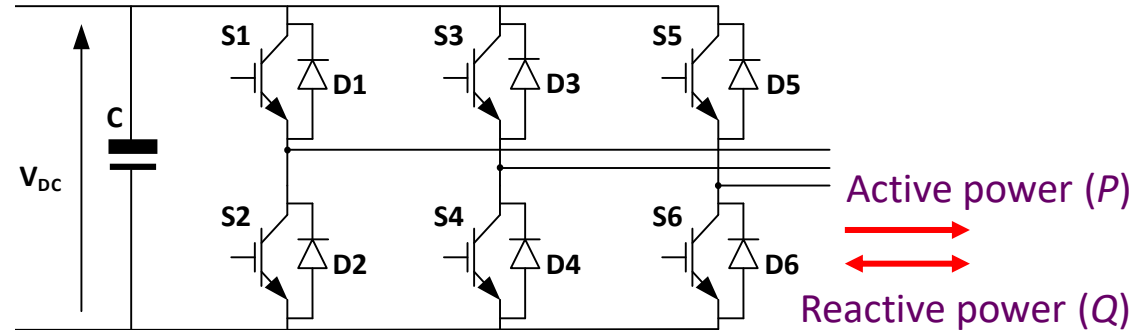
Machine side VSC

Grid side VSC



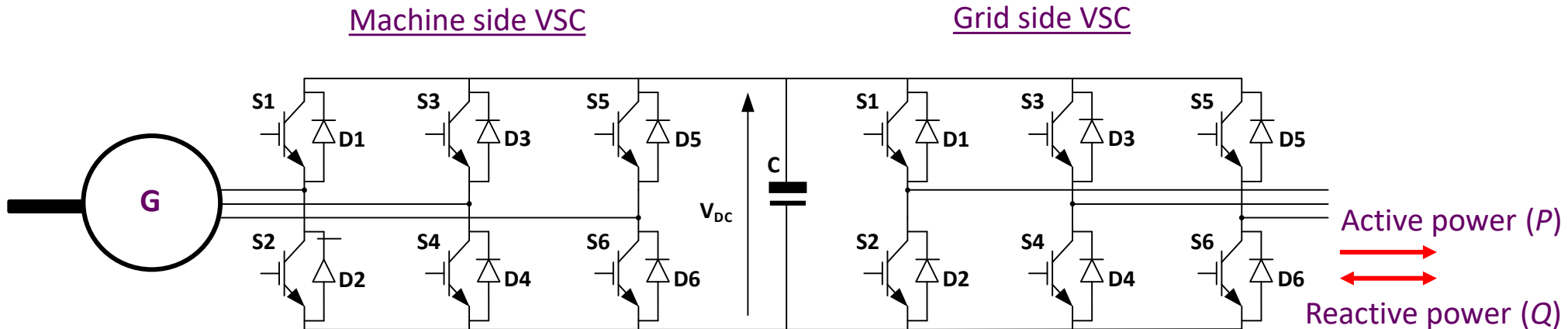
Back-to-Back Voltage Source Converters (VSC)

Grid side VSC

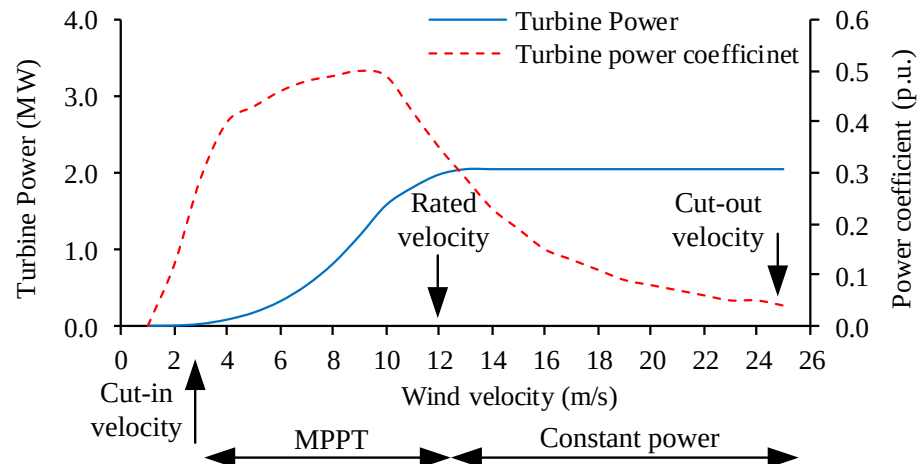


- Maintains a fixed DC voltage at the DC-link
- Controls the active power flow (P), and reactive power flow (Q)

Back-to-Back Voltage Source Converters (VSC)



- Performs a vector control over the generator to extract maximum power i.e. maximum point tracking (MPPT)
- Maintains a fixed DC voltage at the DC-link
- Controls the active power flow (P), and reactive power flow (Q)

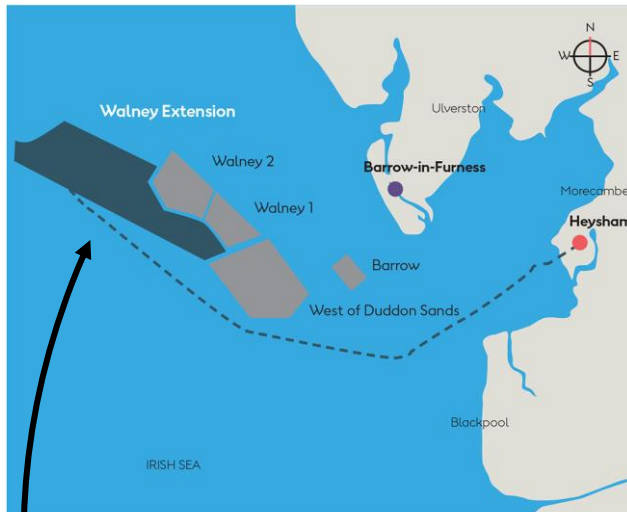


Walney Wind Farm Configuration

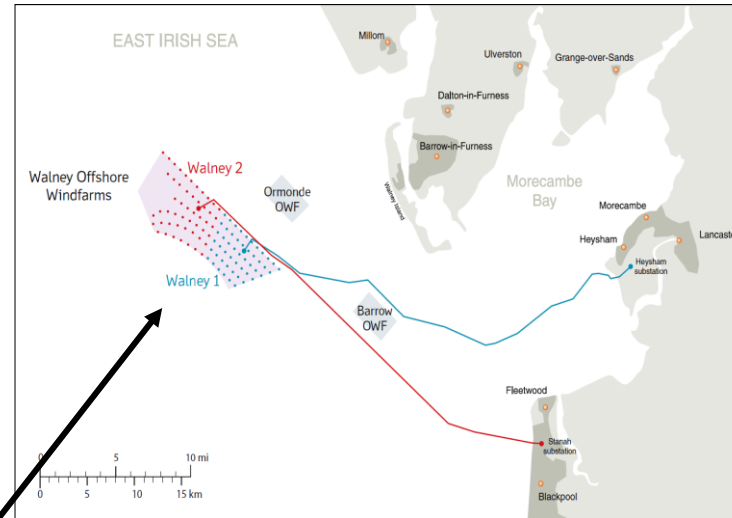


- Walney wind farm
- Located offshore in Irish Sea
- 102 Siemens WT 3.6 MW
- 47 Siemens WT 7 MW
- 40 Vestas WT 8.25 MW
- Total 189 WTs with 1026 MW

Walney Wind Farm Configuration

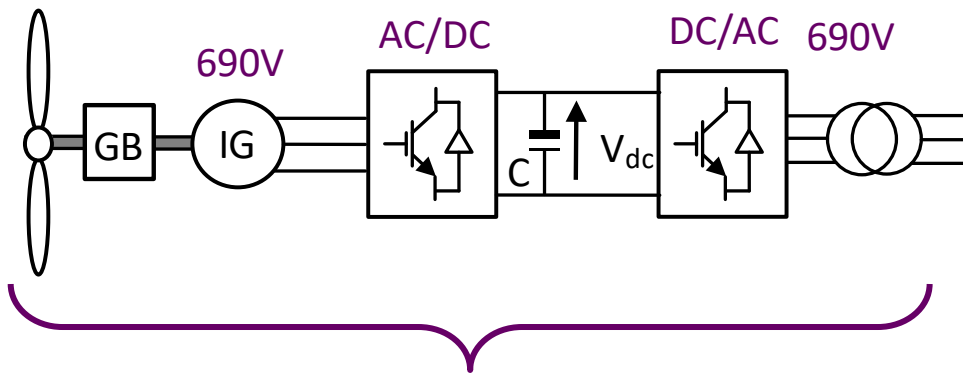


- Walney Extension Offshore Wind Farm
- Cable Corridor / Route
- Onshore Substation
- O&M base



- **Walney wind farm**
- **Located offshore in Irish Sea**
- **102 Siemens WT 3.6 MW**
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- **Total 189 WTs with 1026 MW**

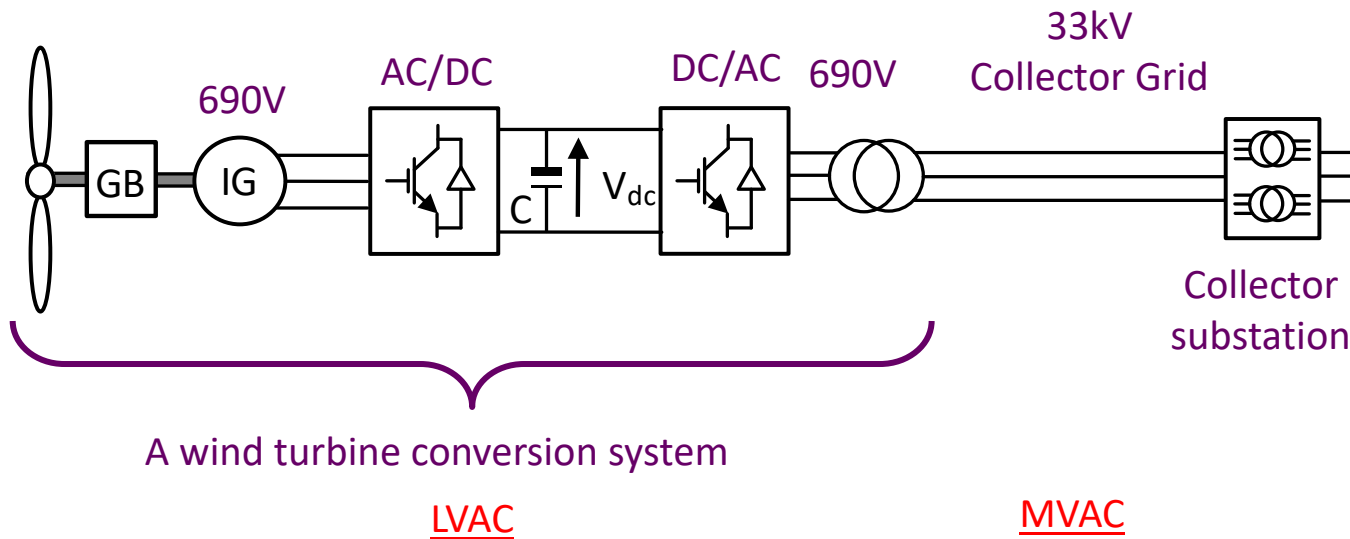
Walney Wind Farm Configuration



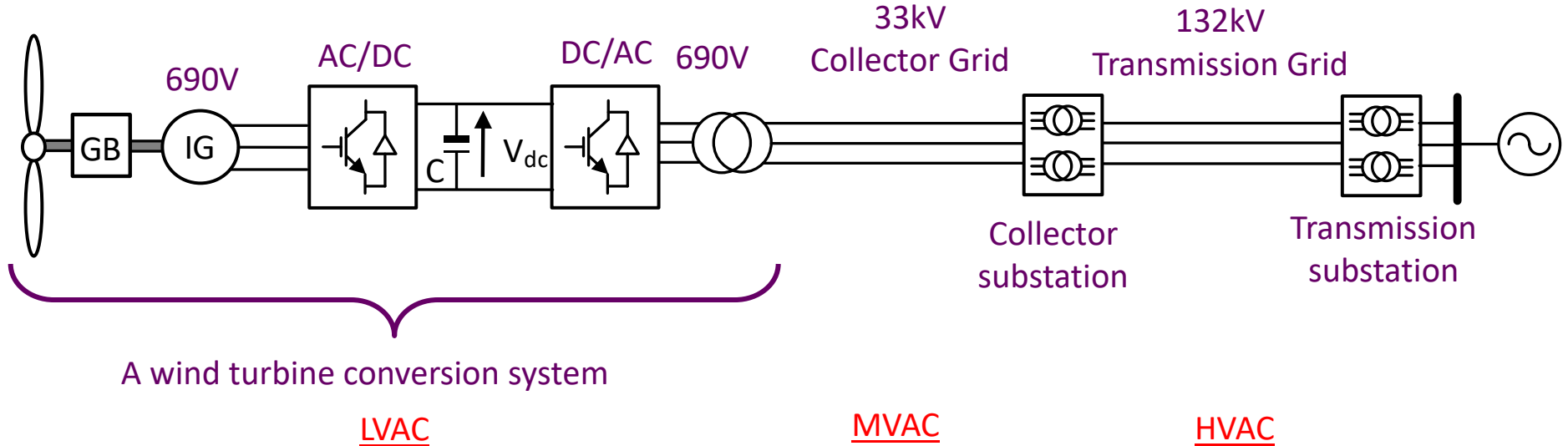
A wind turbine conversion system

LVAC

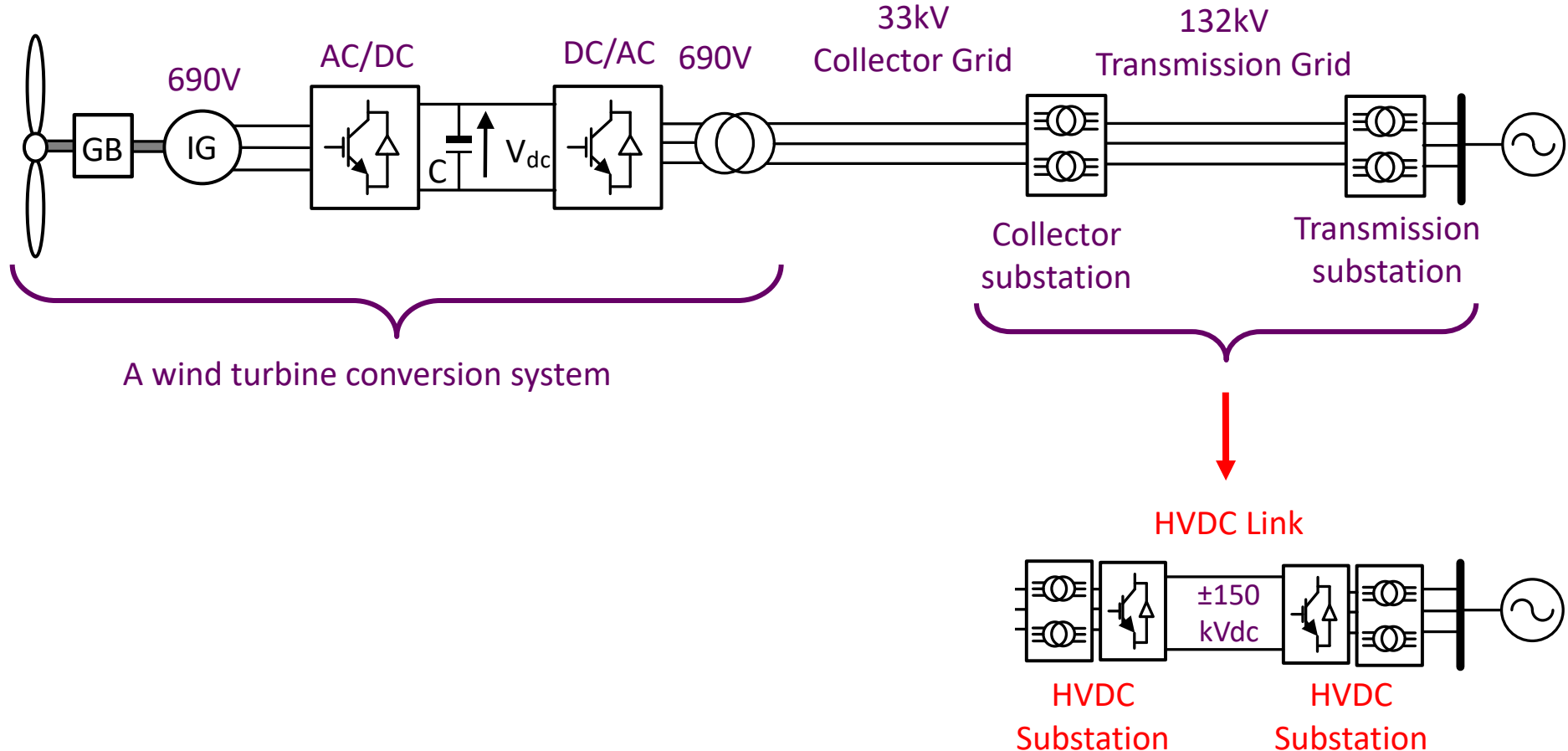
Walney Wind Farm Configuration



Walney Wind Farm Configuration

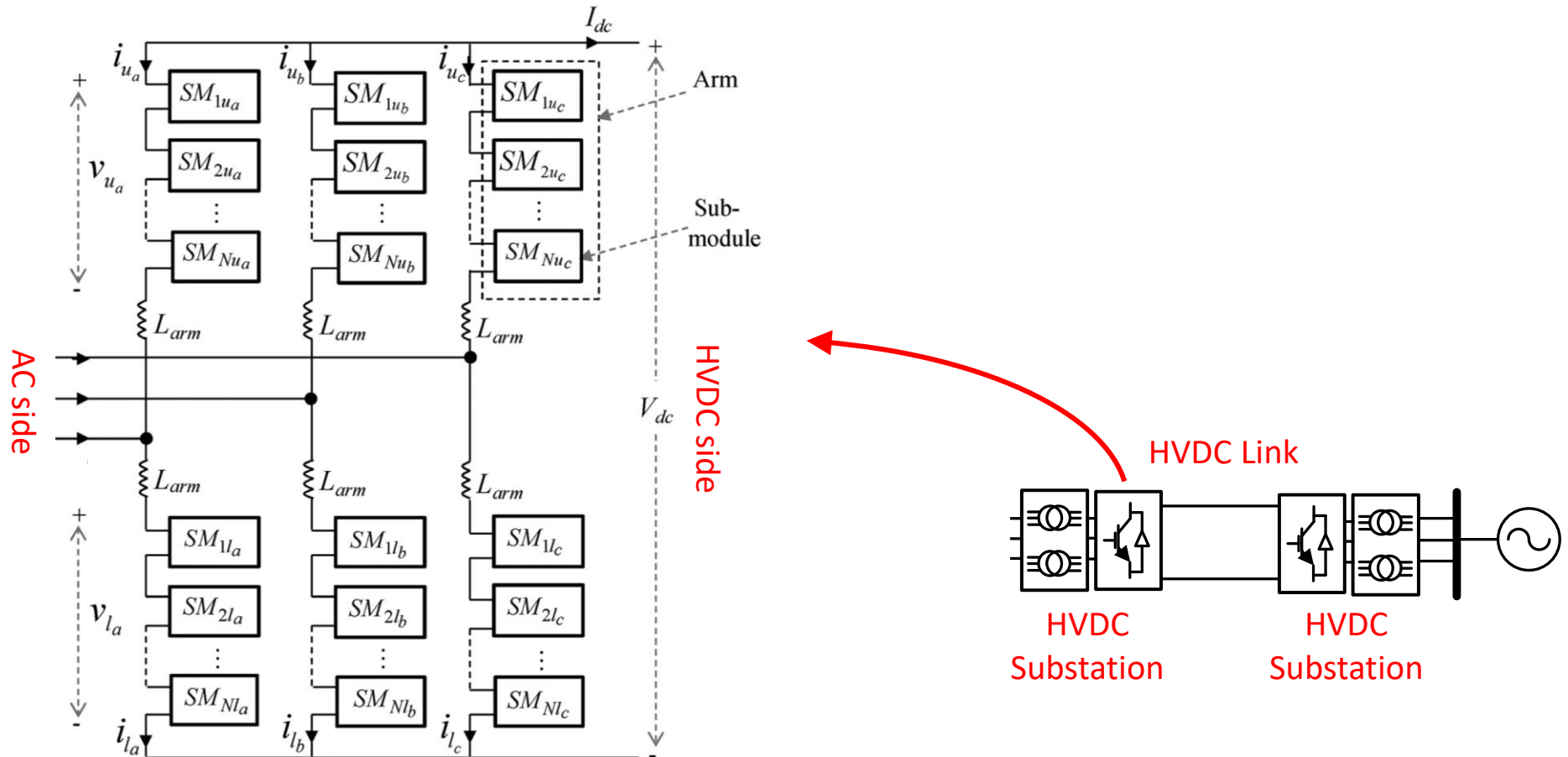


HVDC Transmission Systems



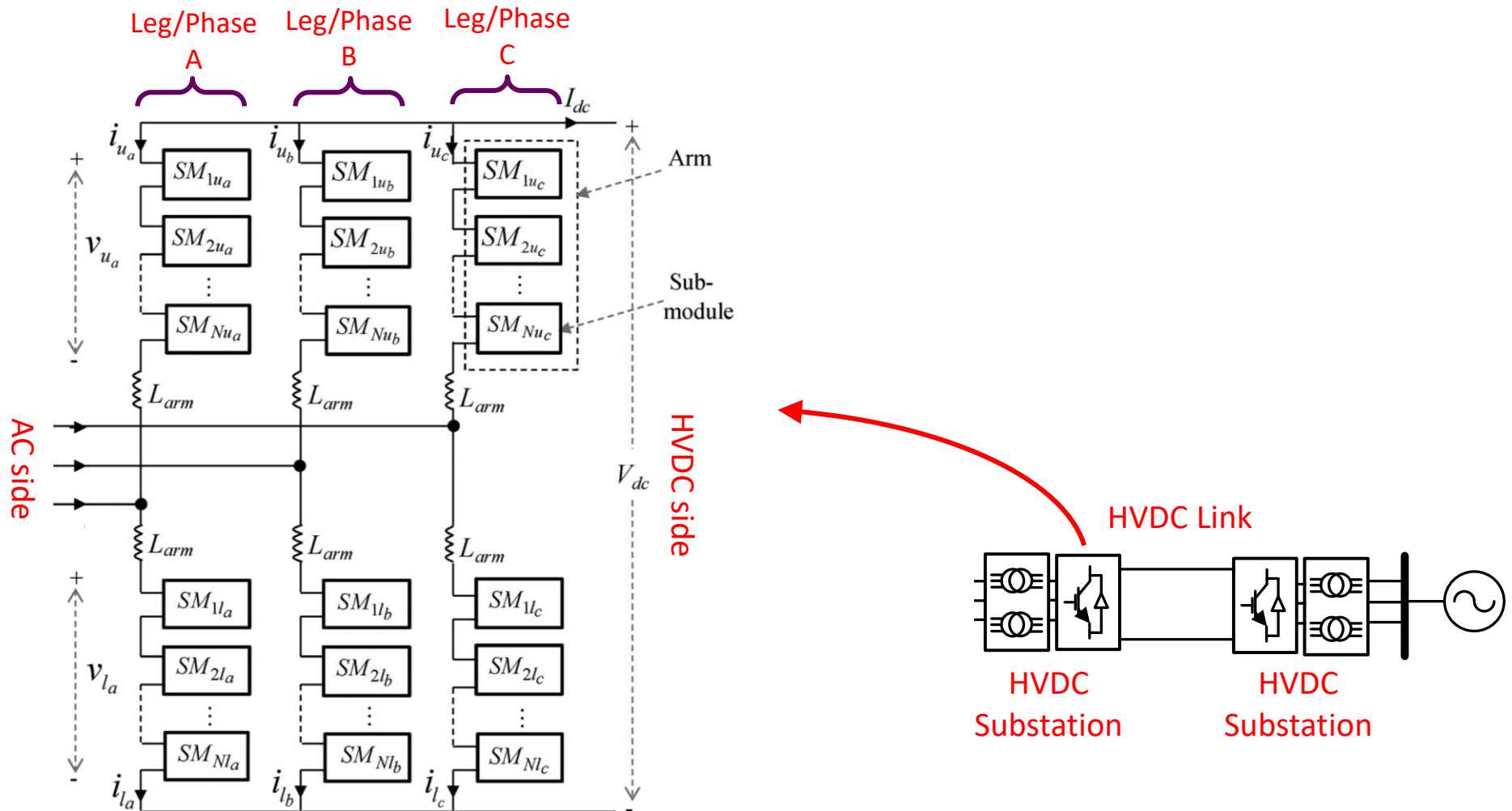
- ❑ With the advancements in power electronics, and the controllability that they offer the HVAC transmission grids are being replaced with HVDC systems.

Multilevel Modular Converters (MMC)



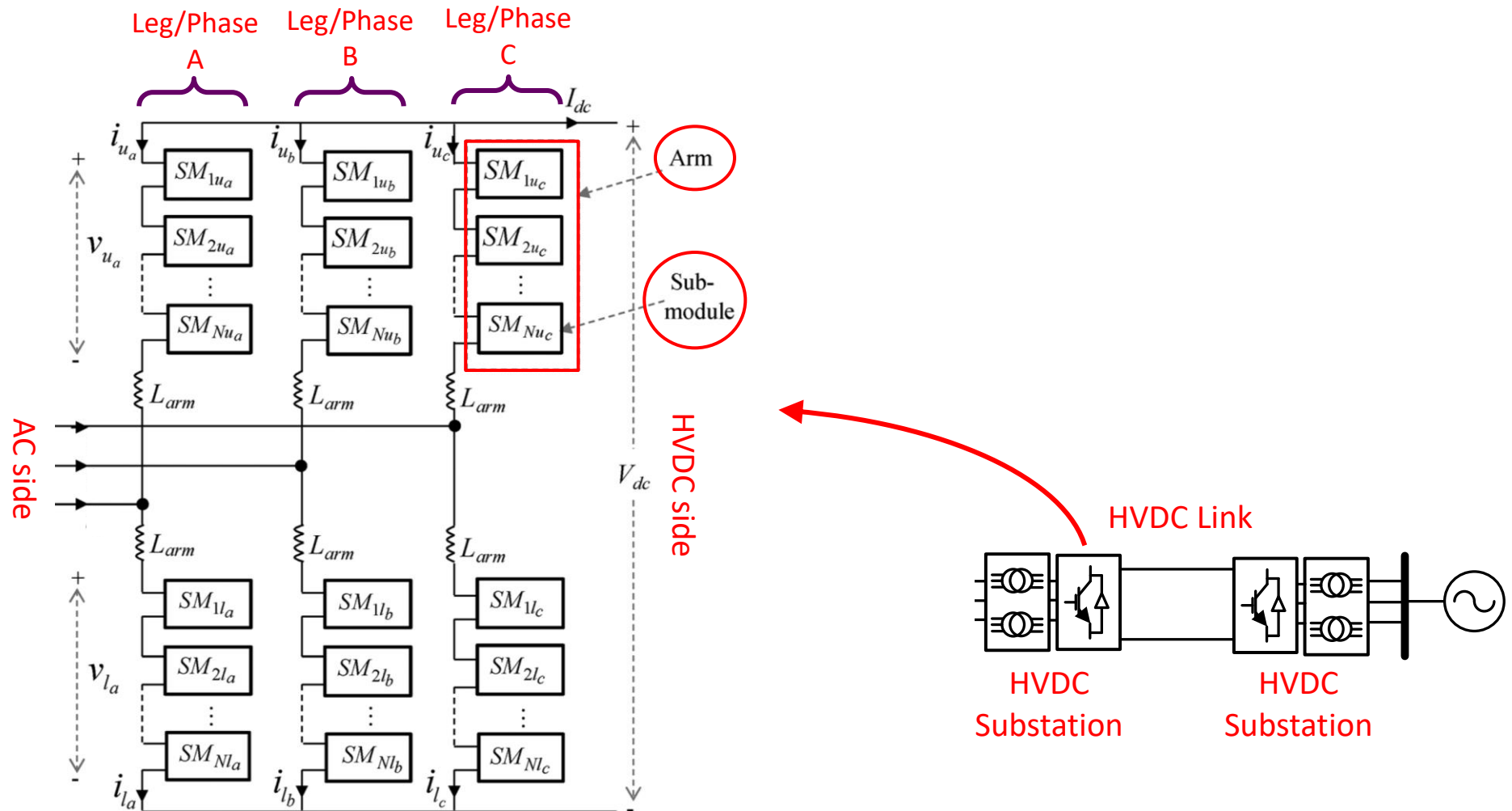
3-phase multilevel modular converter (MMC)

Multilevel Modular Converters (MMC)



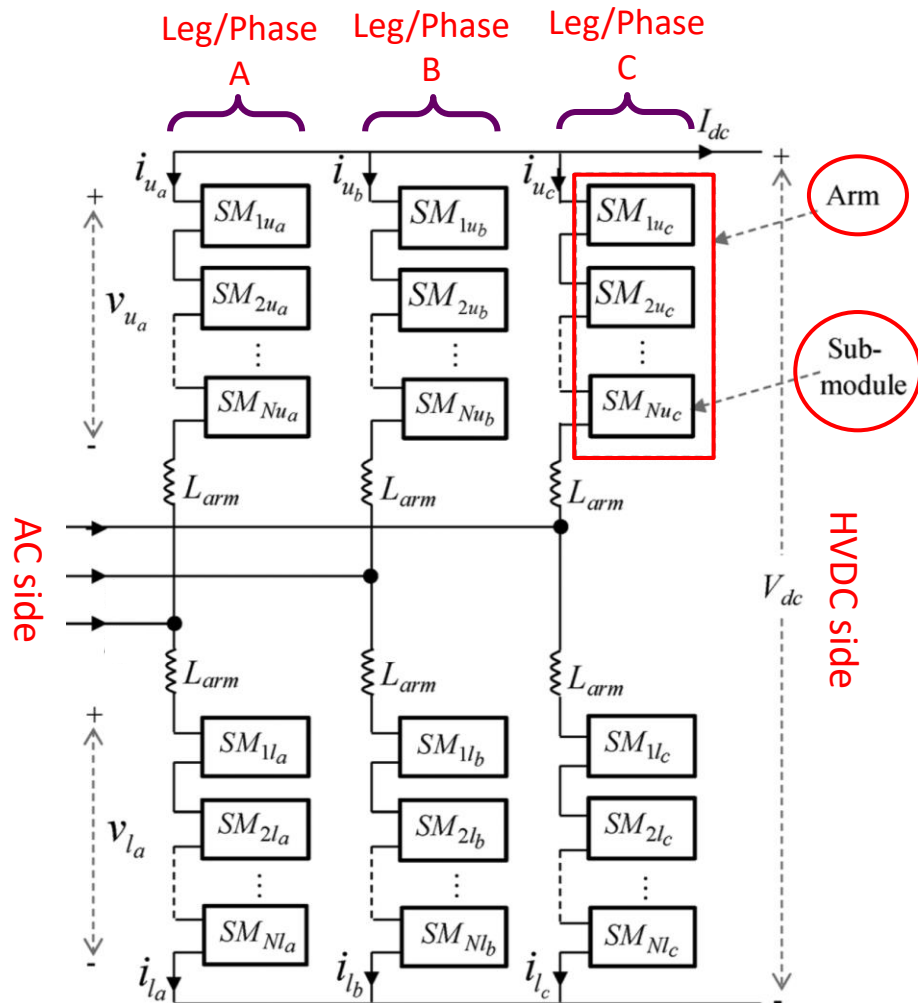
3-phase multilevel modular converter (MMC)

Multilevel Modular Converters (MMC)



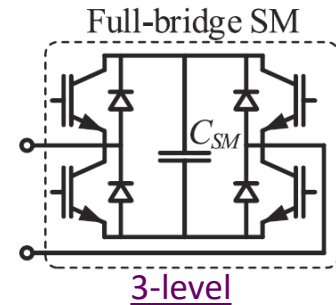
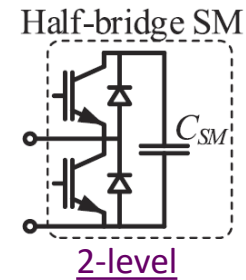
3-phase multilevel modular converter (MMC)

Multilevel Modular Converters (MMC)

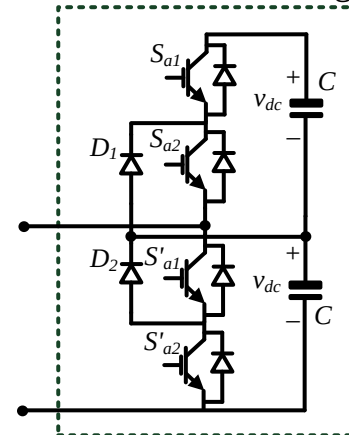


3-phase multilevel modular converter (MMC)

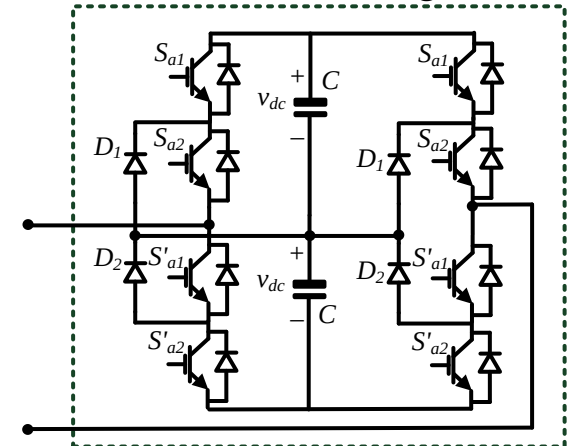
Various types of submodules (SM)



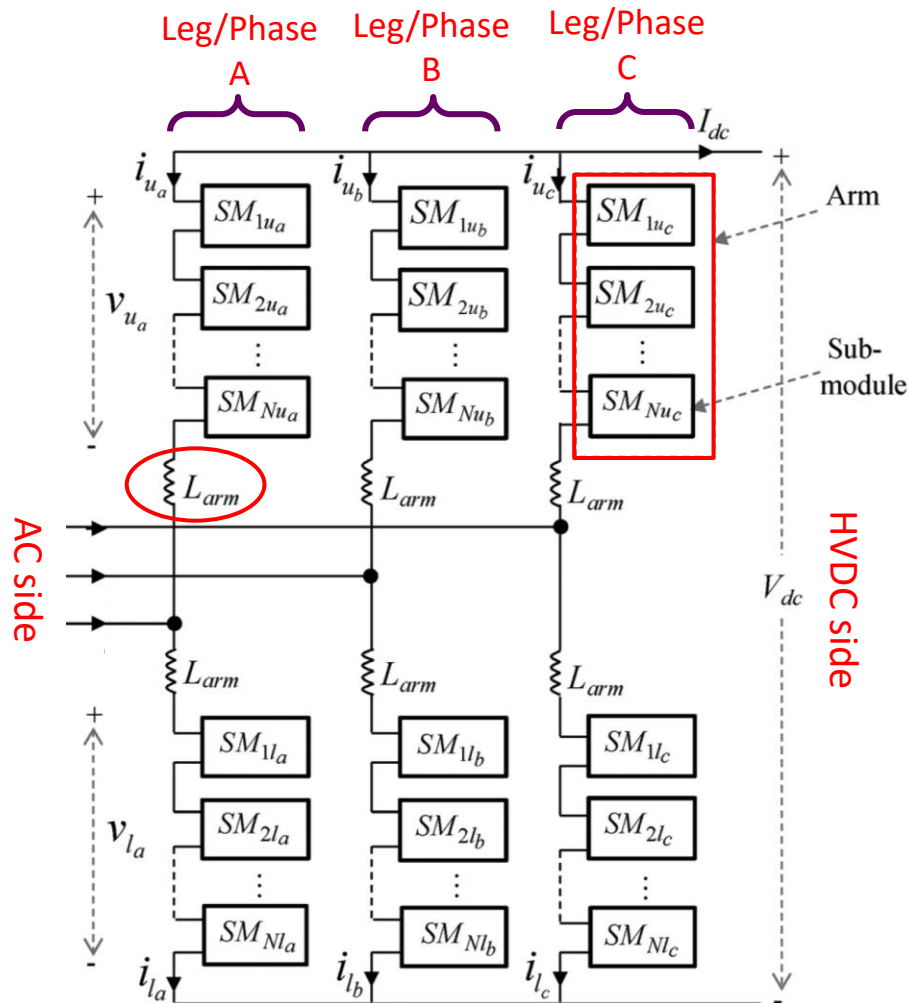
3-level NPC half-bridge SM



5-level NPC full-bridge SM



Multilevel Modular Converters (MMC)



3-phase multilevel modular converter (MMC)

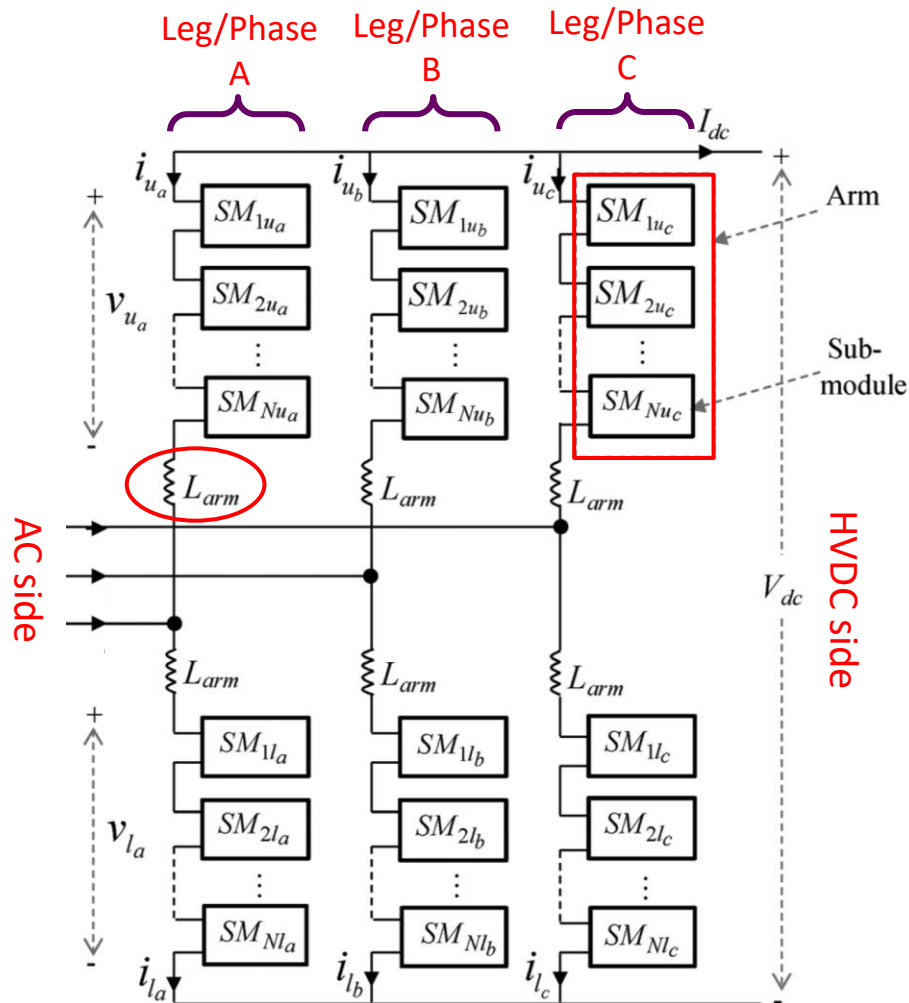
□ The arm inductors have two functions:

- Suppressing circulating currents that may be caused by unequal voltages between legs.
- Limiting the fault currents, in case of a short circuit.

□ Basic operations:

- Because of the structure with a cascaded connection of SMs, every IGBT of the submodules in one arm needs not to be switched on or off at the same time. As a result, concepts such as “on-state” and “off-state” have no meaning in the MMCs.
- The DC current splits equally into the three phases and the AC current splits equally into the upper and lower arms.

Multilevel Modular Converters (MMC): Half-Bridge Modes



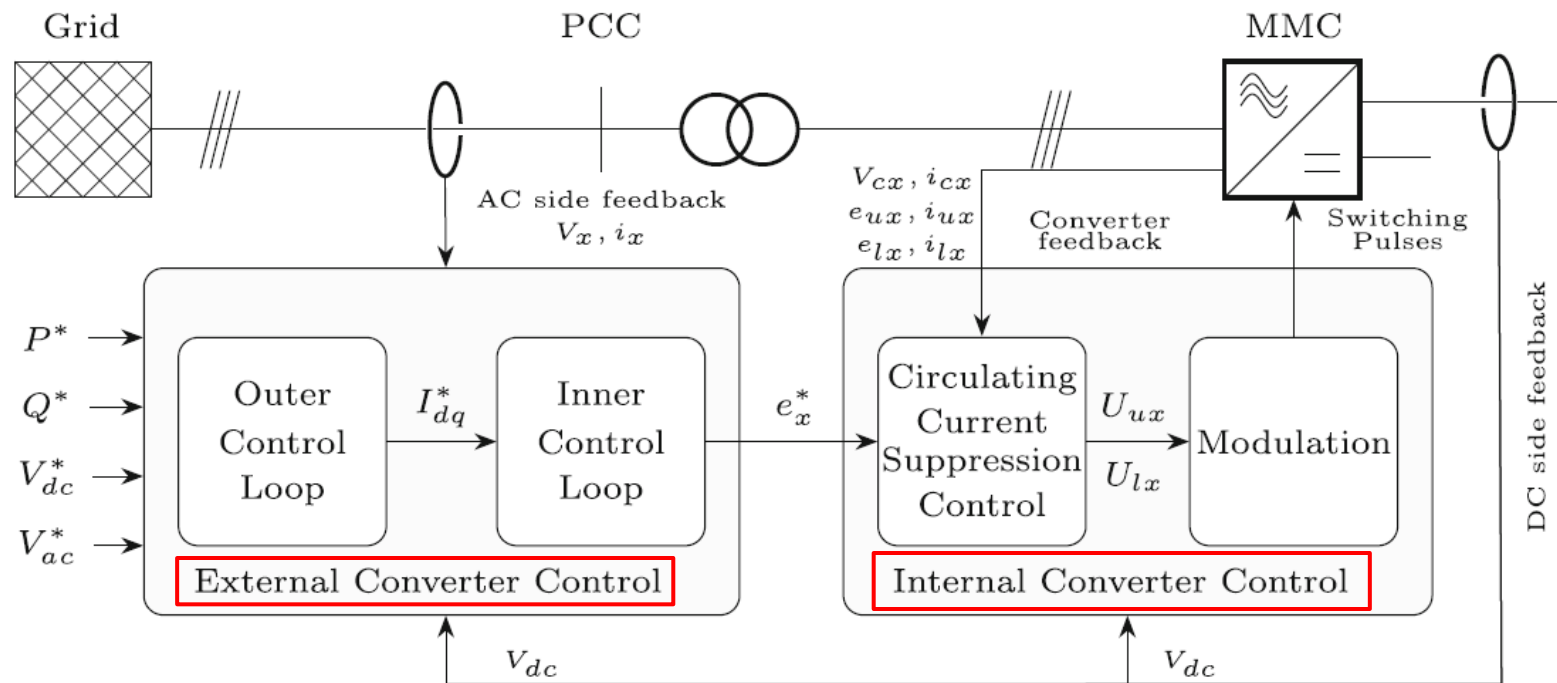
Arm current direction	Inserted	Bypassed
Positive arm current ($i_{arm} > 0$)		
Negative arm current ($i_{arm} < 0$)		

Inserted ($i_{arm} > 0, v_{in} > v_c$)	Bypassed ($i_{arm} < 0, v_{in} < 0$)	High impedance ($0 < v_{in} < v_c$)

3-phase multilevel modular converter (MMC)

Multilevel Modular Converters (MMC): Control

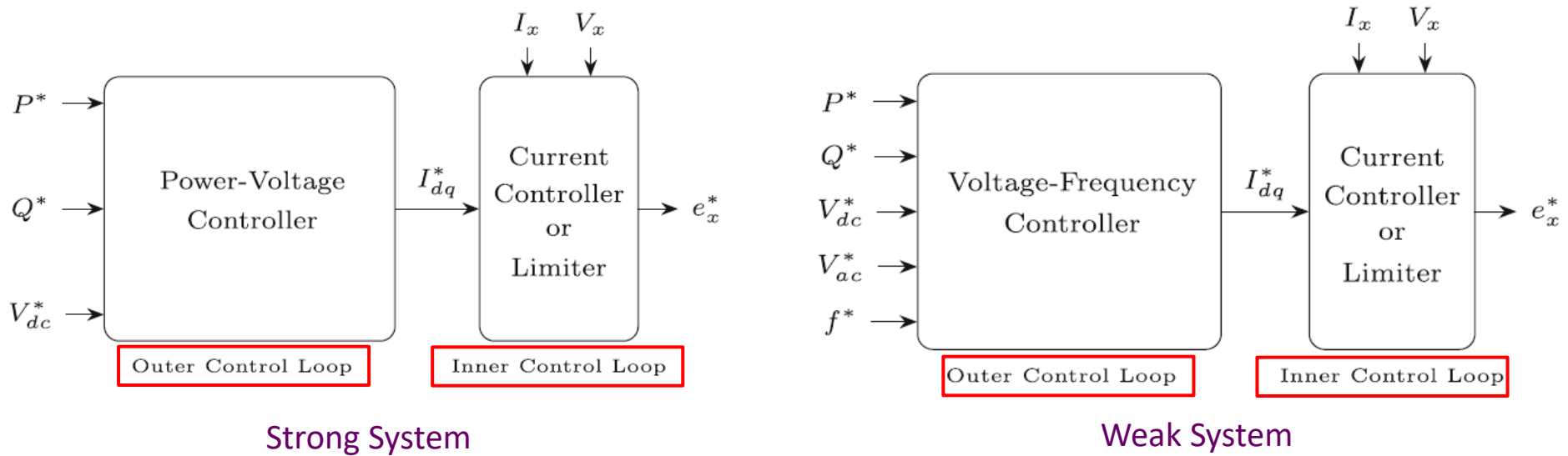
- ❑ The control system includes two main control loops:
 - Internal converter control loops
 - External converter control loops
- ❑ The control system stabilizes both the internal and external dynamics of the MMC-HVDC transmission system.



MMC-HVDC Control Block Diagram

Multilevel Modular Converters (MMC): Control

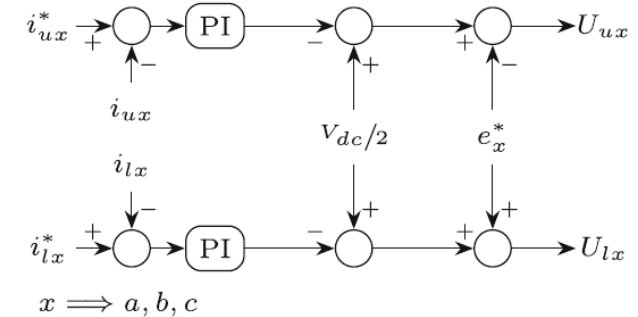
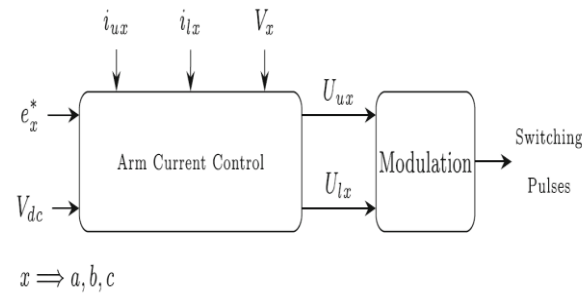
External converter control loops



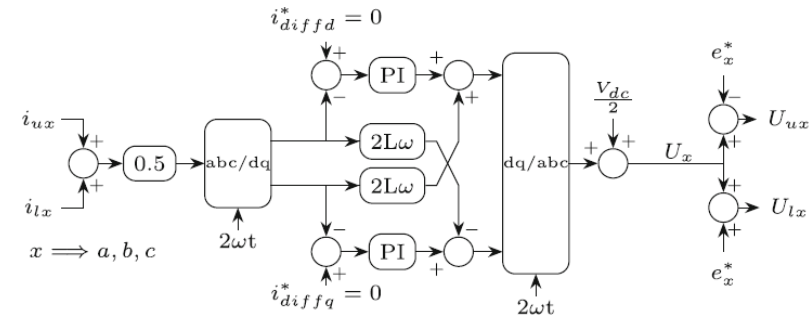
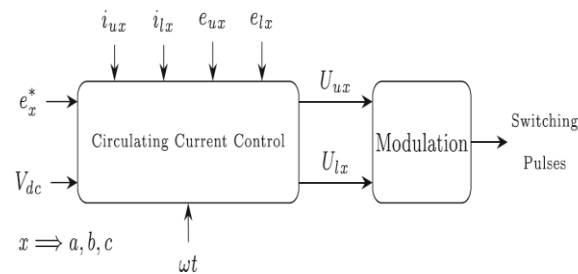
Multilevel Modular Converters (MMC): Control

Internal converter control loops

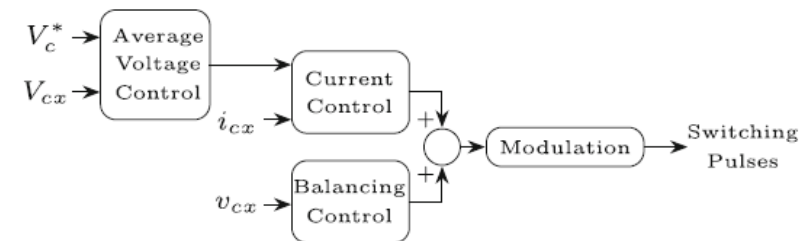
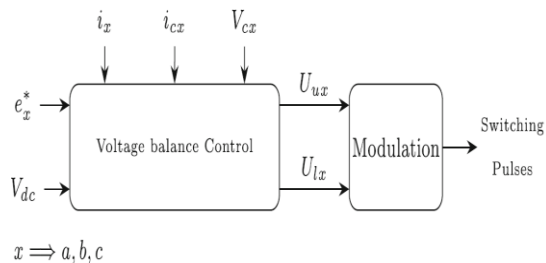
Arm current control



Circulating current control



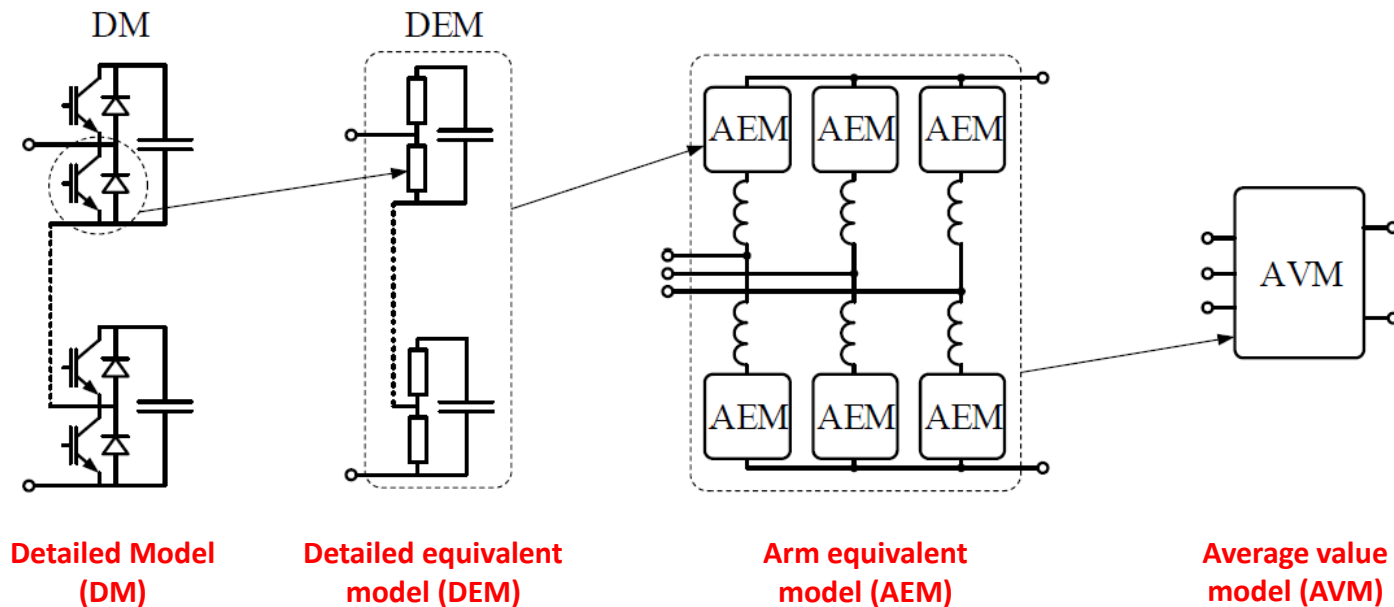
Voltage balance control



Multilevel Modular Converters (MMC): EMT Models

❑ Four electromagnetic transient (EMT) models:

- Detailed model (DM)
- Detailed equivalent model (DEM)
- Arm equivalent model (AEM)
- Average value model (AVM)

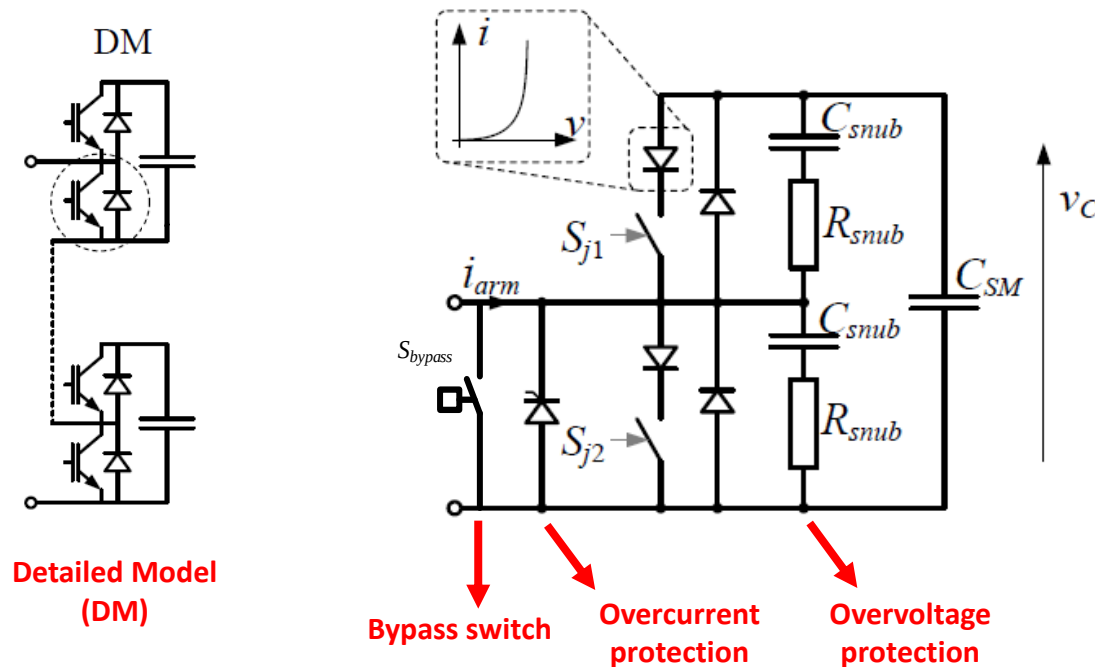


Multilevel Modular Converters (MMC): EMT Models

❑ Four electromagnetic transient (EMT) models:

➤ Detailed model (DM):

- Includes the nonlinear IGBT v-i characteristics and offers the highest degree of precision in EMT studies
- Each SM capacitor, IGBT switches, and other elements, which can include RC snubbers, discharge resistors, bypass thyristors, etc., are represented and solved in the main network equations matrix.
- The DM can be used to validate simplified models, for SM-level studies and internal fault studies.
- However, its application in grid studies is limited because of the high number of nonlinearities, internal nodes, and control signals, which makes simulations time-consuming.

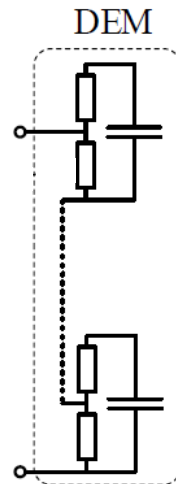


Multilevel Modular Converters (MMC): EMT Models

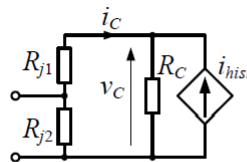
❑ Four electromagnetic transient (EMT) models:

➤ Detailed equivalent model (DEM):

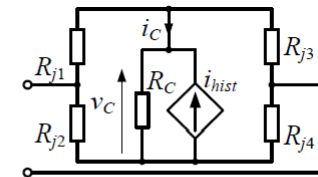
- The detailed equivalent model represents the power switches (i.e. the IGBT and the antiparallel diode) as two-value resistances: the conducting switches have a low resistance ON (in the order of mΩ) whereas the turned off ones have a high resistance OFF (in the order of MΩ).
- In this model, all individual SM voltages and gating signals are available.
- The DEM is often implemented independently from the main EMT solver and is interfaced with it using a two-port Thevenin or Norton equivalent circuit.



**Detailed equivalent
model (DEM)**



a) HB-SM



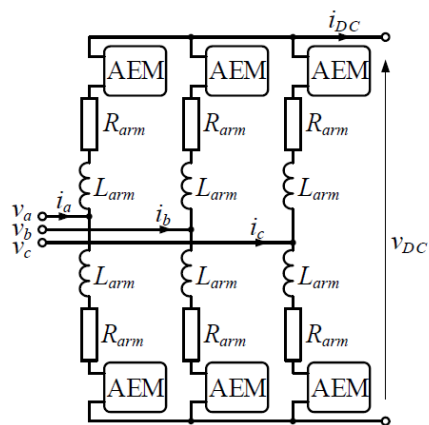
b) FB-SM

Multilevel Modular Converters (MMC): EMT Models

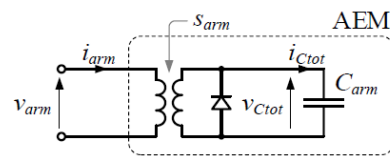
❑ Four electromagnetic transient (EMT) models:

➤ Arm equivalent model (AEM):

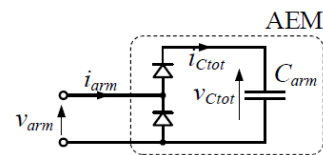
- The arm equivalent model, assumes that all SM capacitors in each arm have identical voltages, so only one equivalent capacitor arm C is used to represent the whole arm
- Grid studies and controller design can be performed.
- During normal operation, the arm switching function acts as a variable ideal transformer ratio between the arm capacitor and the rest of the circuit (When FB-SMs are used, the value of S_{arm} can become negative to represent negative insertion).



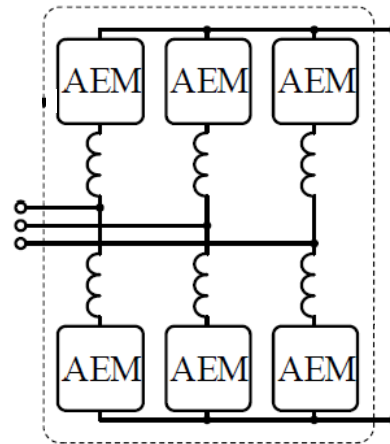
a) converter structure using the AEM



b) circuit for the normal operation



c) circuit for the blocked mode



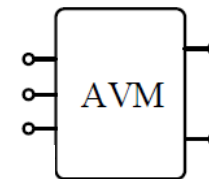
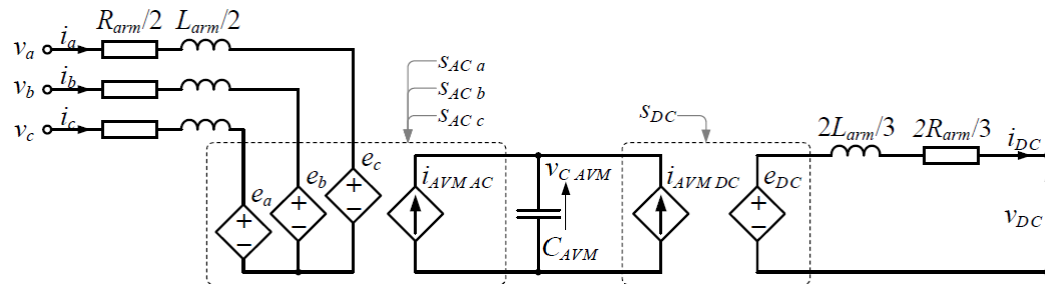
Arm equivalent
model (AEM)

Multilevel Modular Converters (MMC): EMT Models

❑ Four electromagnetic transient (EMT) models:

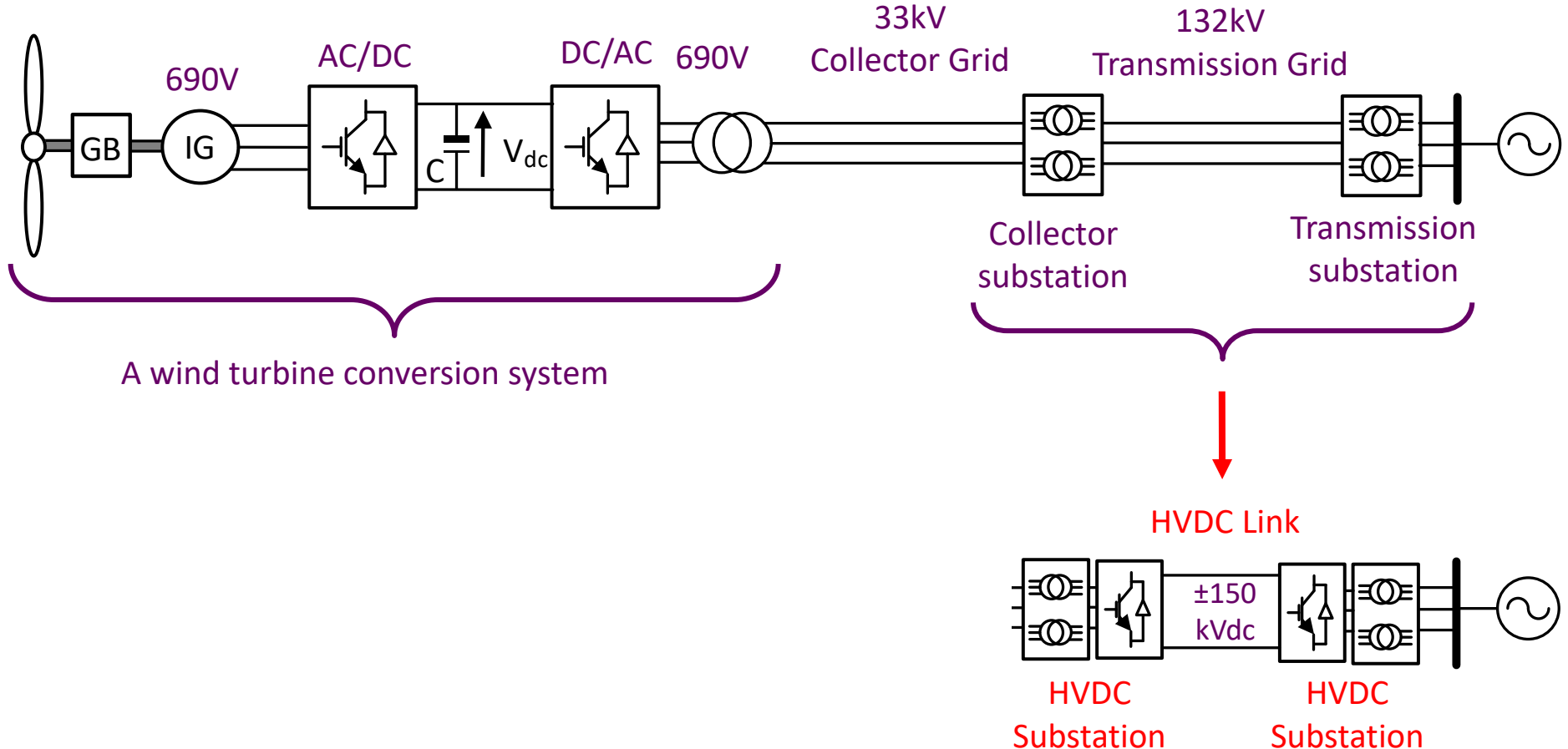
➤ Average value model (AVM):

- The average value model typically comprises two parts, AC and DC, disconnected from each other.
- All SM capacitors of all arms are aggregated into a single DC side capacitor.
- Neither the voltage ripple nor the circulating current are present but the AC and DC currents and voltages in normal balanced operating conditions are accurate.



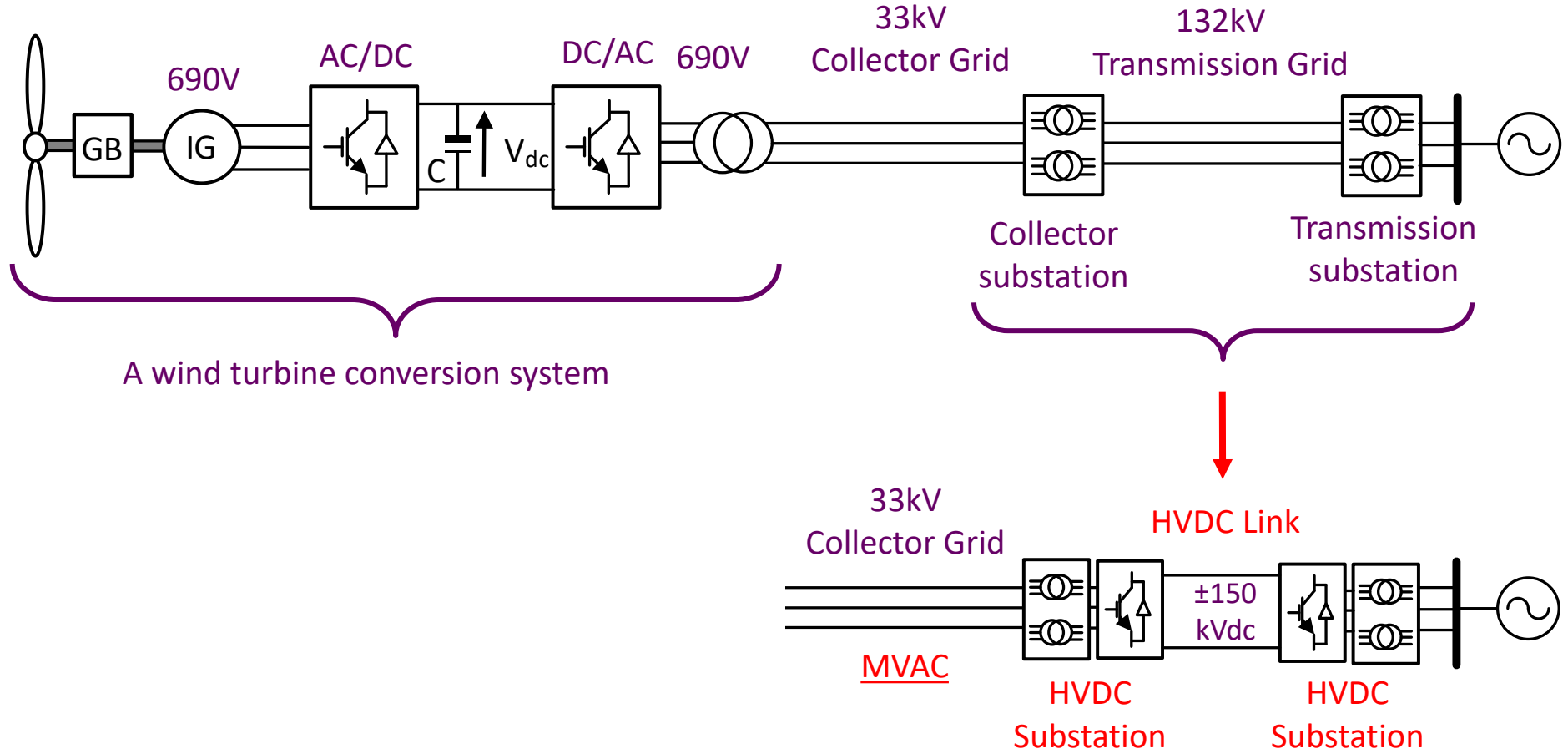
Average value
model (AVM)

Walney Wind Farm Configuration



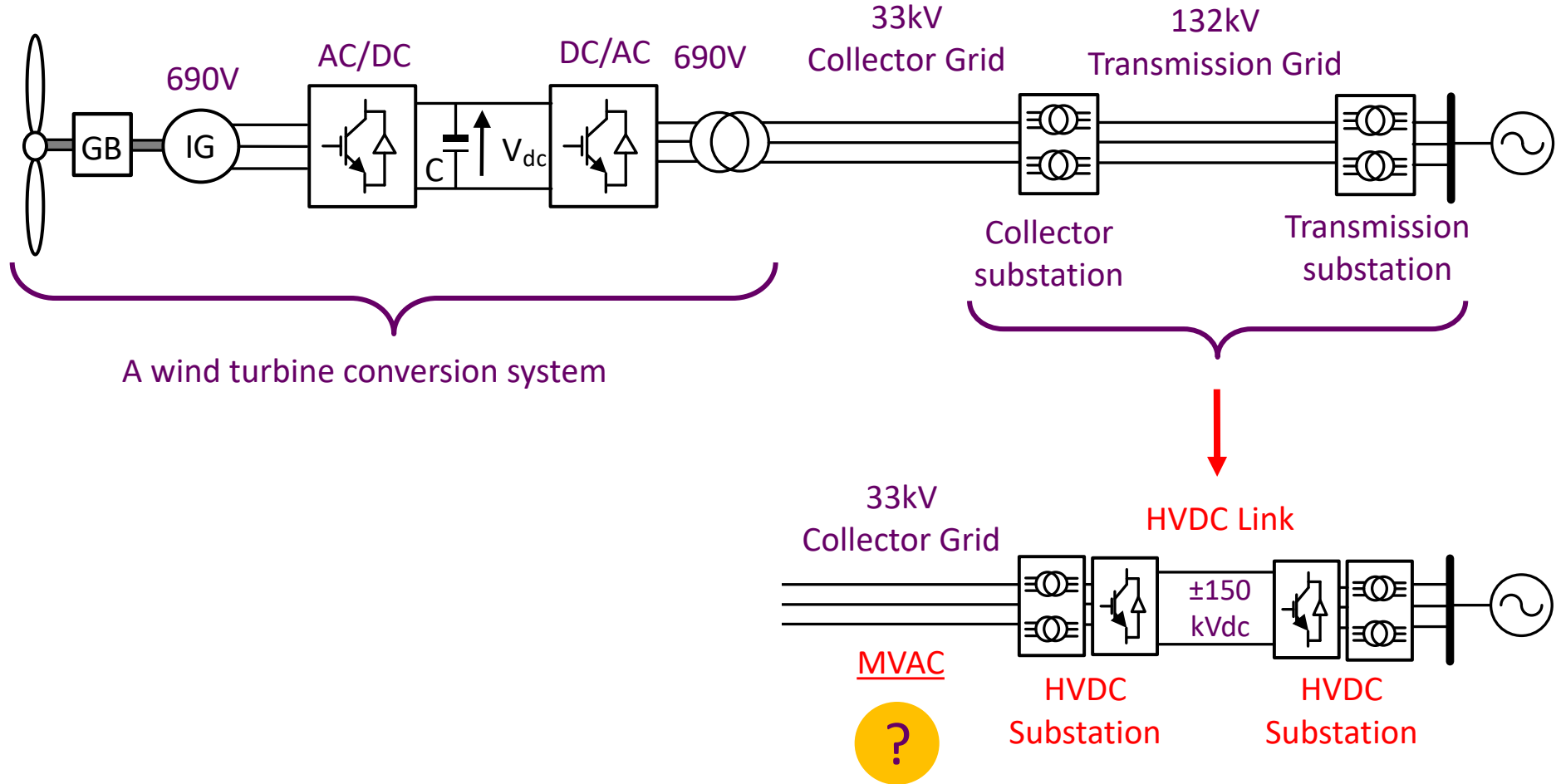
- ❑ With the advancements in power electronics, and the controllability that they offer the HVAC transmission grids are being replaced with HVDC systems.

Walney Wind Farm Configuration



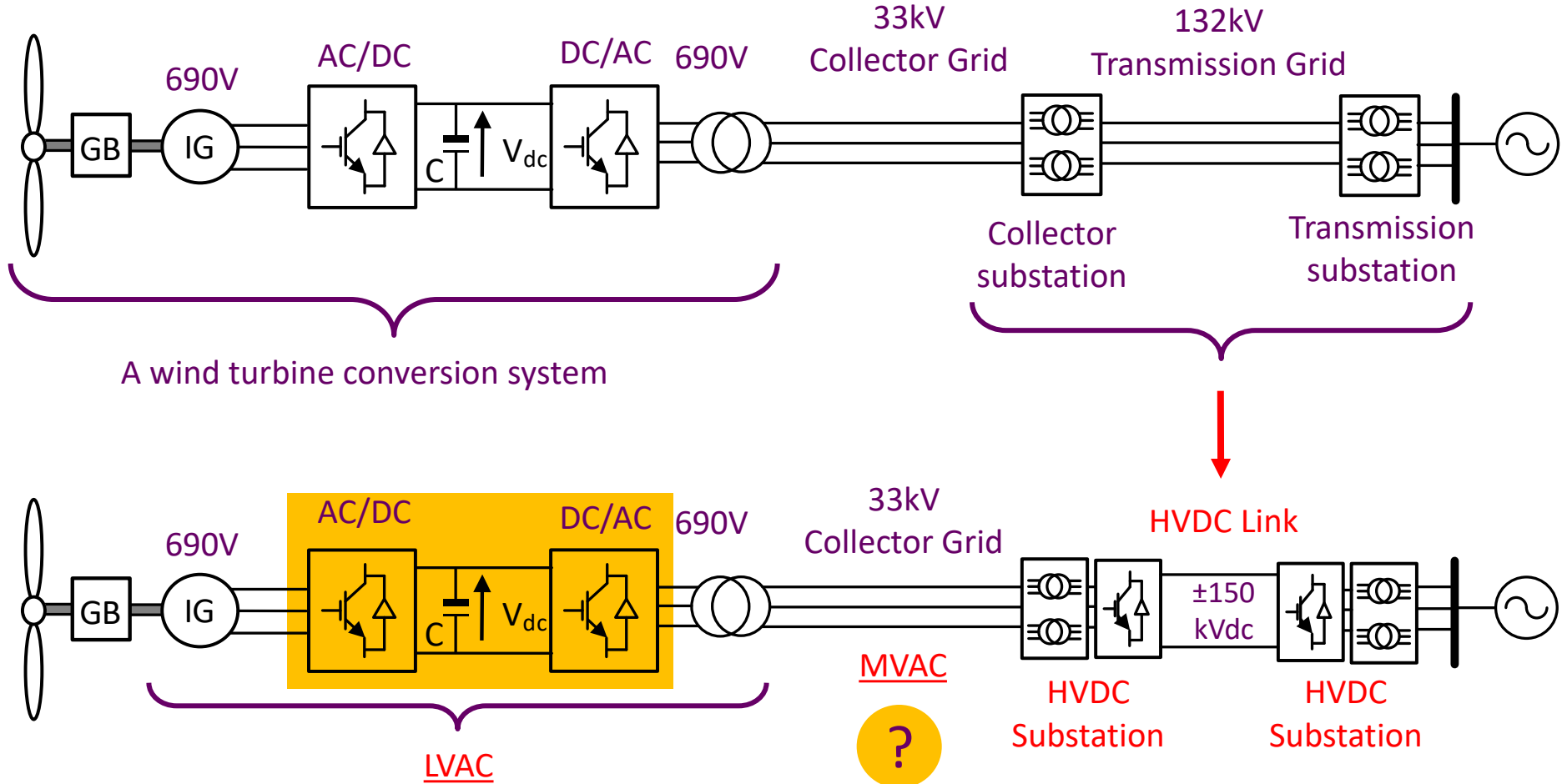
- ❑ With the advancements in power electronics, and the controllability that they offer the HVAC transmission grids are being replaced with HVDC systems.
- ❑ But the MVAC collector grid and the rest of the wind generation systems are largely unchanged.

Walney Wind Farm Configuration



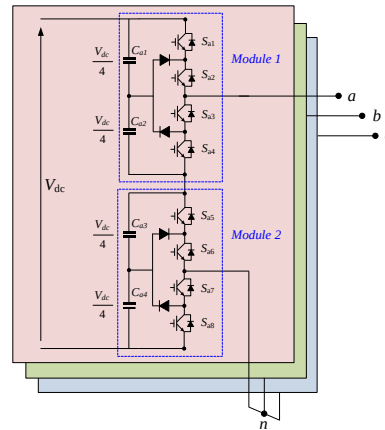
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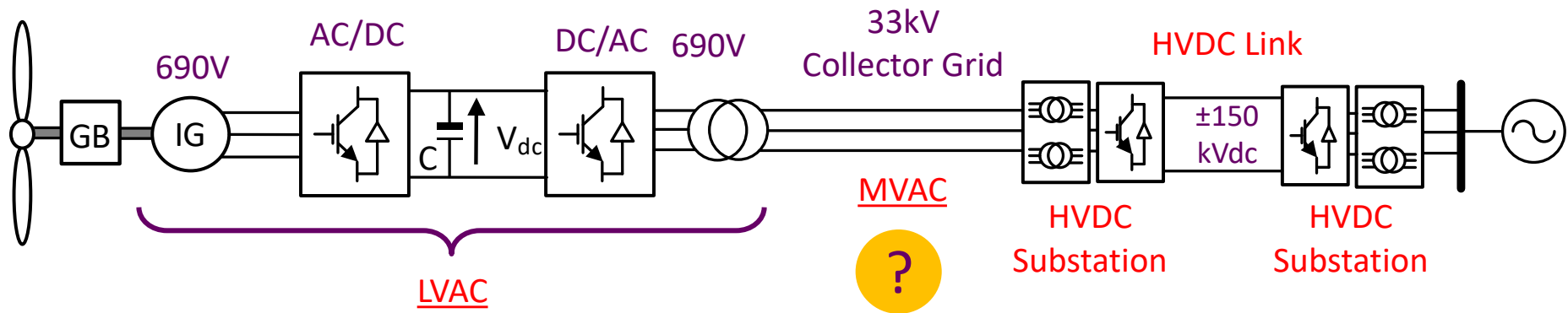


- ❑ Challenges exist in moving to high-voltage power electronics converters in wind turbines
- ❑ Power electronics switches (IGTBs/MOSFETs) are not commercially available at high-voltage and high-power
- ❑ For high-voltage and power switches are connected in series and parallel in a multilevel/modular structure

Walney Wind Farm Configuration

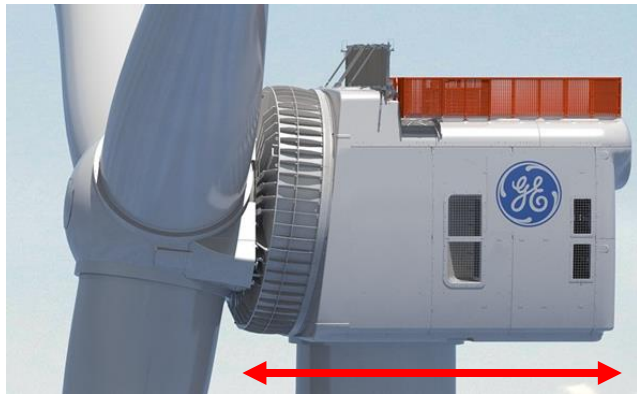


High-voltage multilevel converter



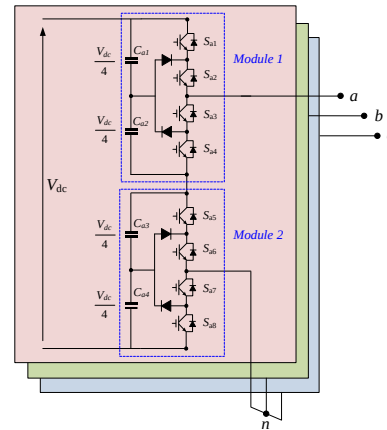
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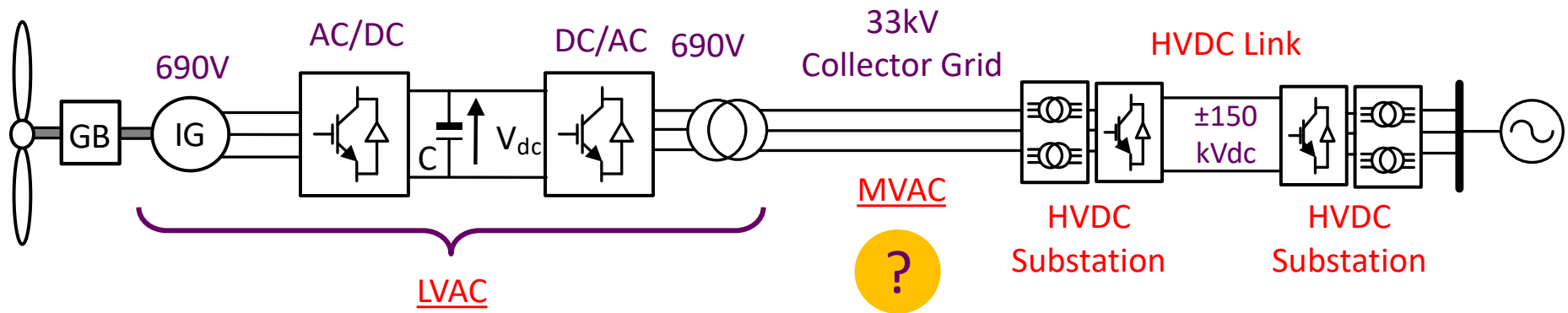


20 m

10 m

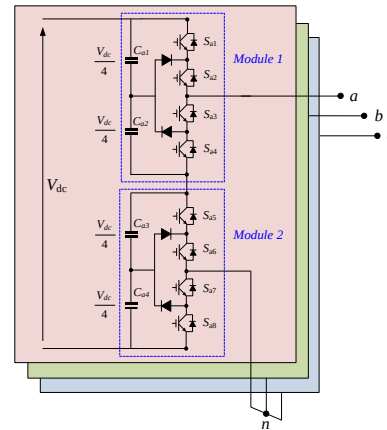
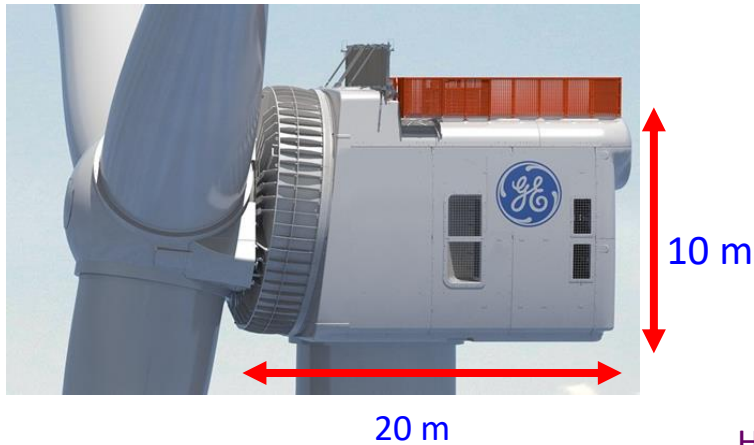


High-voltage multilevel converter



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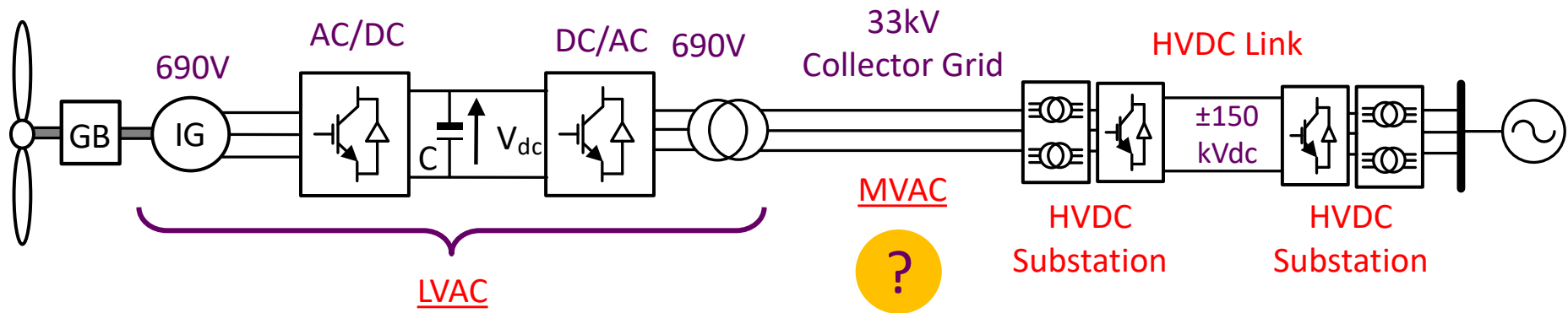
Walney Wind Farm Configuration



High-voltage multilevel converter

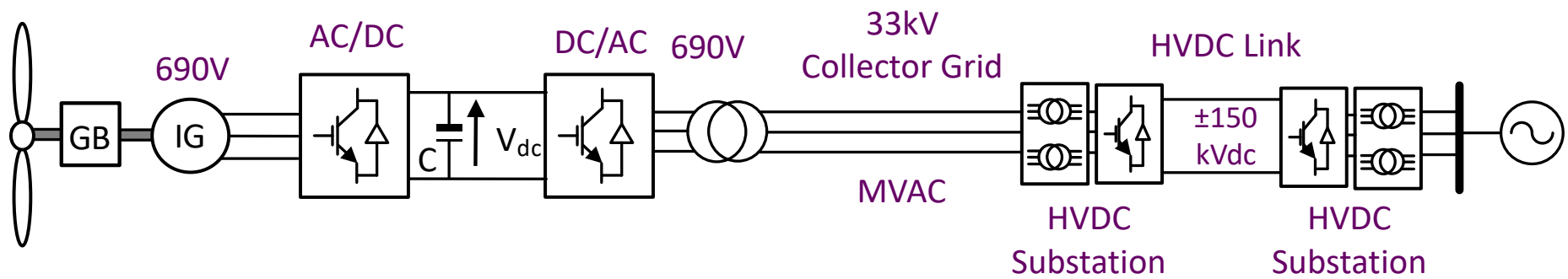


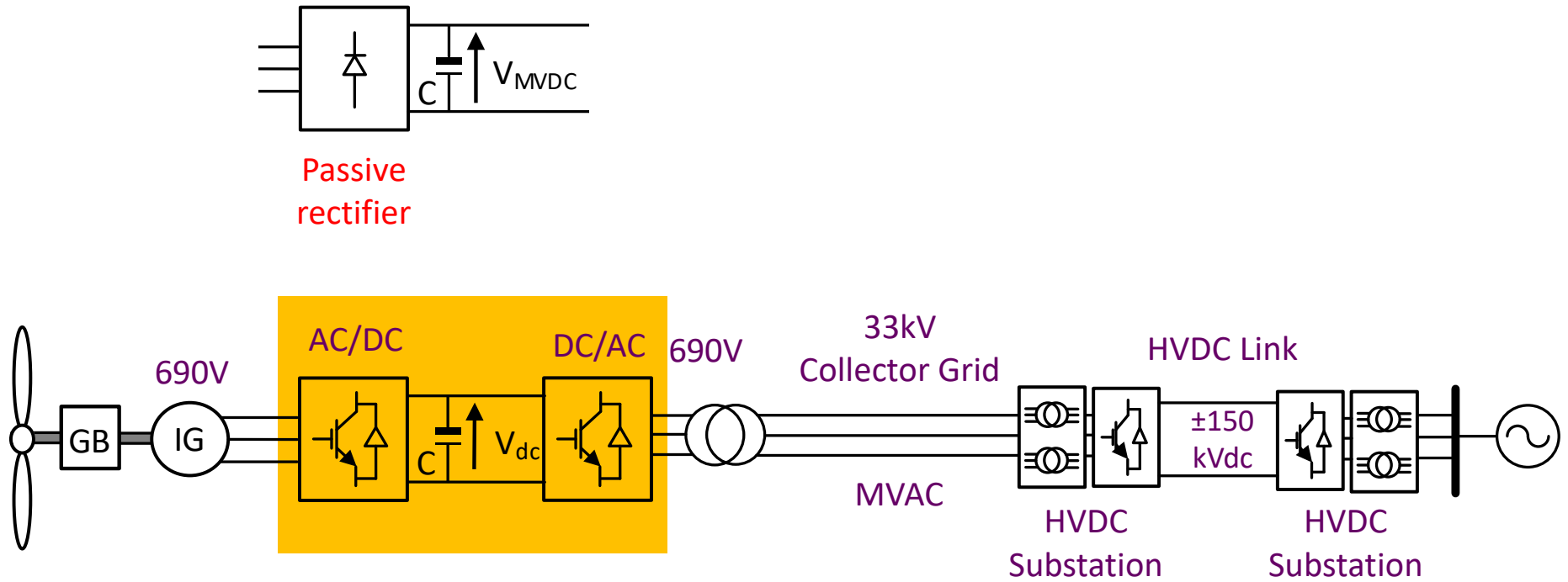
Photo courtesy of TenneT



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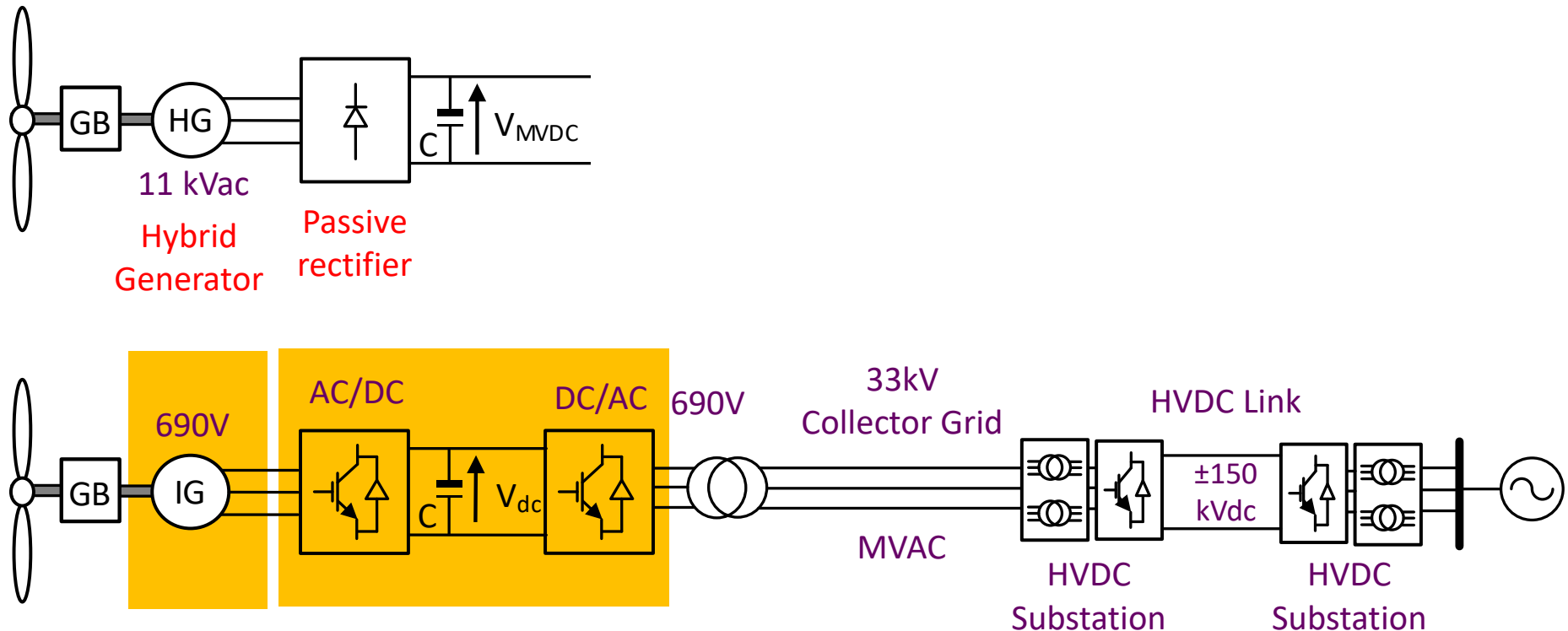
All-DC Wind Generation Systems





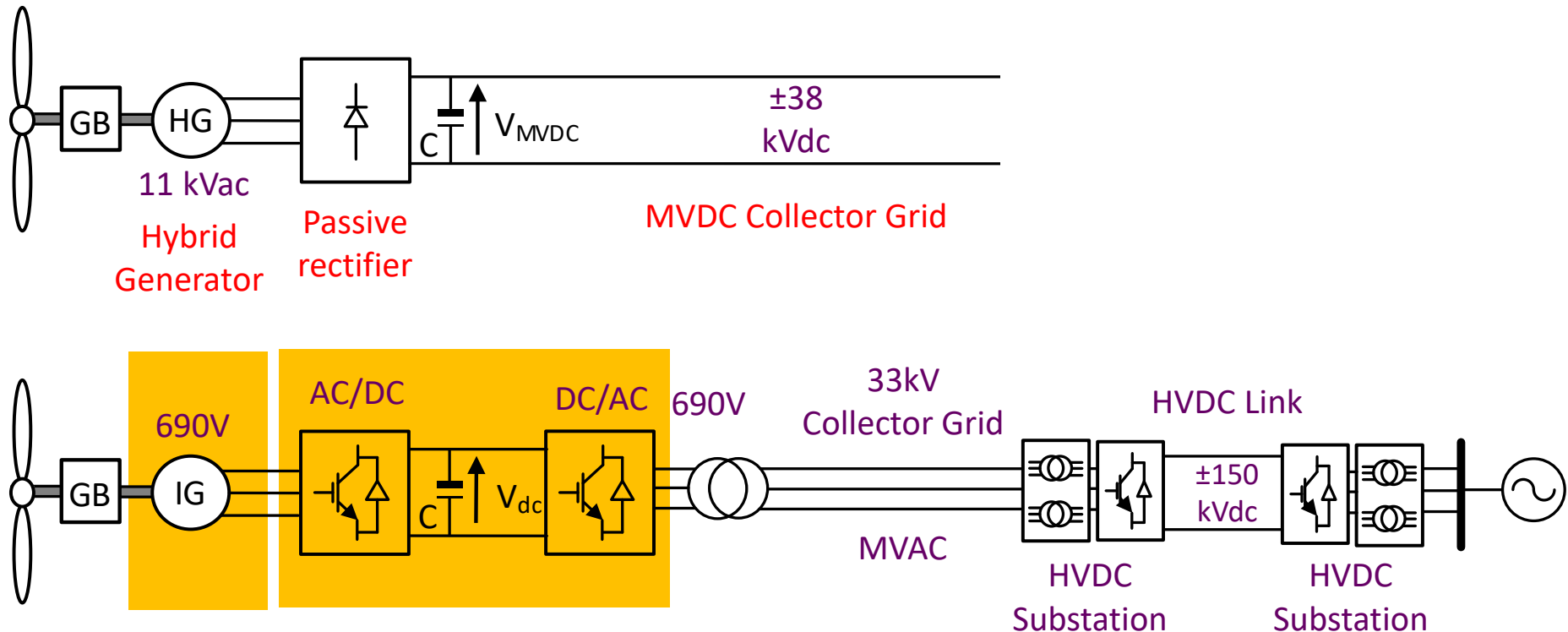
- ❑ Active converters replaced with passive rectifier that is commercially available at high-voltage and high-power

All-DC Wind Generation Systems



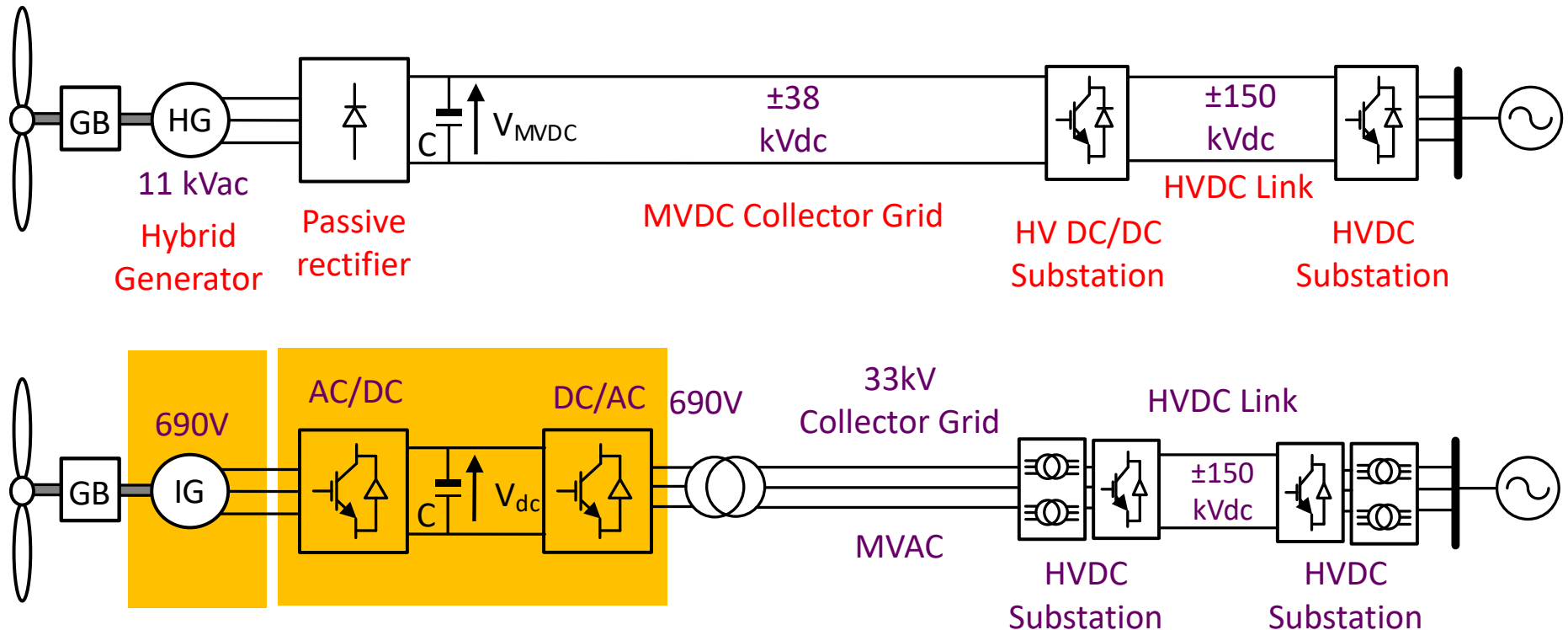
- ❑ Active converters replaced with passive rectifier that is commercially available at high-voltage and high-power
- ❑ Variable speed control of the generator, i.e. maximum power point tracking (MPPT), is lost
- ❑ Shift the controls to the generator with the concept of a hybrid generator (HG) system

All-DC Wind Generation Systems



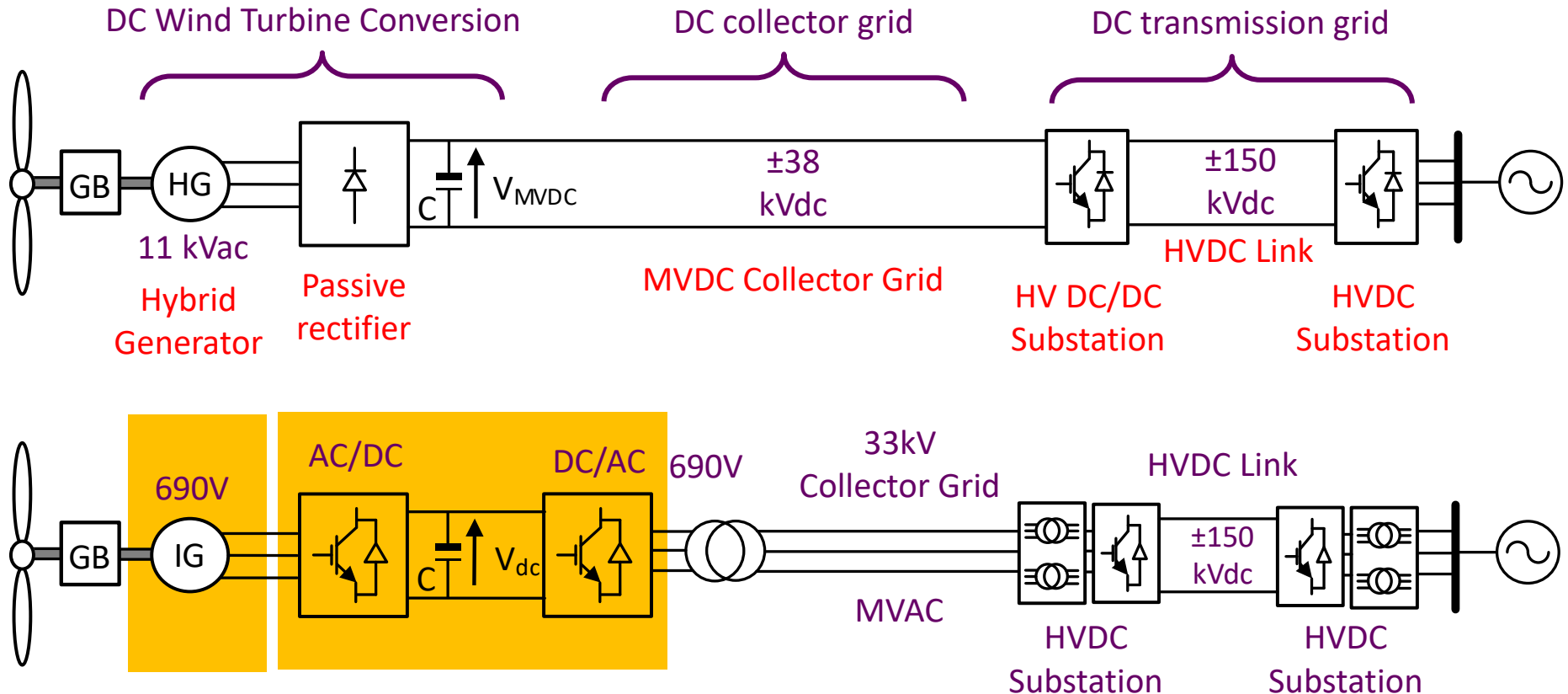
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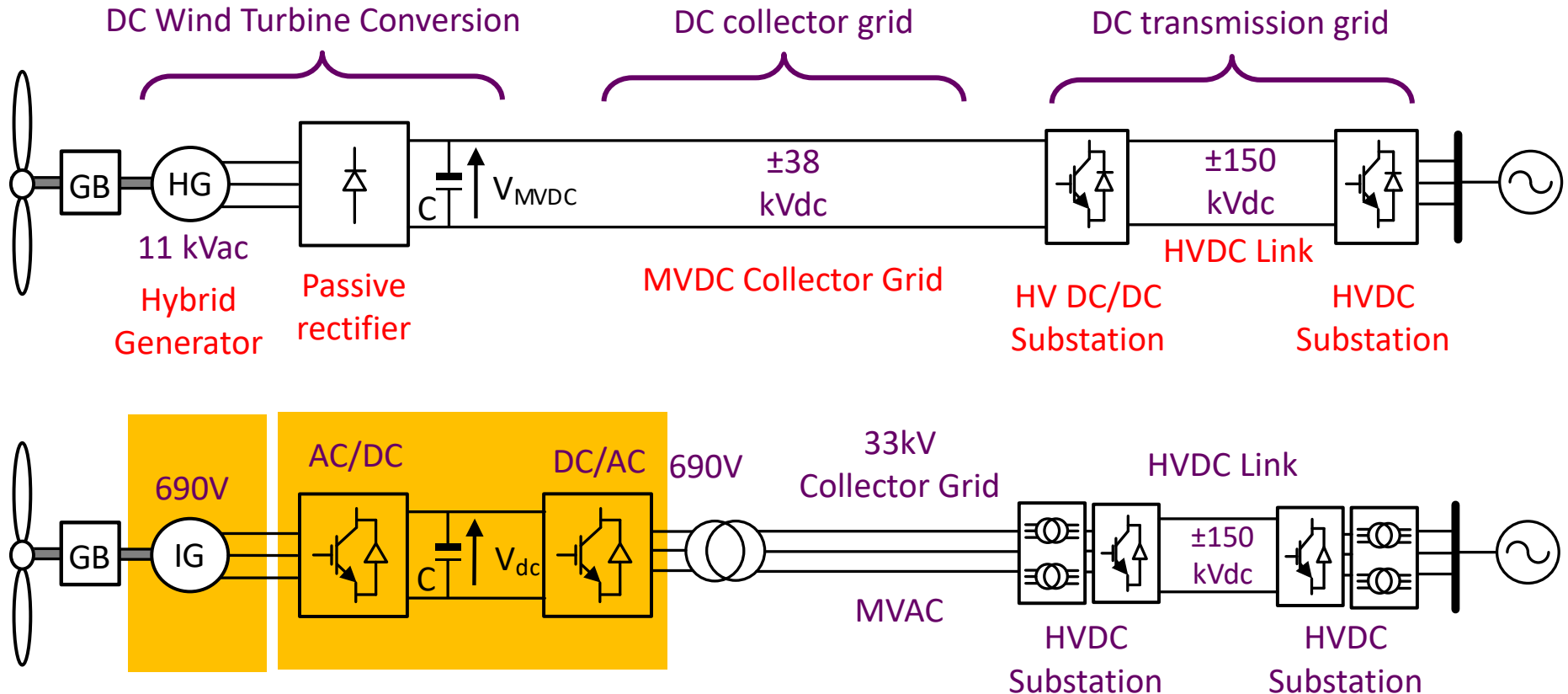
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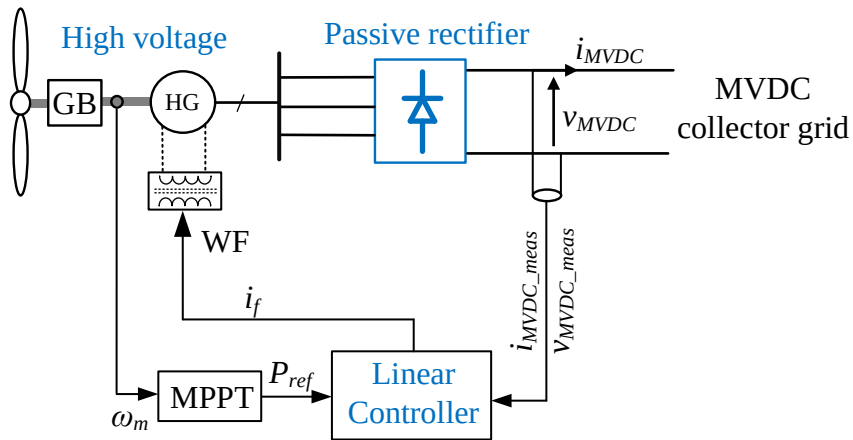
All-DC Wind Generation Systems

All-DC Wind Generation System



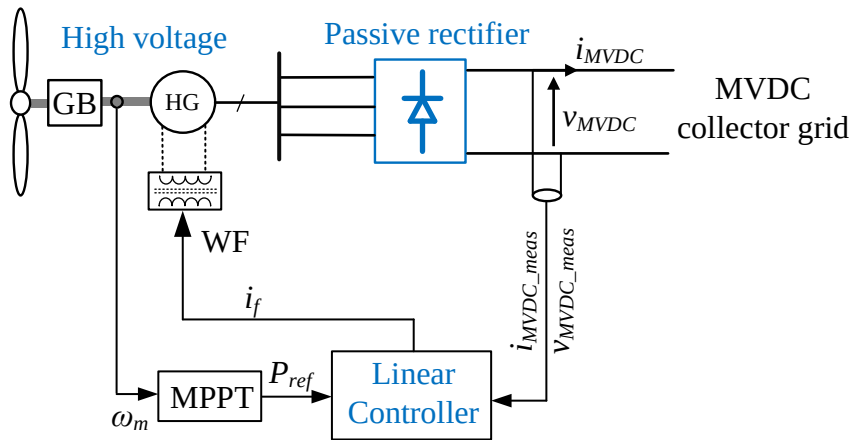
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MVDC Collector Grid with Hybrid Generator Scheme

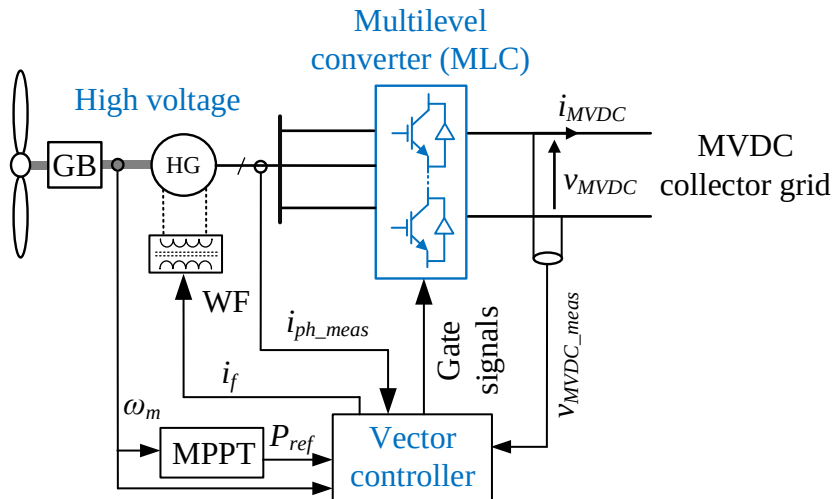


- ❑ High voltage hybrid generator.
- ❑ MPPT and grid power flow control is performed by HG.
- ❑ MVDC voltage can be variable or fixed.

MVDC Collector Grid with Hybrid Generator Scheme

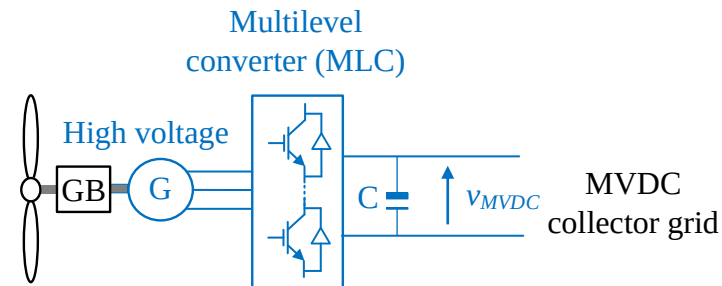
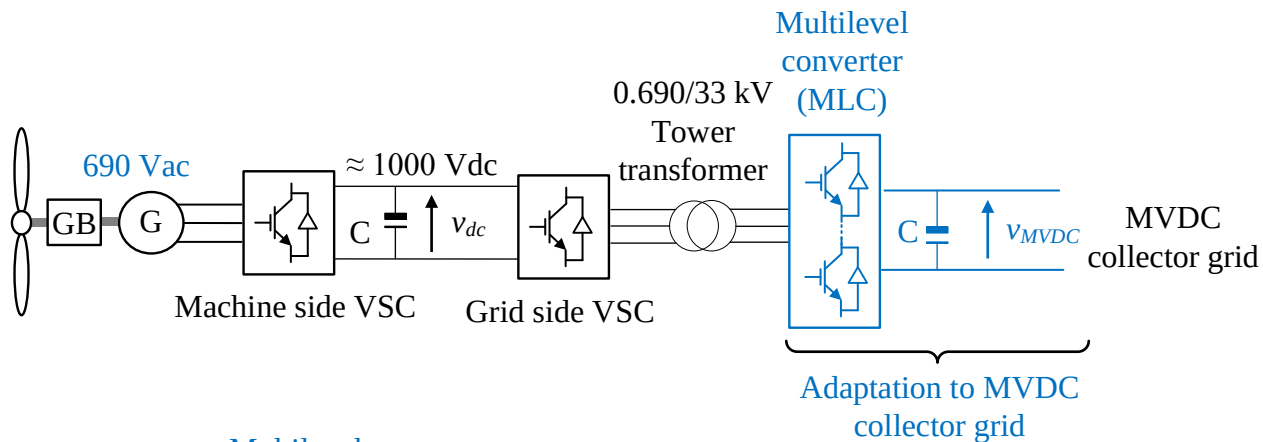
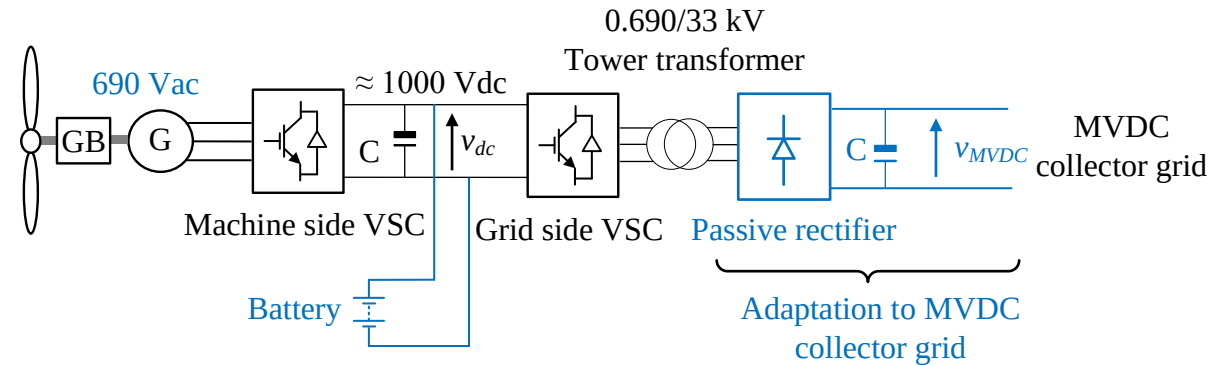


- ❑ High voltage hybrid generator.
- ❑ MPPT and grid power flow control is performed by HG.
- ❑ MVDC voltage can be variable or fixed.



- ❑ High voltage hybrid generator
- ❑ Multilevel converter (MLC) replaces the passive rectifier.
- ❑ MPPT and grid power flow control is shared between HG and the MLC.
- ❑ MVDC voltage need to be fixed.

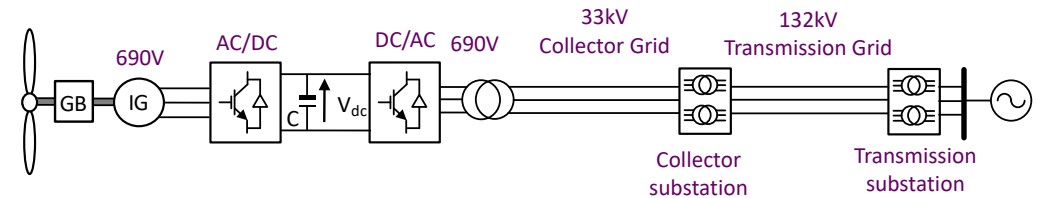
Other Possible MVDC Collector Grid Schemes



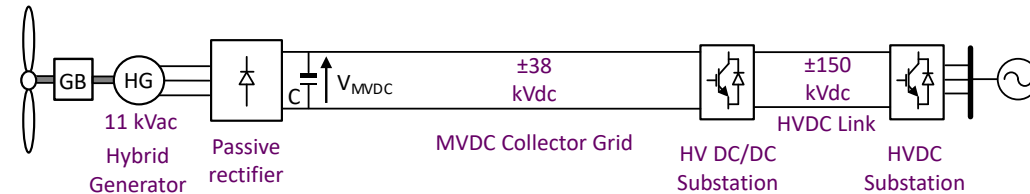
- ❑ Challenging to implement as the change in velocity in parallel wind turbines may cause the passive rectifier to turn-off. Hence, variable MVDC voltage control or a coordinate control of GSCs among parallel wind turbines is required.
- ❑ To maintain a fixed DC-link voltage for MSC, a battery is required.
- ❑ Another challenge is to find space in wind turbine for battery pack.
- ❑ Multilevel converter (MLC) at the output of turbine transformer.
- ❑ Three stages of conversion. Reduced efficiency.
- ❑ MVDC voltage maintained constant by the offshore substation.
- ❑ Low voltage Generator replaced with a high voltage machine.
- ❑ Multilevel converter (MLC) needs to perform MPPT and grid power flow control.
- ❑ MVDC voltage maintained constant by the offshore substation.

All-DC Wind Generation Systems

Item	Walney system		Proposed system	
	Mass (Tonnes)	Mass (%)	Mass (Tonnes)	Mass (%)
Power-train, turbine and tower mass				
Blades × 3	54	12.13	54	12.42
Hub mass	38.5	8.65	38.5	8.85
Shaft	27.5	6.18	27.5	6.32
Gearbox	42.5	9.55	-	-
IG	10	2.25	-	-
HG	-	-	52.5	12.07
Two VSC's	2.4	0.54	-	-
Rectifier	-	-	0.25	0.06
Turbine transformer	8	1.80	-	-
Blades and hub bolts	2.16	0.49	2.16	0.50
Tower*	260	58.42	260	59.78
Total	445.06	100	434.91	100
Cable mass				
Tower cable	4.78	0.49	0.03	0.01
Inter-array cables between turbines	133.06	13.56	12	5.06
Cable, Circuits to off-shore	91.24	9.3	9.89	4.17
Cable, off-shore sub. to shore	751.89	76.65	215.33	90.76
Total	980.97	100	237.25	100



Walney wind generation system



All-DC wind generation system

Item	Walney system	Proposed system
Turbine power, MW	3.6	
IG efficiency	90 %	-
HG efficiency	-	90%
Converter 1 efficiency	90%	-
Converter 2 efficiency	90%	-
Rectifier efficiency	-	98%
Turbine transformer efficiency	99.31%	-
Off-shore substation transformer efficiency	99.1 %	-
Efficiency of the DC/DC converters at off-shore substation	-	95%
Total power, MW	129.9	153.14
Total losses, MW	53.8	30.5
Efficiency	70.75%	83.41%

- ❑ 90% reduction in mass of the MVDC collector grid cables
- ❑ 70% reduction in mass of the HVDC transmission grid cables
- ❑ 75% reduction in collective mass of the MVDC & HVDC cables

Thank You