Electric Energy Conversion

10. Applications of electric energy conversion

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Introduction

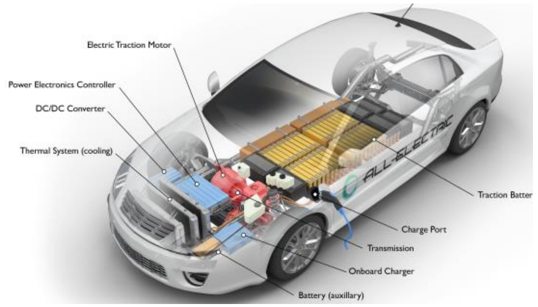
- Electric energy conversion based on power electronics can be found in several applications:

Power supplies

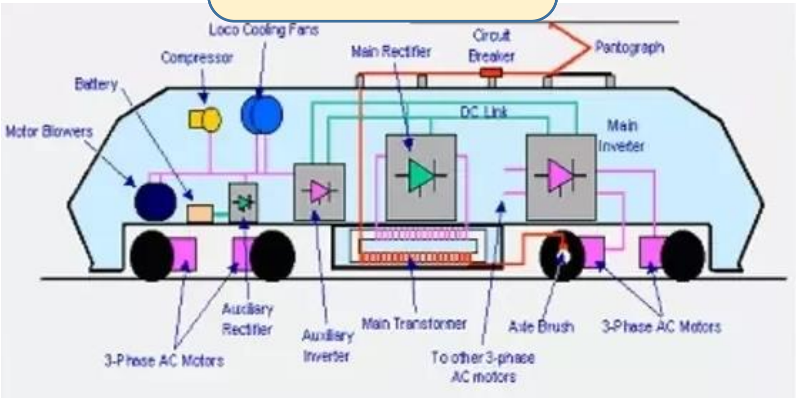
Motor drives

FACTS

Electric vehicles



Electric traction

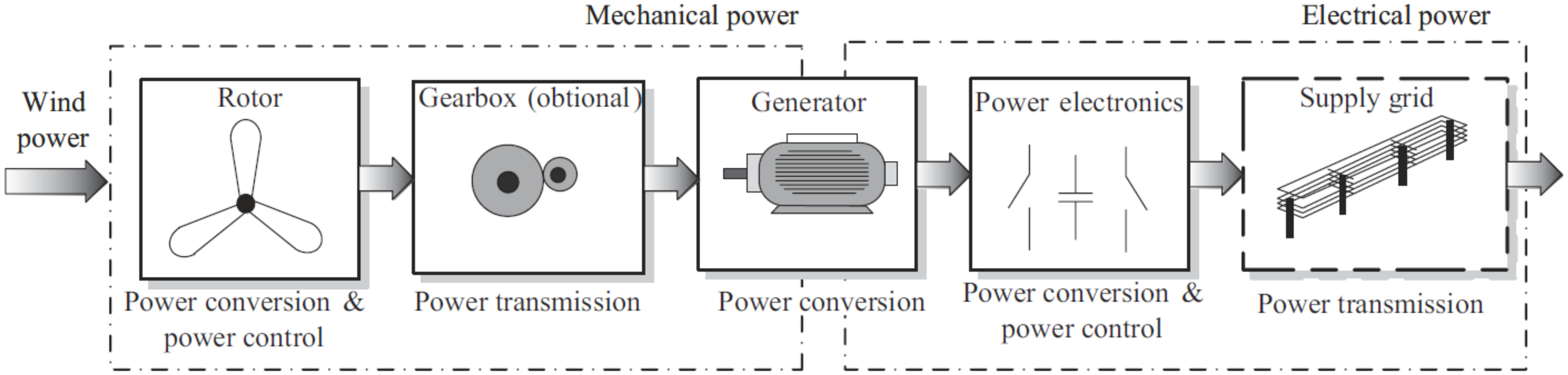


Renewable Generation

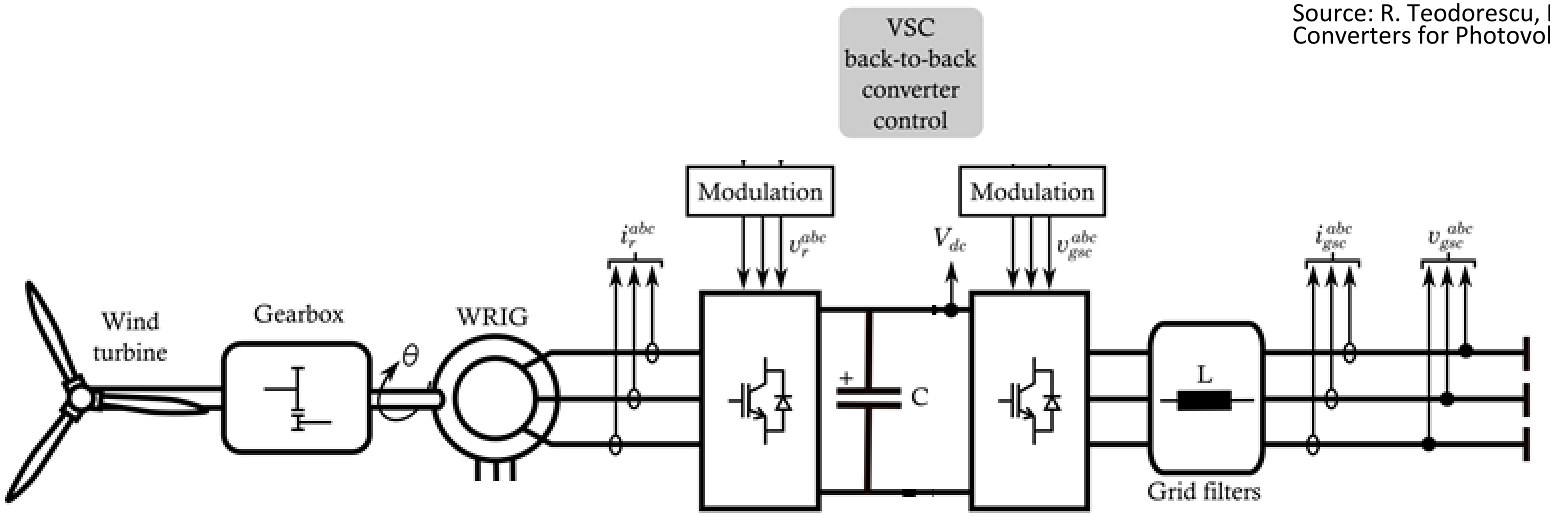
HVDC transmission

Power electronics in wind generation

- Using a VSC is it possible to create an AC wave with lower and higher frequency, to extract optimal power from the wind turbine.

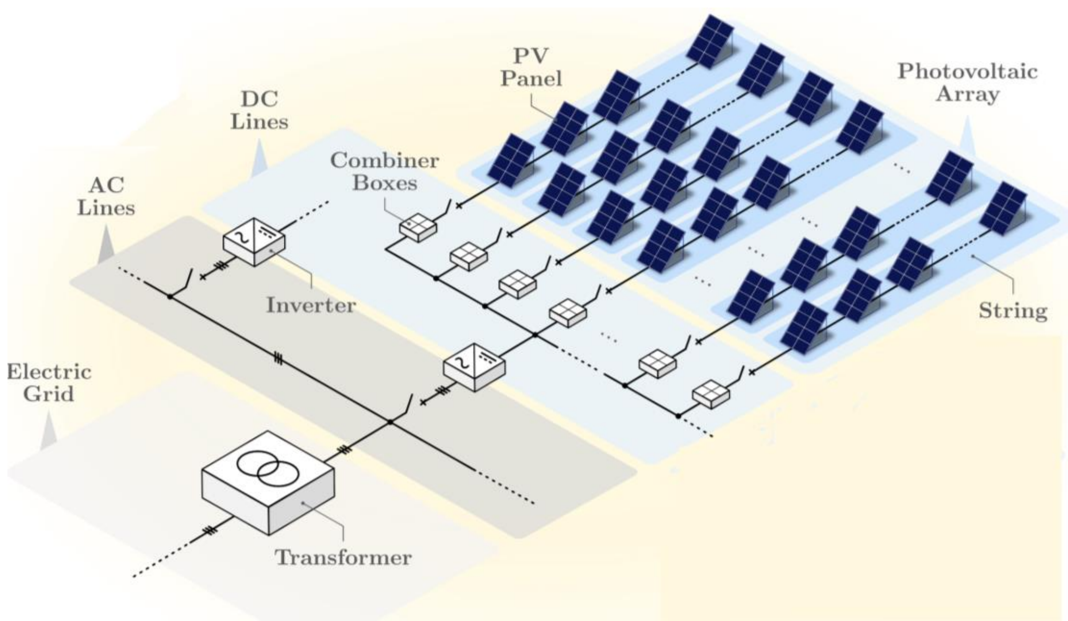


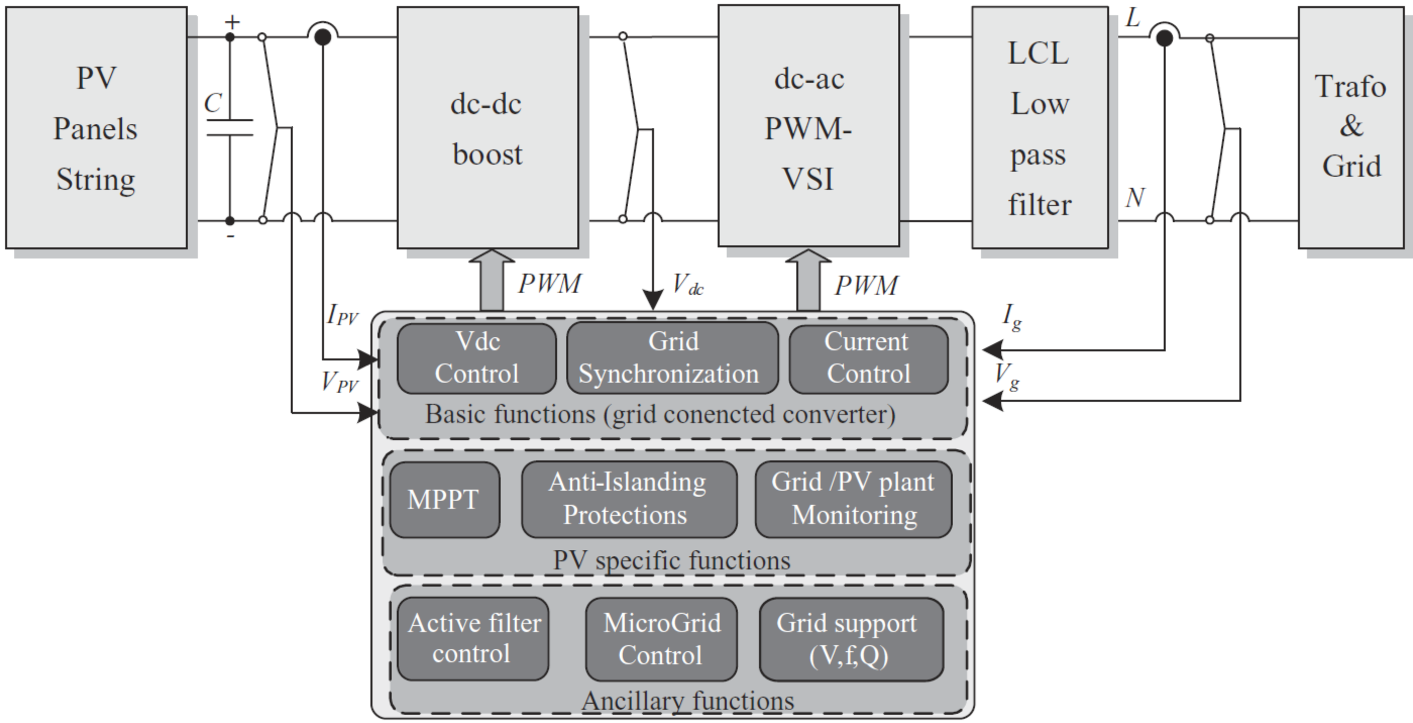
Source: R. Teodorescu, M. Liserre and P. Rodríguez (2011), Grid Converters for Photovoltaic and Wind Power Systems, ohn Wiley & Sons.



Power electronics in PV generation

- The DC current from the PV charges the DC capacitor and the VSC creates the AC voltage by modulating the DC voltage across the capacitor





Source: R. Teodorescu, M. Liserre and P. Rodríguez (2011), Grid Converters for Photovoltaic and Wind Power Systems, ohn Wiley & Sons.

High-Voltage Direct Current (HVDC) systems

Source: Siemens.

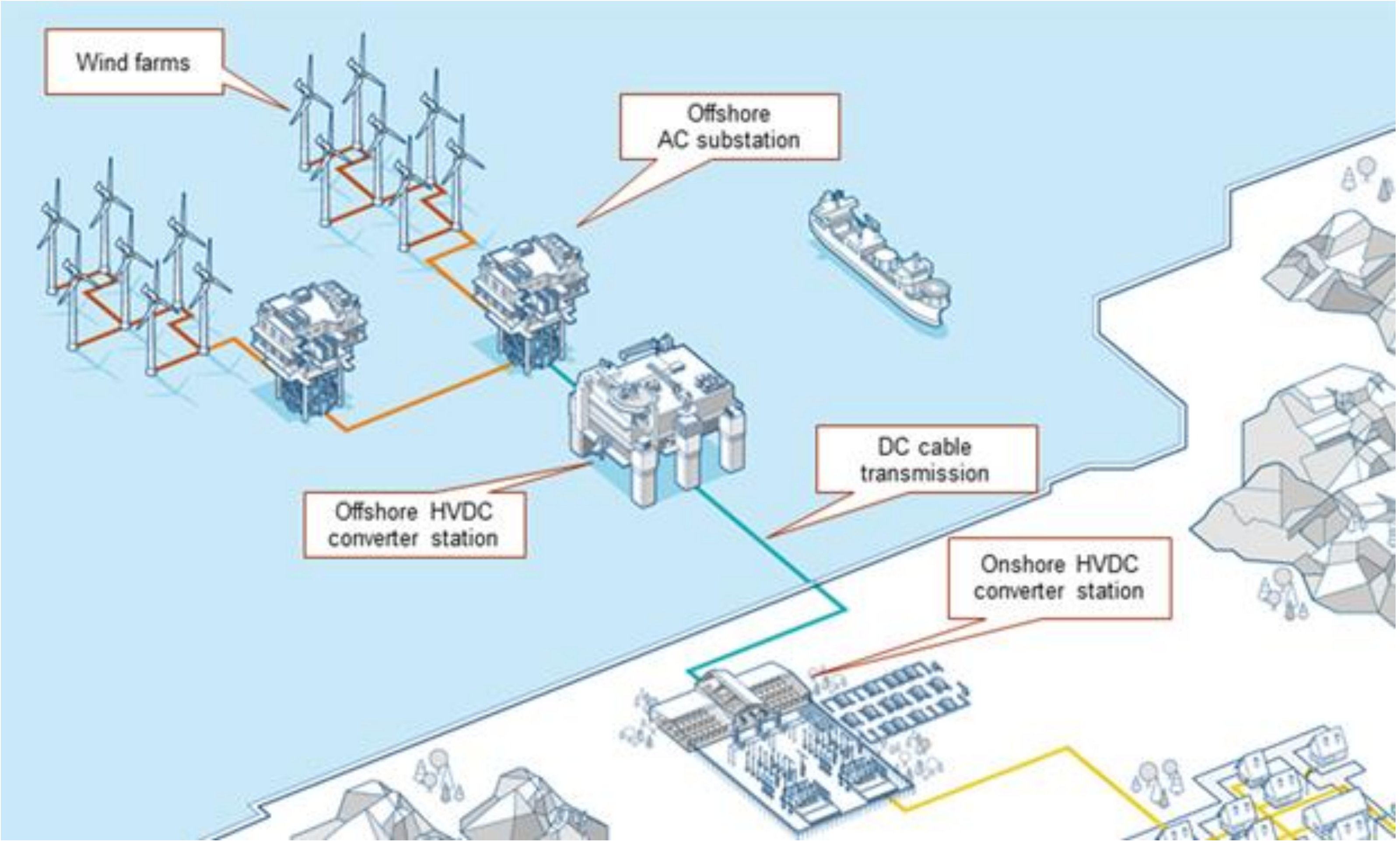
High-Voltage Direct Current (HVDC) systems

- ***Submarine power transmission***. The AC cables have large capacitance and for cables over 40–70 km the reactive power circulation is unacceptable. For larger distances, HVDC is more economical than HVAC. e.g the 580 km, 700 MW, ±450 kV NorNed HVDC between Norway and the Netherlands.
- ***Long-distance overhead lines***. Long AC lines require variable reactive power compensation. Typically 600–800 km is the breakeven distance and, for larger distances, HVDC is more economical. e.g the 1360 km, 3.1GW, ±500 kV Pacific DC intertie along the west coast of the United States.
- ***Interconnecting two AC networks of different frequencies***. e.g the 500 MW, ±79 kV back-to-back Melo HVDC between Uruguay and Brazil. The Uruguay system operates at 50 Hz whereas Brazil's national grid runs at 60 Hz.
- ***Interconnecting two unsynchronized AC grids***. If phase difference between two AC systems is large, they cannot be directly connected. e.g the 150 MW, ±42 kV McNeill back-to-back HVDC link between Alberta and Saskatchewan interconnecting asynchronous eastern and western American systems.

SourceD. Jovcic and K. Ahmed (2015), High-Voltage Direct-Current Transmission: Converters, Systems and DC Grids, John Wiley & Sons.

High-Voltage Direct Current (HVDC) systems

- **Submarine power transmission**. One station offshore, a DC link and another station onshore.



Fonte:http://new.abb.com/systems/offshore-wind-connections/dc-solutions

Photo gallery

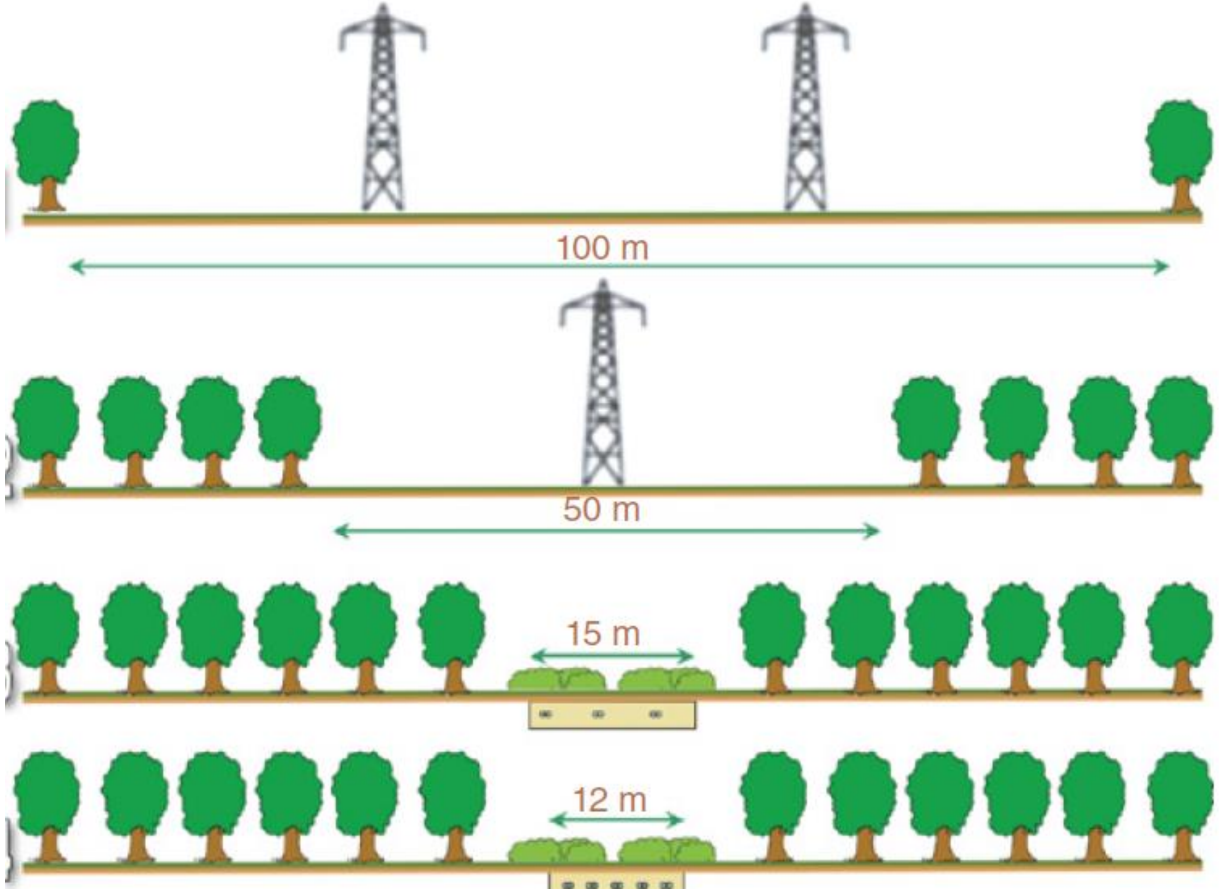
Source: ABB

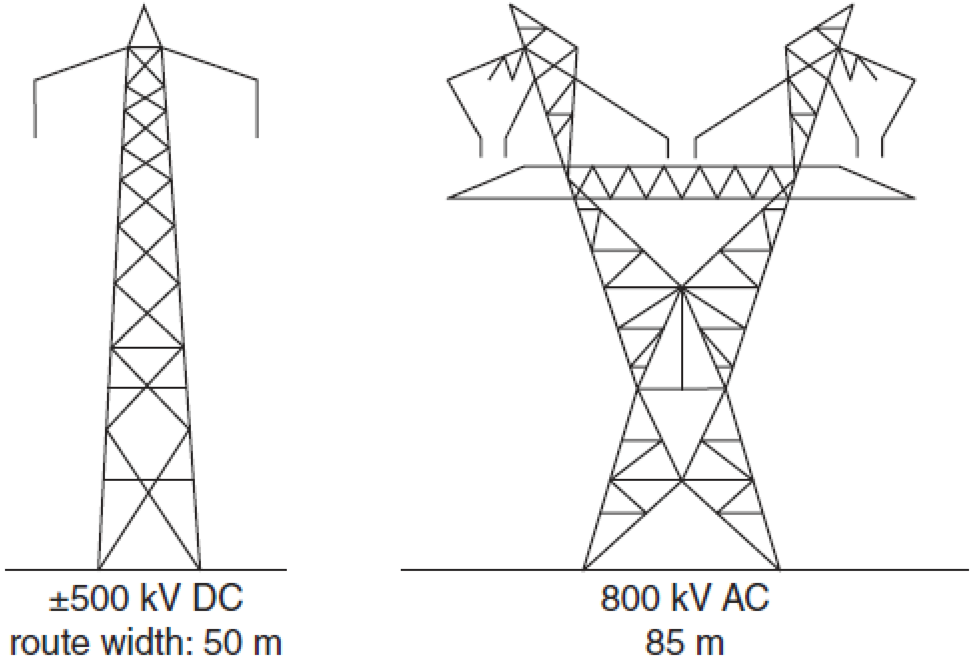
Photo gallery

Source: ABB

High-Voltage Direct Current (HVDC) systems

- HVDC is more compact to transmit the same amount of power.

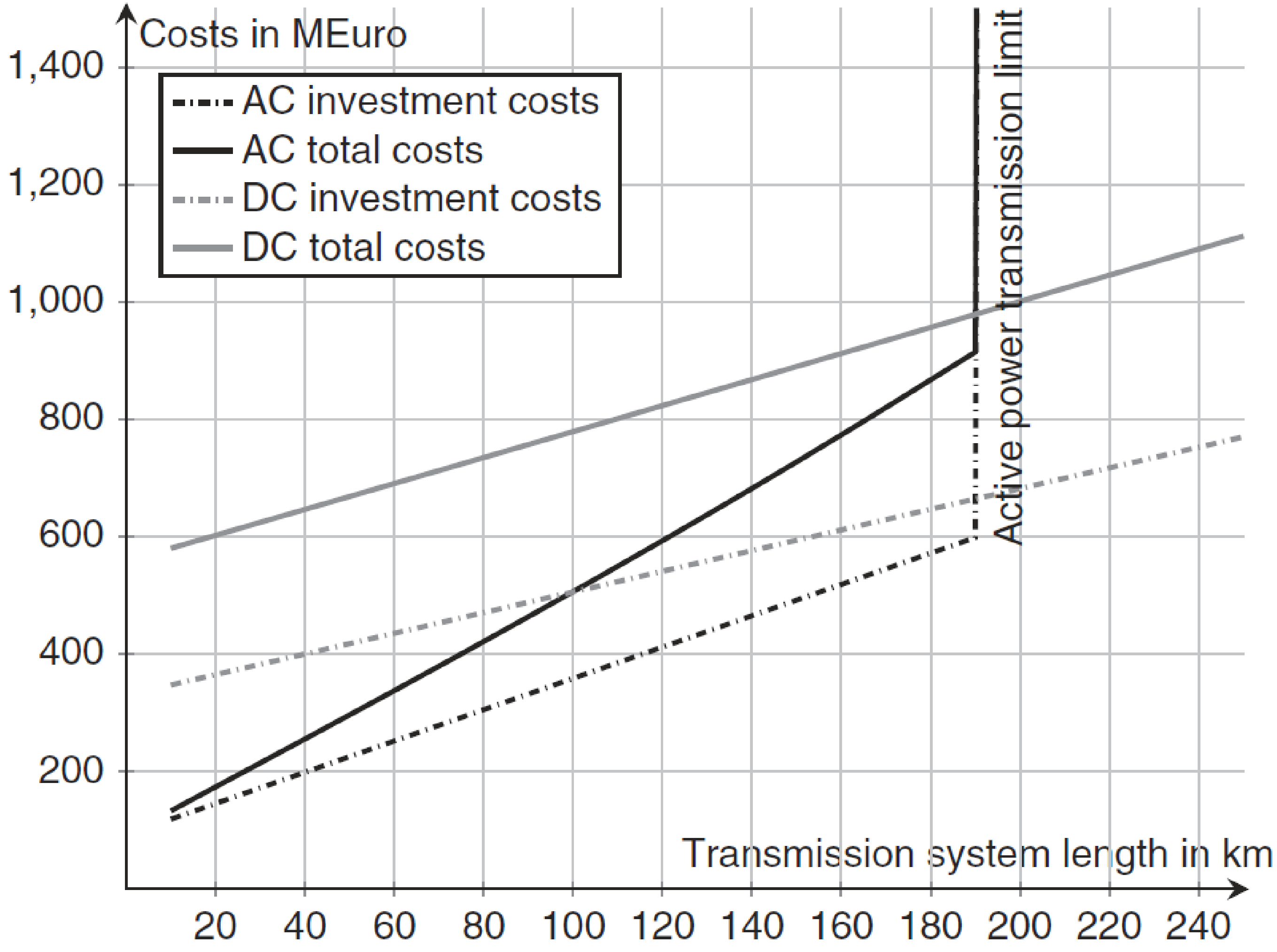




Source:D. V. Hertem, O. Gomis-Bellmunt, and J. Liang. HVDC Grids: For Offshore and Supergrid of the Future (2016) IET, John Wiley & Sons

High-Voltage Direct Current (HVDC) systems

- HVDC is more expensive for short distances, but cheaper than HVAC for longer distances.

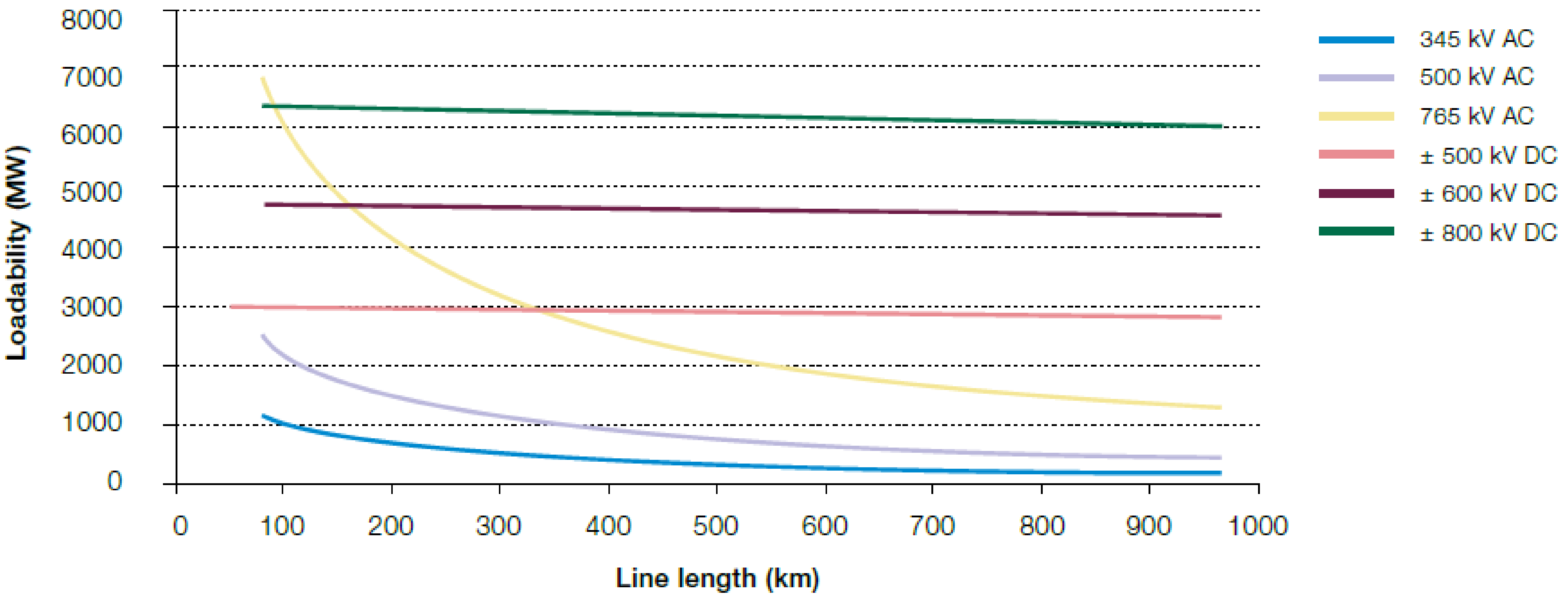


Submarine cable

SourceD. V. Hertem, O. Gomis-Bellmunt, and J. Liang. HVDC Grids: For Offshore and Supergrid of the Future (2016) IET, John Wiley & Sons

High-Voltage Direct Current (HVDC) systems

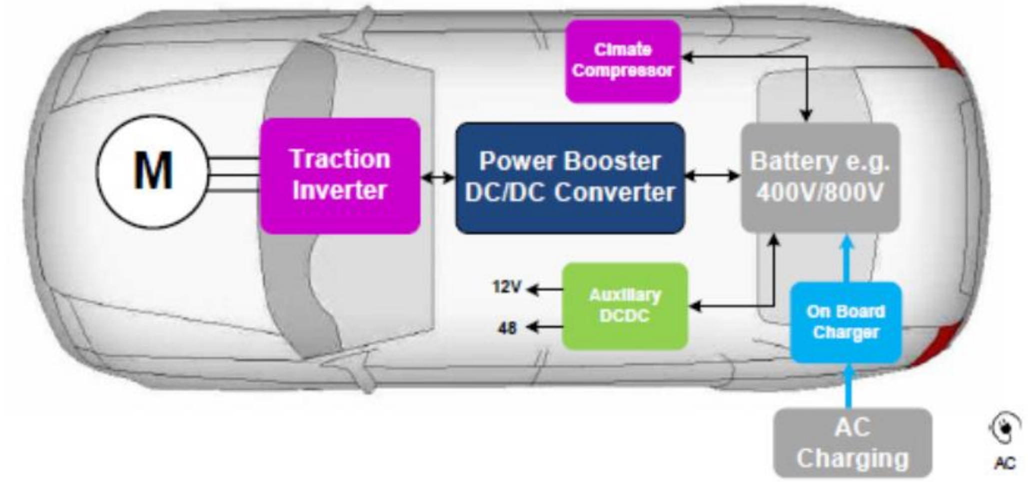
- Due to excess of reactive power, cables require compensation in HVAC, which increase the costs and reduces the maximum cable length.

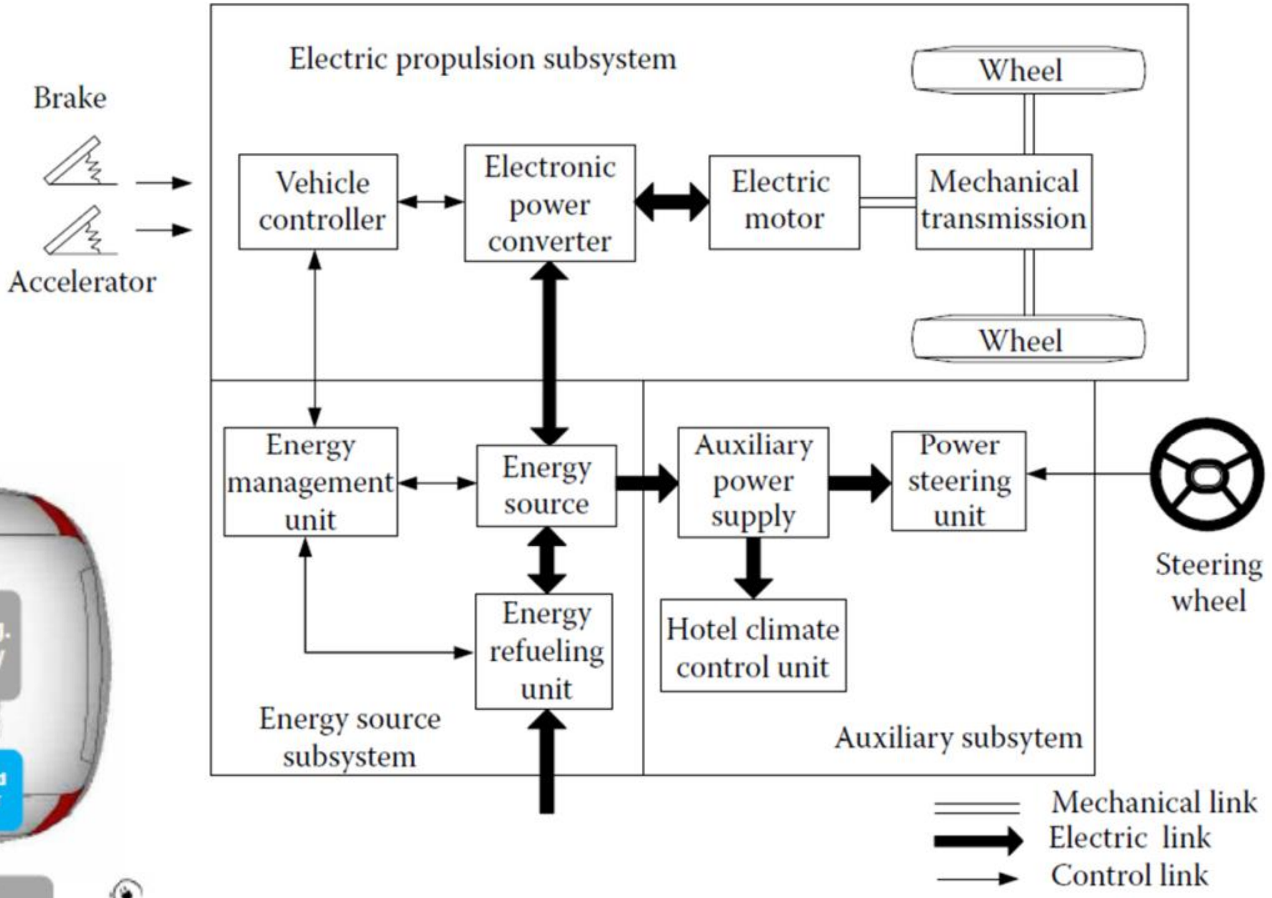


Source: ABB HVDC Light - It’s time to connect;

Electric vehicles

- Electric vehicles



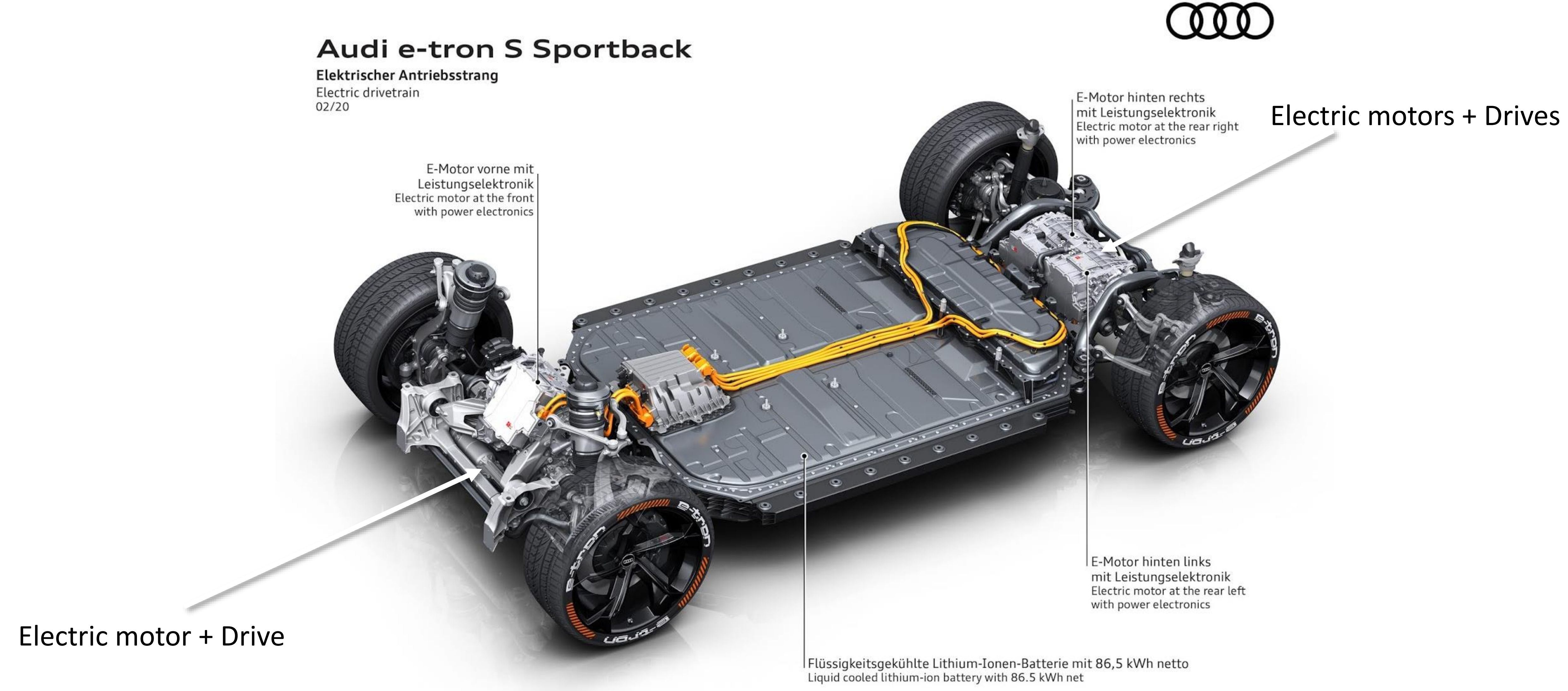


Typical power converters in electric vehicles applications.

Source: M. Gaertner, “SiC power modules: towards power revolution,” ST Microelectronics. 2020.

Source: Daniel Montesinos-Miracle, Samuel Galceran-Arellano, Roberto Villafáfila-Robles, Francisco Díaz-González, Joan Rull-Duran, Carlos Miguel-Espinar

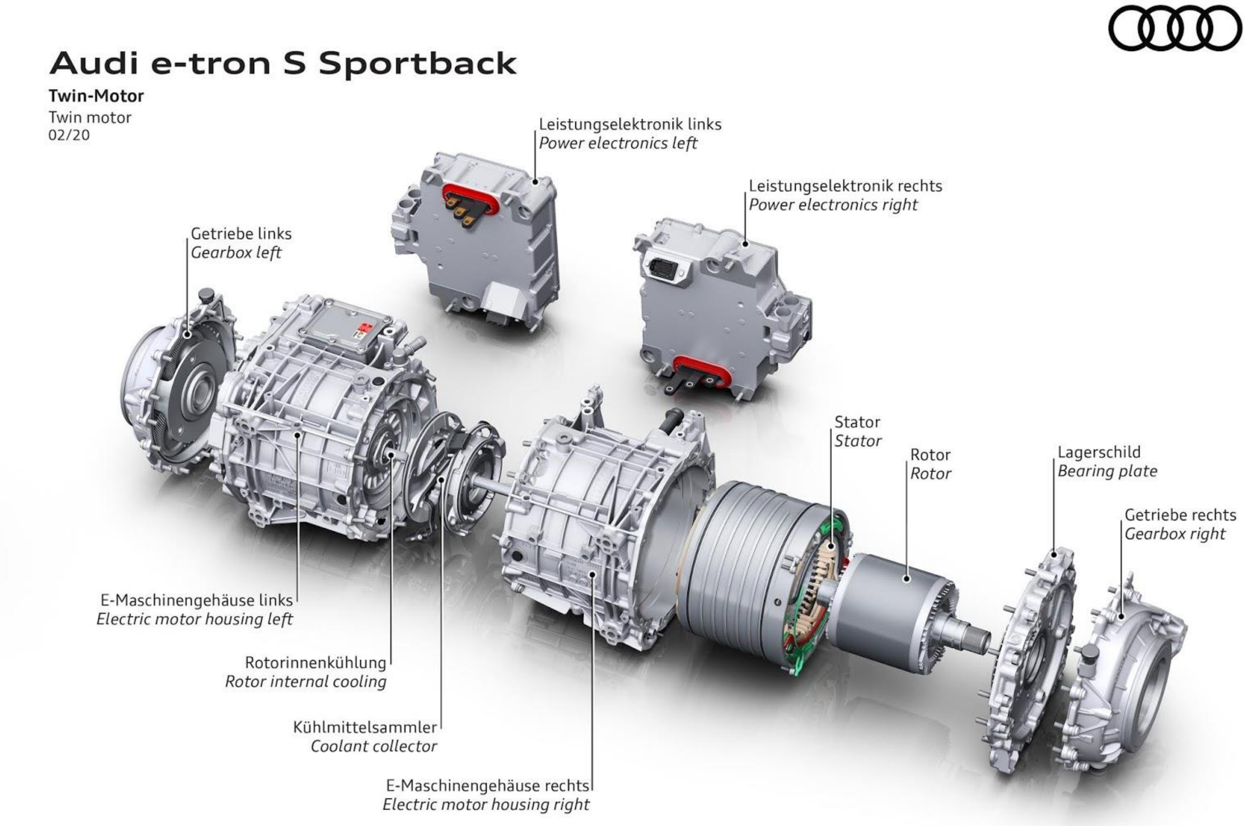
Electric vehicles



http://www.electric-vehiclenews.com/2020/03/audi-claim-world-first-with-mass.html

Electric vehicles

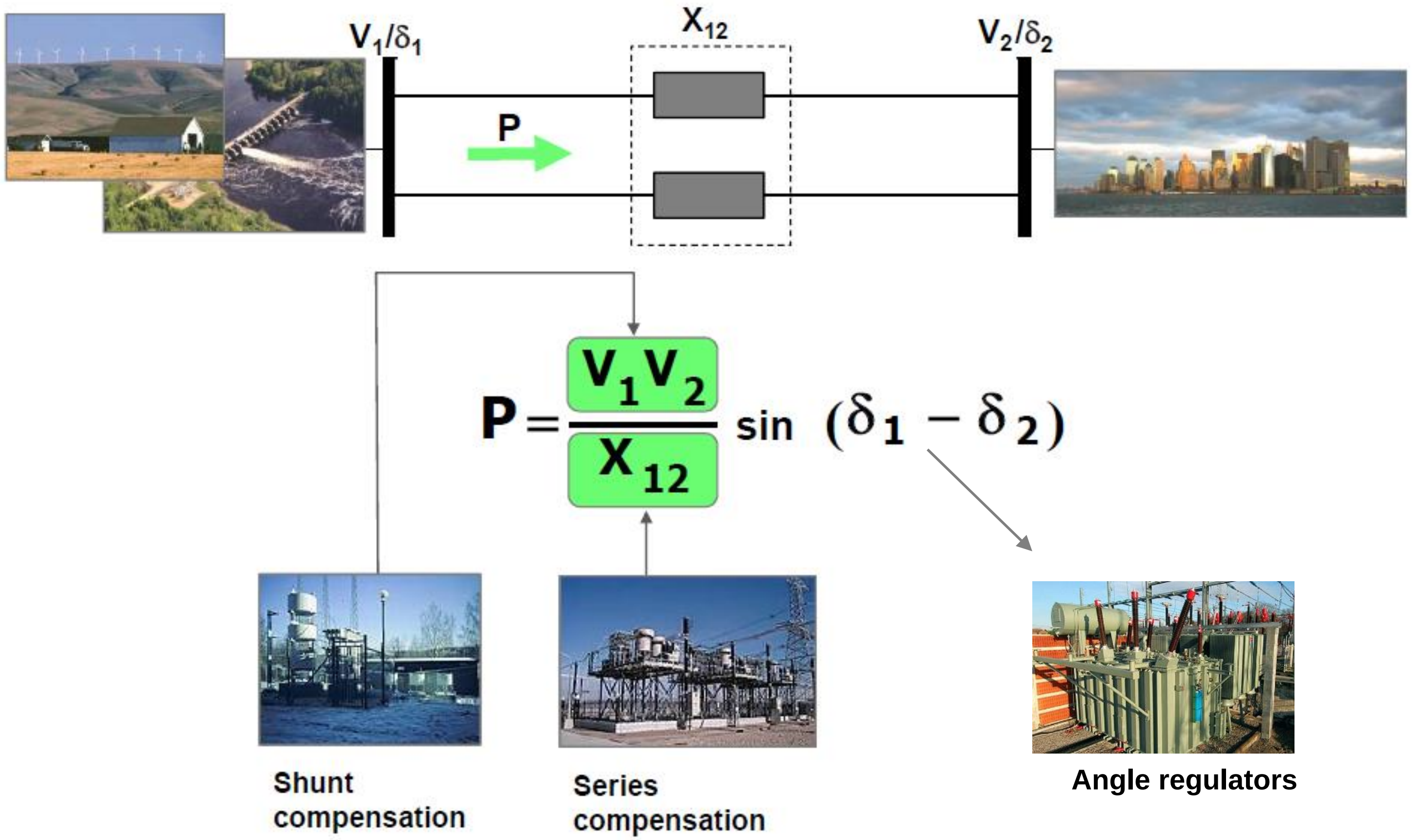
Two Electric motors + Drives



FACTS

- According to the IEEE, Flexible AC Transmission Systems (FACTS) are

> ''A power electronic based system and other static equipment that provides control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability''
>
> — IEEE



FACTS work by regulating

- voltage magnitude
- current magnitude
- voltage phase angle
- current phase angle
- impedance

FACTS

- Overview of FACTS technologies

	Series	Shunt	Series-shunt
Conventional	L, C	L, C	Phase Shifting Transformer (PST)
Thyristor valve	Thyristor Switched/ Controlled Series Capacitor (TSSC/TCSC)	Static VAR Compensator (SVC)	Dynamic Power Flow Controller (DPFC) HVDC-LCC Back to back
VSC	Static Synchronous Series Compensator (SSSC)	Static Synchronous Compensator (STATCOM)	Unified/Interline Power Flow Controller (UPFC/ IPFC) HVDC-VSC Back to back

FACTS

- Manufacturers

ABB SIEMENS ALSTOM

RXPE RONGXIN POWER ENGINEERING Nidec Nidec ASI S.p.A. SMART WIRES

HYOSUNG GreenPower tech

MITSUBISHI ELECTRIC Changes for the Better 南瑞继保 NR Electric Ingeteam

Series FACTS

- Series FACTS

	Series	Shunt	Series-shunt
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Thyristor valve	Thyristor Switched/ Controlled Series Capacitor (TSSC/TCSC)	Static VAR Compensator (SVC)	Dynamic Power Flow Controller (DPFC) HVDC-LCC Back to back
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Series FACTS

Benefits:

- Increase of **power transfer** capability.
- Increase of **voltage stability** and **transient (angle) stability**.
- Enhance **power oscillation damping.**
- **Limit short-circuit** currents.

Main types:

FSC (C): Fixed Series Capacitor

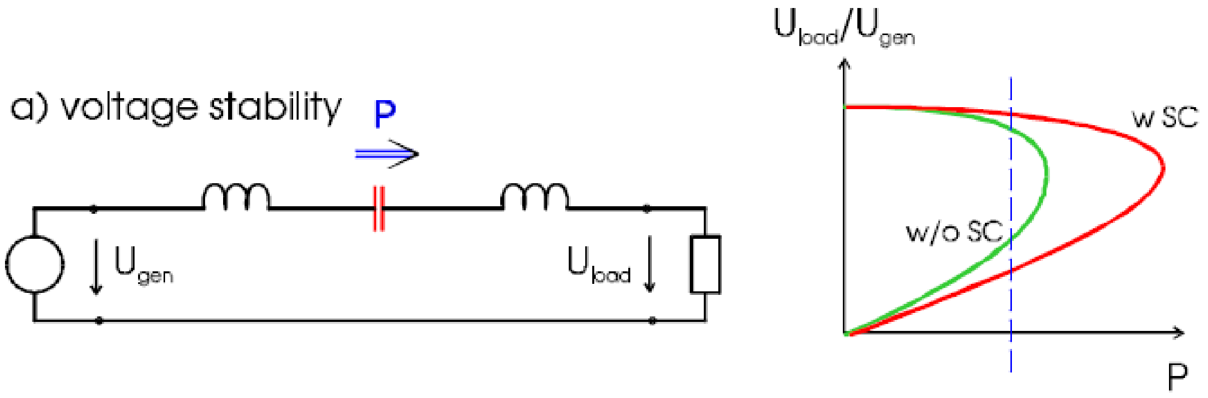
OLC (L): Overload Line Controller

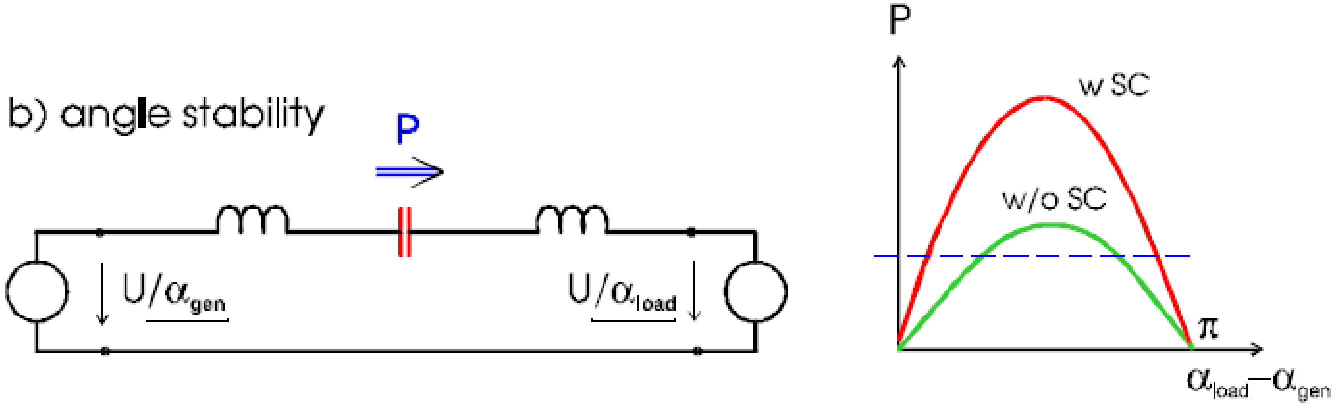
TSSC: Thyristor Switched Series Capacitor

TCSC: Thyristor Controlled Series Capacitor

TPSC: Thyristor Protected Series Capacitor

SSSC: Static Synchronous Series Compensator



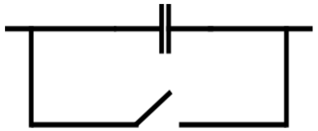


Degree of compensation: $k = \dfrac{X_{cap}}{X_{line}}$ (0,3 – 0,6 typically)

Source: The Stöde Thyristor controlled series capacitor

Series FACTS

- Fixed Series Capacitor (FSC)



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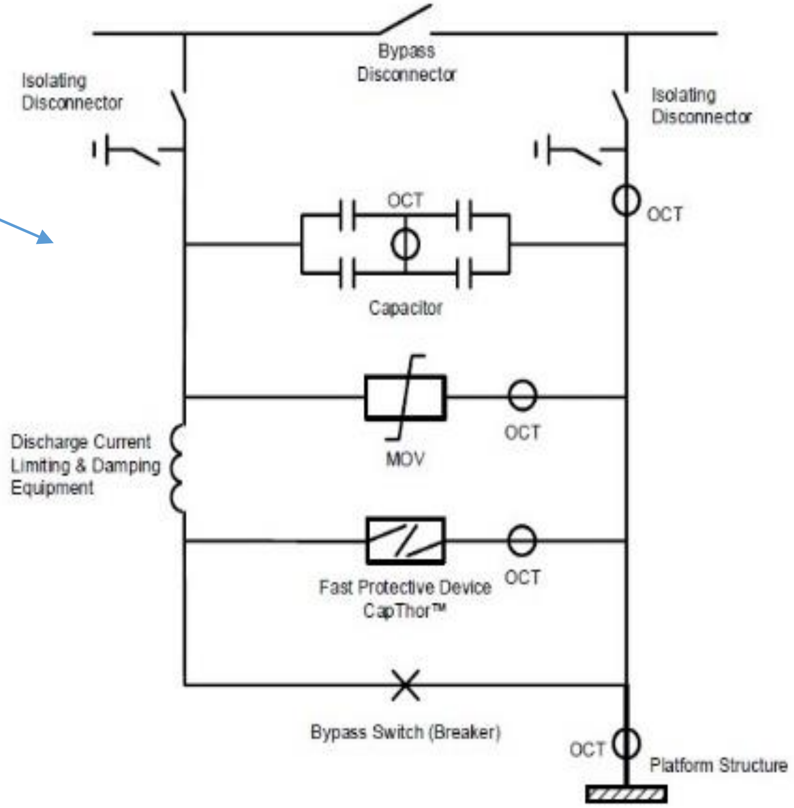
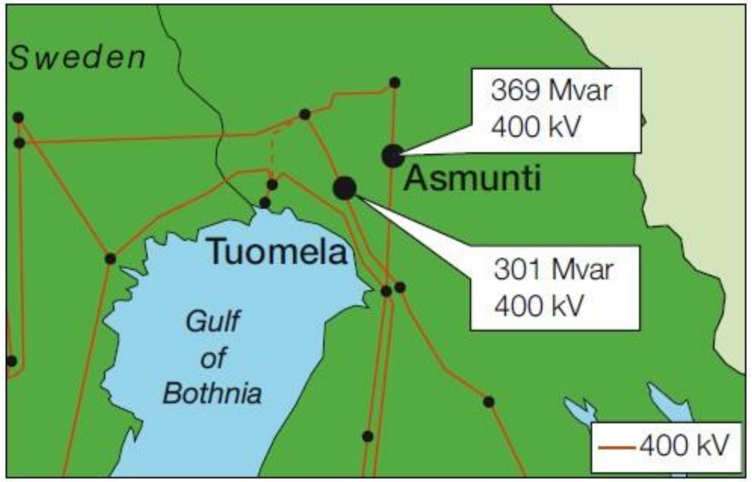
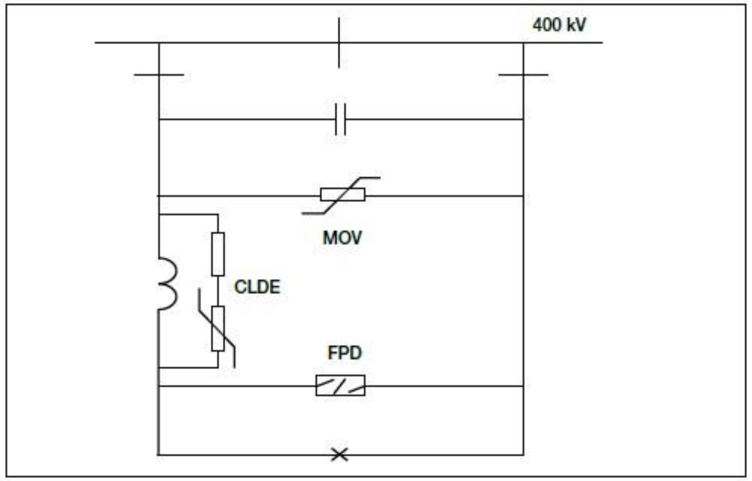


  - Capacitor bank
  - MOV (+ spark gap): ~2,3 pu
  - Damping circuit
  - Fast Protective Device (ABB, GE): <1 ms
  - Bypass breaker: 50 ms
  - Optical transducers

Series FACTS

- Example 1 - Asmunti (2009)



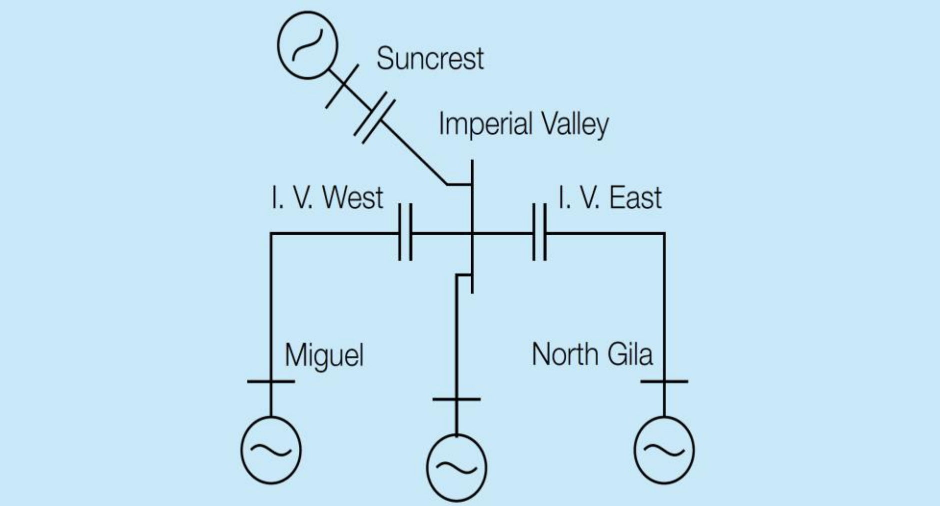


Proveedor	ABB	
Cliente	Finngrid	
Nivel de tensión	400 kV	400 kV
Potencia reactiva nominal	369 Mvar	301 Mvar
Intensidad nominal	1800 A	1800 A
Reactancia	38 Ω	31 Ω
Grado de compensación	70 %	70 %
Intensidad sobrecarga	2430 A	2430 A

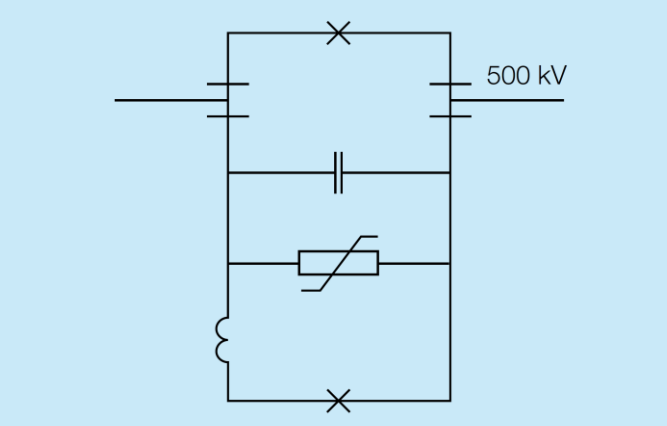
Source: Series Capacitors for increased power transmission capacity in the Finnish 400 kV grid, ABB

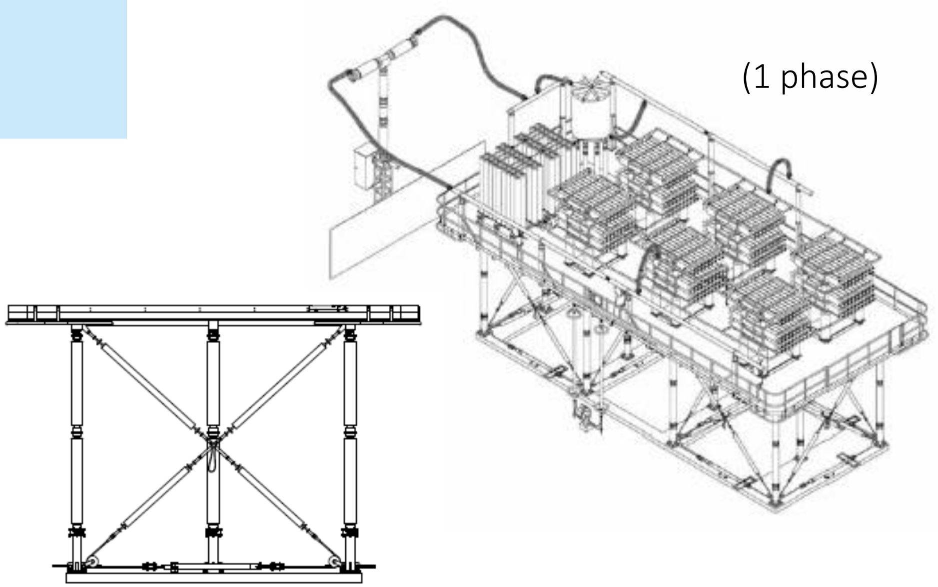
Series FACTS

- Example 2 - Imperial Valley (2012)



Seismic security: spring damping mechanism structure



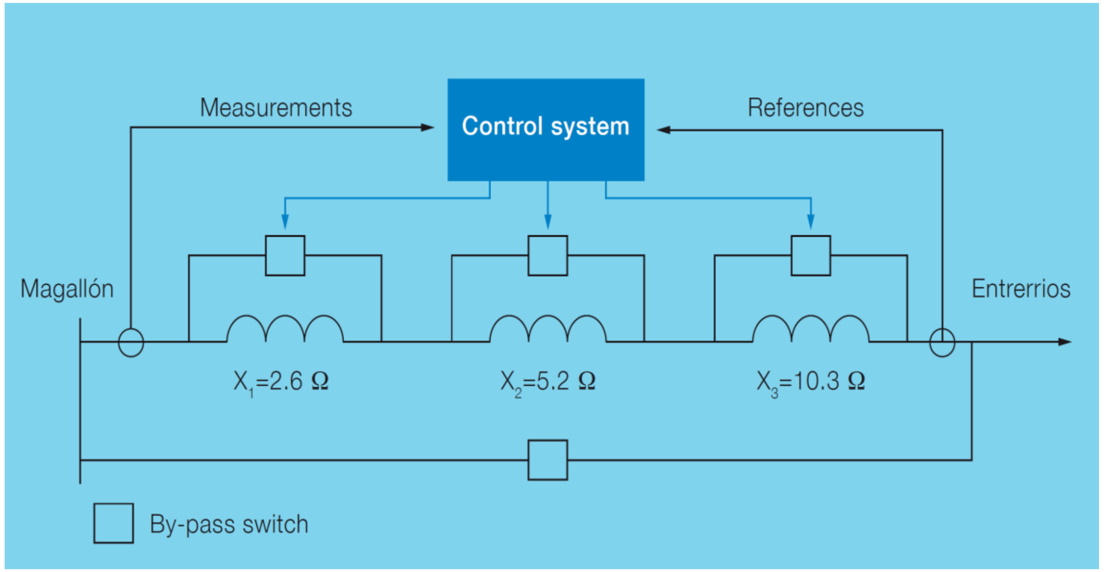


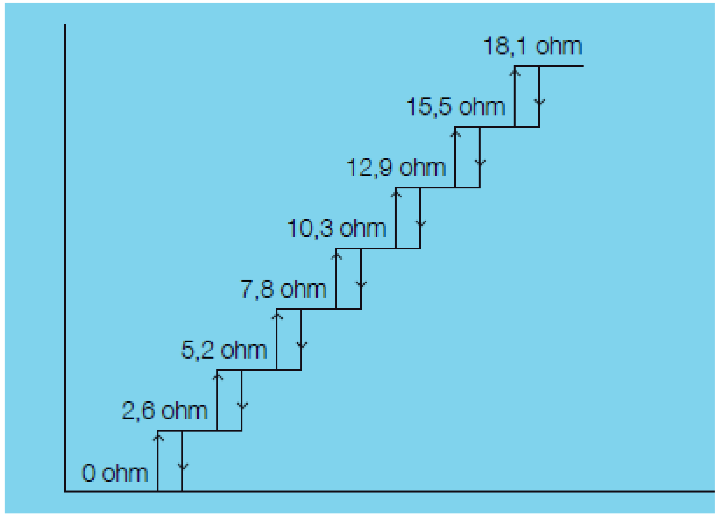
(1 phase)

Source: Series Capacitors to increase power transmission capability of 500 kV lines, ABB

Series FACTS

- Overload Line Controller (OLC)





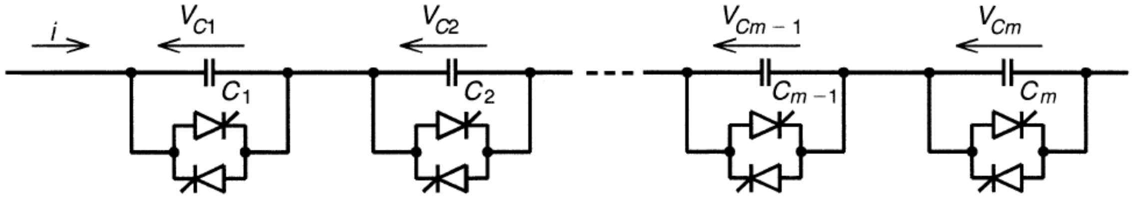
- **Inductive reactance** in series with the line.
- Opposite effect than FSC: **line impedance increases**.
- Very **simplistic** solution.
- **Limit overload** in a transmission system with high wind generation.

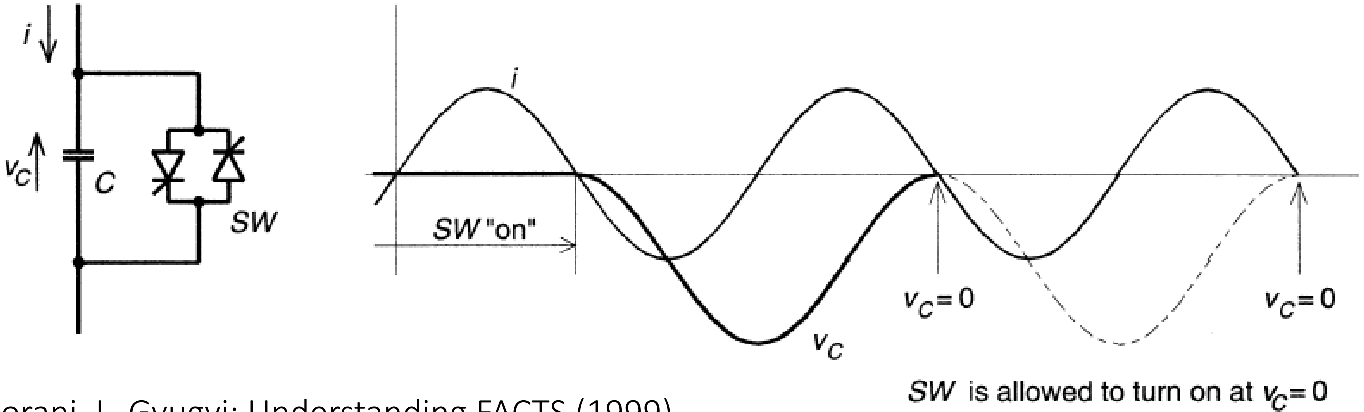
Source: Overload control of a 220 kV transmission line by means of an OLC, ABB

Series FACTS

- Thyristor Switched Series Capacitor (TSSC)

  - **Stepwise on-off** capacitor bank control: first approach to dynamic power flow control.
  - **Synchronized** thyristors, minimize the switching transients.
  - **No harmonics** and **moderate** response time (half cycle) → Only suitable for power flow control, power oscillation daming (POD)





Source: N. Hingorani, L. Gyugyi: Understanding FACTS (1999)

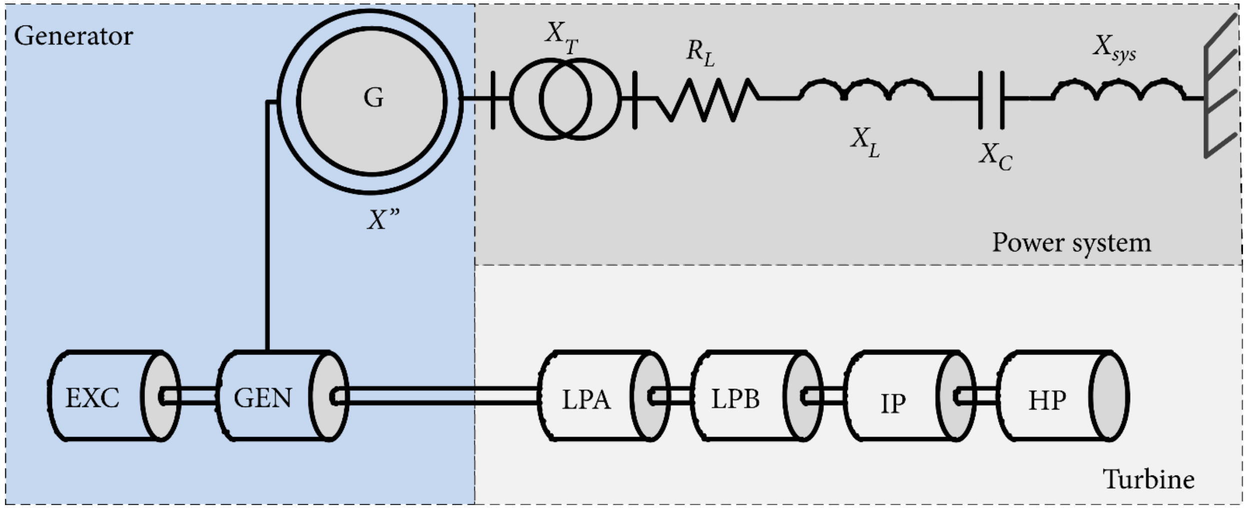
Series FACTS

- Subsynchronous Resonance

  - Interaction between a turbine generator shaft system and a series compensated transmission line.
  - Studies: frequency scanning in both mechanical and electrical systems.

$$k_S = X_C/X_L = 25\% \dots 75\%$$

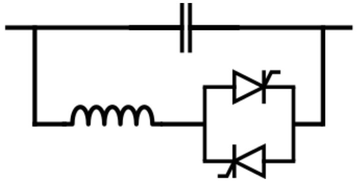
$$f_{series} = f\sqrt{X_C/X_L}$$



Source1: M. Eremia, C. C. Liu, A.A Edris: Advanced Solutions in Power Systems (2016)
Source2: Subsynchronous Resonance and FACTS-Novel Control Strategy for Its Mitigation

Series FACTS

- Thyristor Controlled Series Capacitor (TCSC)



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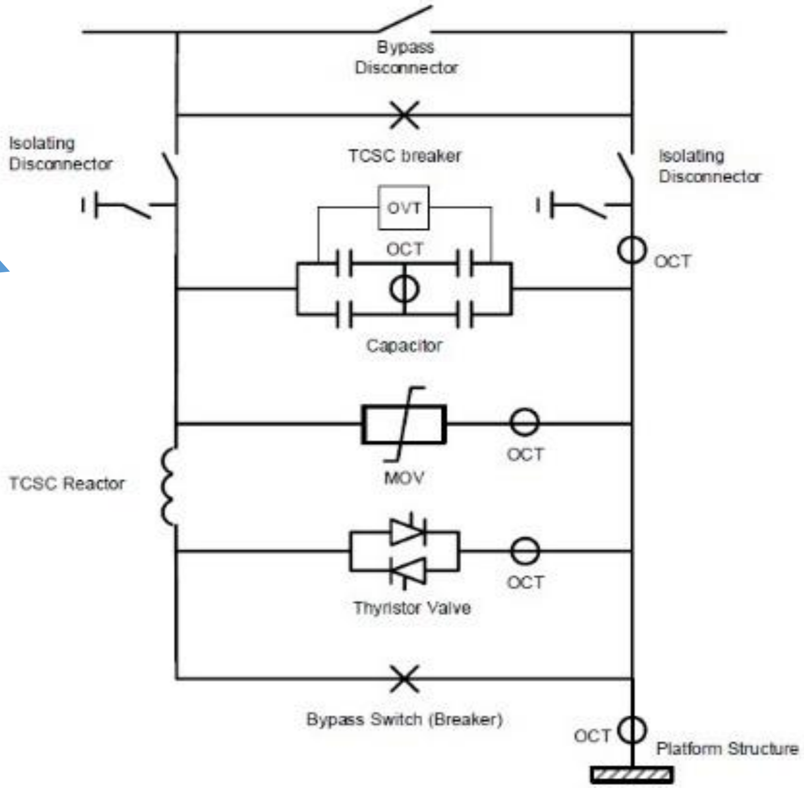


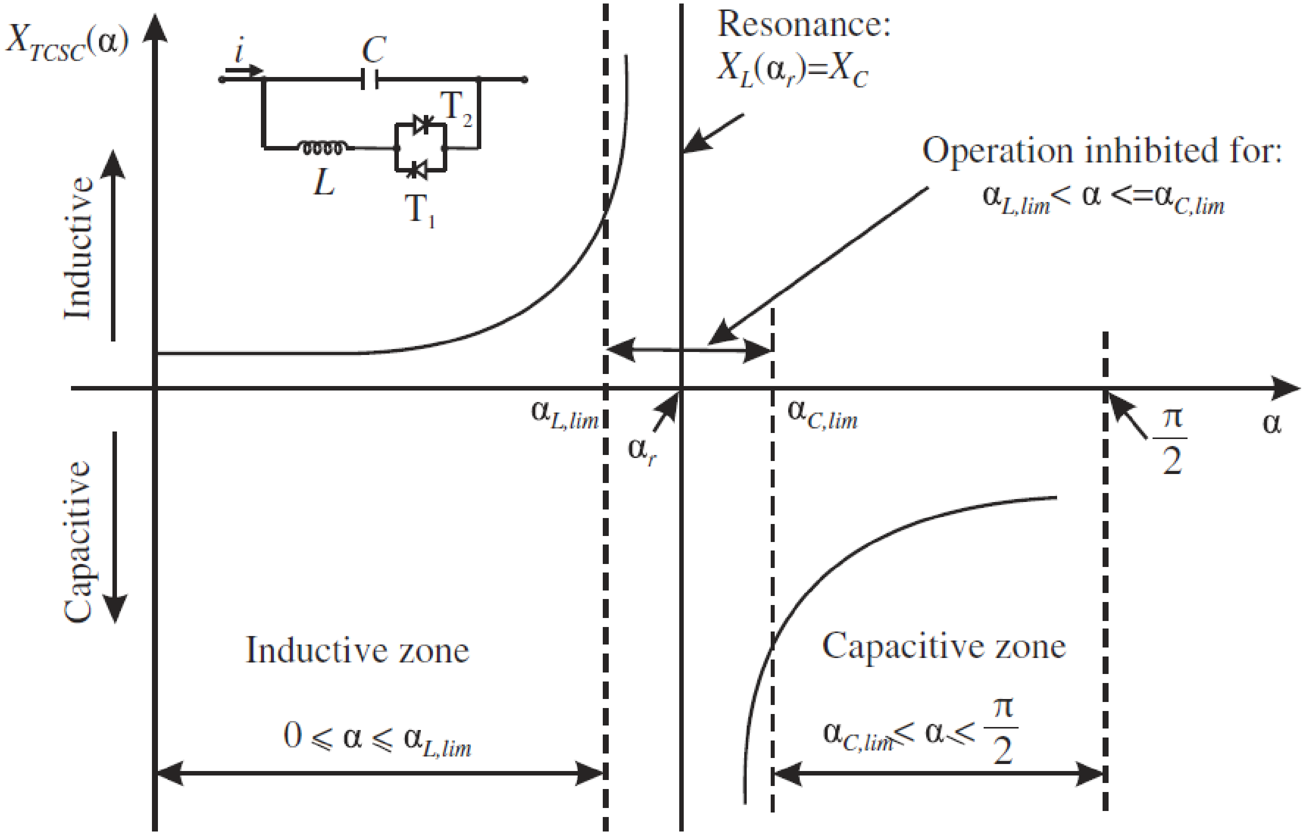
- Capacitor bank
- MOV
- Damping circuit
- Bypass breaker
- Optical transducers
- TCR branch

Operation modes

- **Blocking mode**: thyristor valve is always off, opening inductive branch, and effectively causing the TCSC to operate as FSC.
- **Bypass mode**: thyristor valve is always on, causing TCSC to operate as capacitor and inductor in parallel, reducing current through TCSC.
- **Capacitive boost mode**: forward voltage thyristor valve is triggered slightly before capacitor voltage crosses zero to allow current to flow through inductive branch, adding to capacitive current → increases the apparent capacitance.

Series FACTS

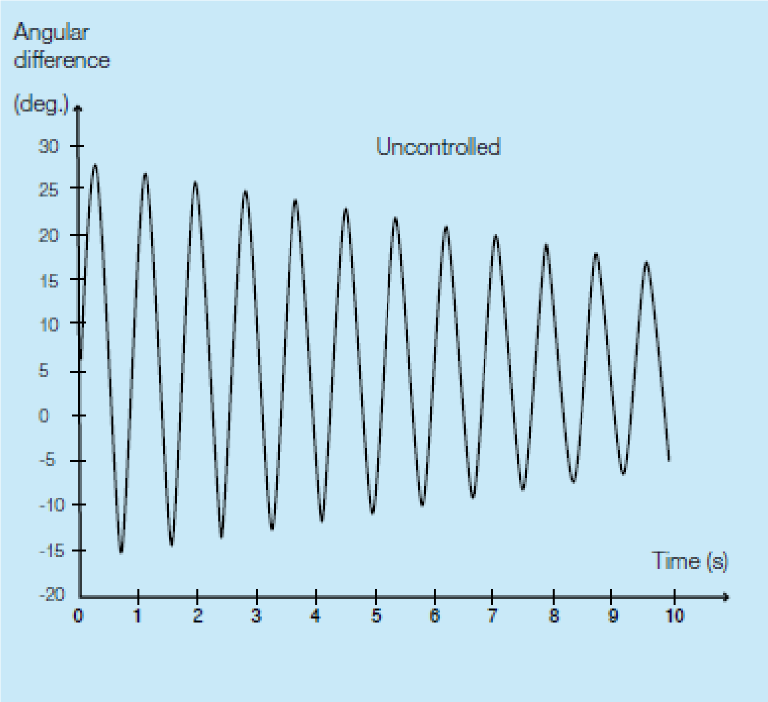
- TCSC operation range



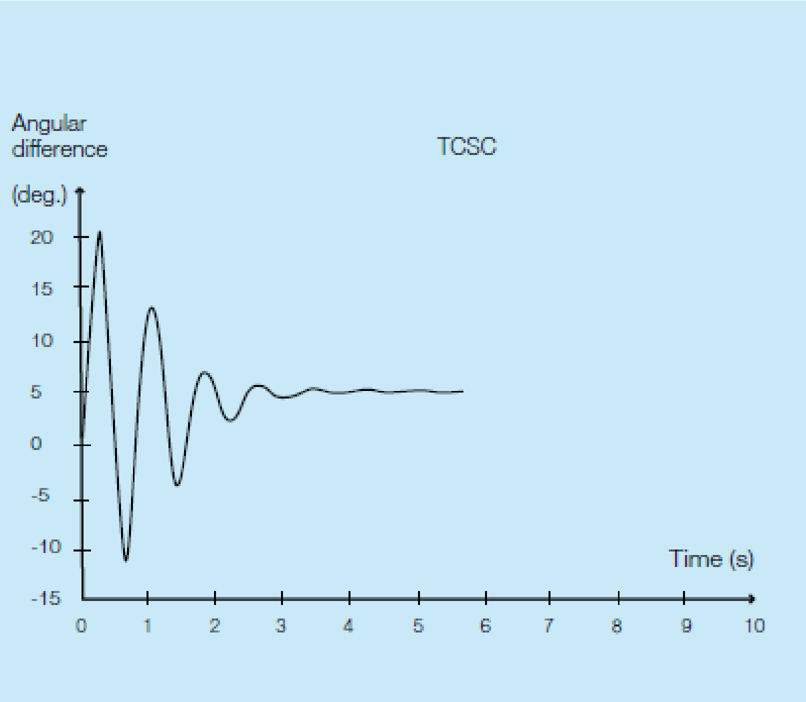
Source: M. Eremia, C. C. Liu, A.A Edris: Advanced Solutions in Power Systems (2016)

Series FACTS

- TCSC can be used to damp power oscillations in the grid



Power oscillations on a 500 kV intertie excited by a temporary short circuit. Power flow through the intertie: 2000 MW.

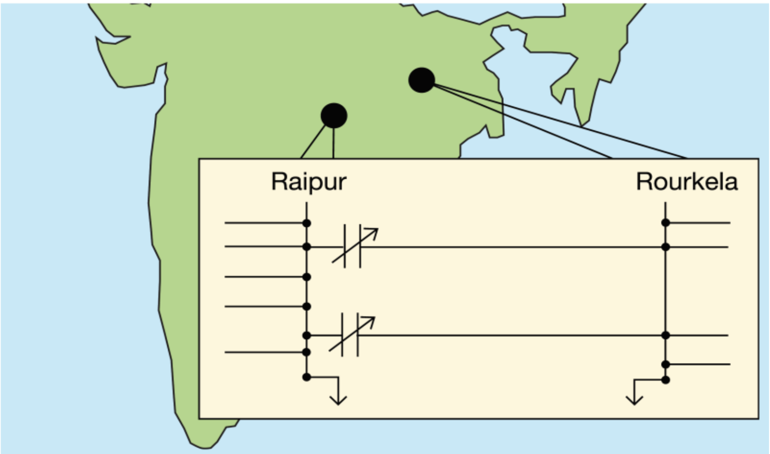


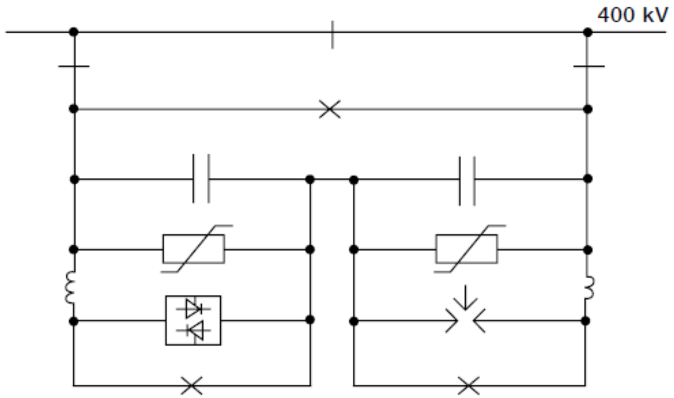
Power oscillations damped out by means of TCSC.

Source: TCSC Keeping grids together, ABB

Series FACTS

- TCSC – Example 1: Raipur-Rourkela (2003)





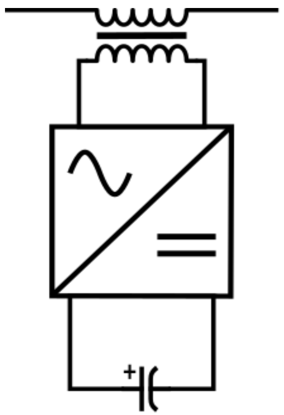
Proveedor	ABB	
Cliente	Power Grid Corporation of India	
Dispositivo	Condensador serie	TCSC
Nivel de tensión	400 kV	400 kV
Potencia reactiva nominal	394 Mvar	71 Mvar
Intensidad nominal	1550 A	1550 A
Reactancia nominal	54,7 Ω	6,83 Ω
Grado de compensación	40%	5%
Intensidad de sobrecarga (10 min)	2325 A	2325 A
Intensidad de sobrecarga (30 min)	2093 A	2093 A

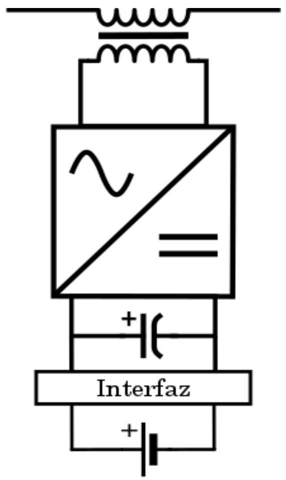
Source: TCSC for stable transmission of surplus power from Eastern to Western India, ABB

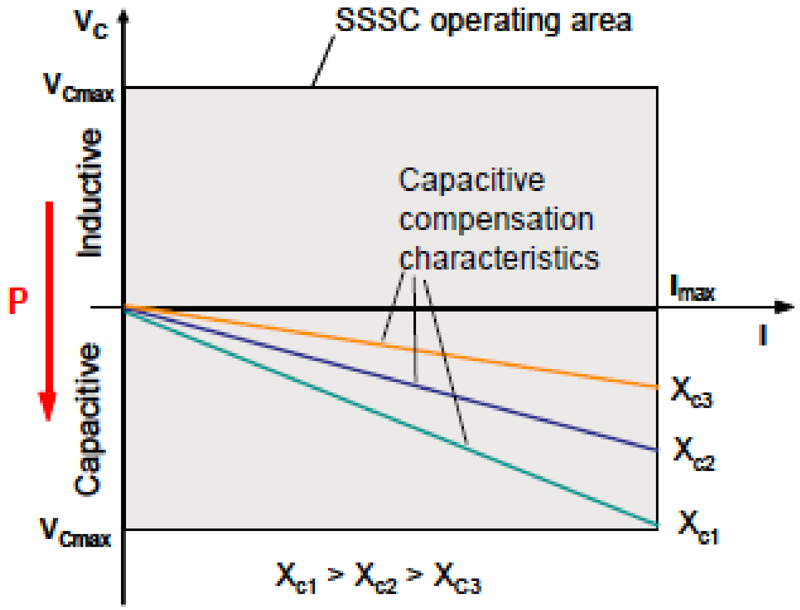
Series FACTS

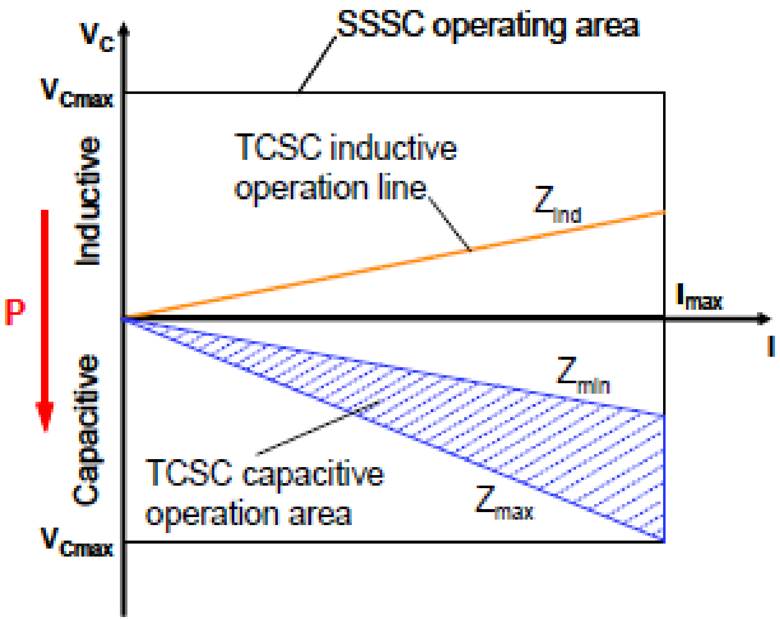
- Static Synchronous Series Compensator (**SSSC**)

- Voltage source in series (instead of impedance).
- Independent from line current.
- No excitation of subsynchronous resonance.





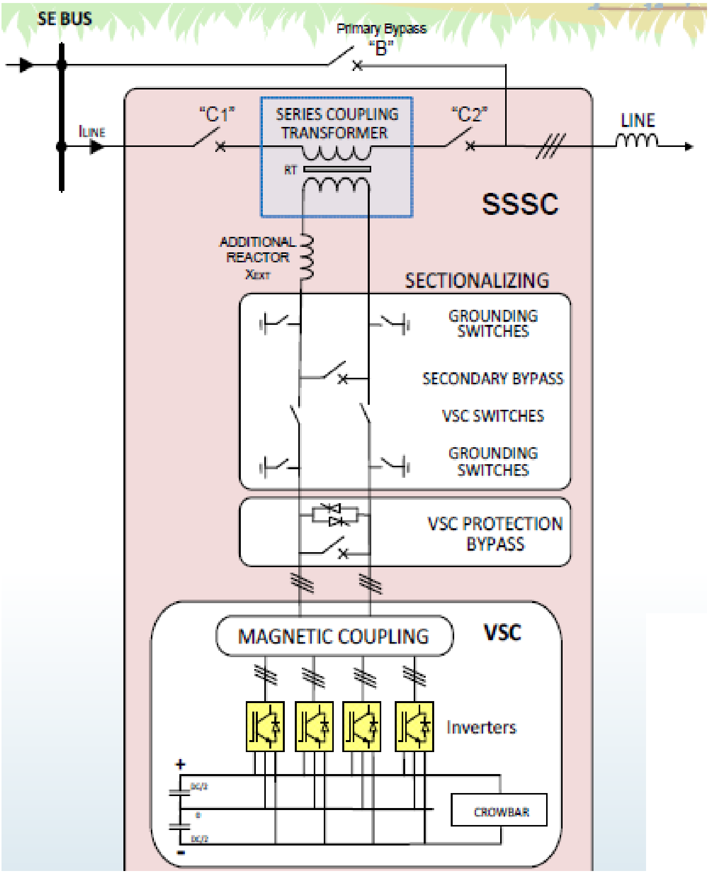




Source: SSSC, CIGRE B4,40 Working Group

Series FACTS

- SSSC Example 1 - Torres de Segre (2013)



- One of the few installations in the world.
- Reduce line overload.
- Control modes:
  - Power flow regulation
  - Power flow limitation
  - Regulated impedance
  - Maximum impedance

47,8 Mvar
-4 , +10 Ω

RED ELÉCTRICA DE ESPAÑA

Ingeteam

Shunt FACTS

- Shunt FACTS

	Series	Shunt	Series-shunt
Conventional	L, C	L, C	Phase Shifting Transformer (PST)
Thyristor valve	Thyristor Switched/ Controlled Series Capacitor (TSSC/TCSC)	Static VAR Compensator (SVC)	Dynamic Power Flow Controller (DPFC) HVDC-LCC Back to back
VSC	Static Synchronous Series Compensator (SSSC)	Static Synchronous Compensator (STATCOM)	Unified/Interline Power Flow Controller (UPFC/ IPFC) HVDC-VSC Back to back

Shunt FACTS

- The shunt FACTS provide voltage support along the lines.

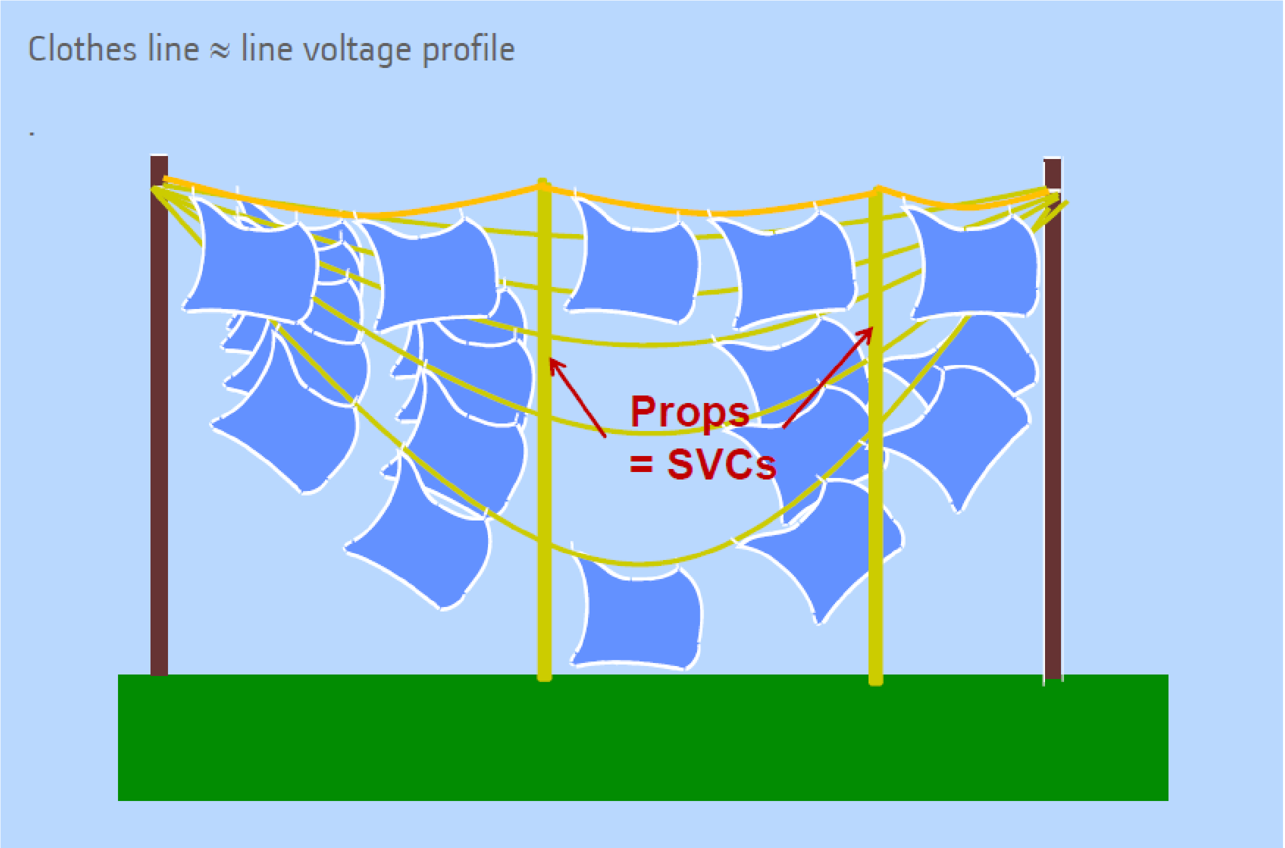
Benefits

- **Voltage control** and regulation to the set point.
- Fast **reactive power** compensation.
- **Overvoltage prevention** after loss of load.
- **Undervoltage prevention** during faults.
- Detecting and **damping** of active power **oscillations**.
- **Load balancing.**

Technologies

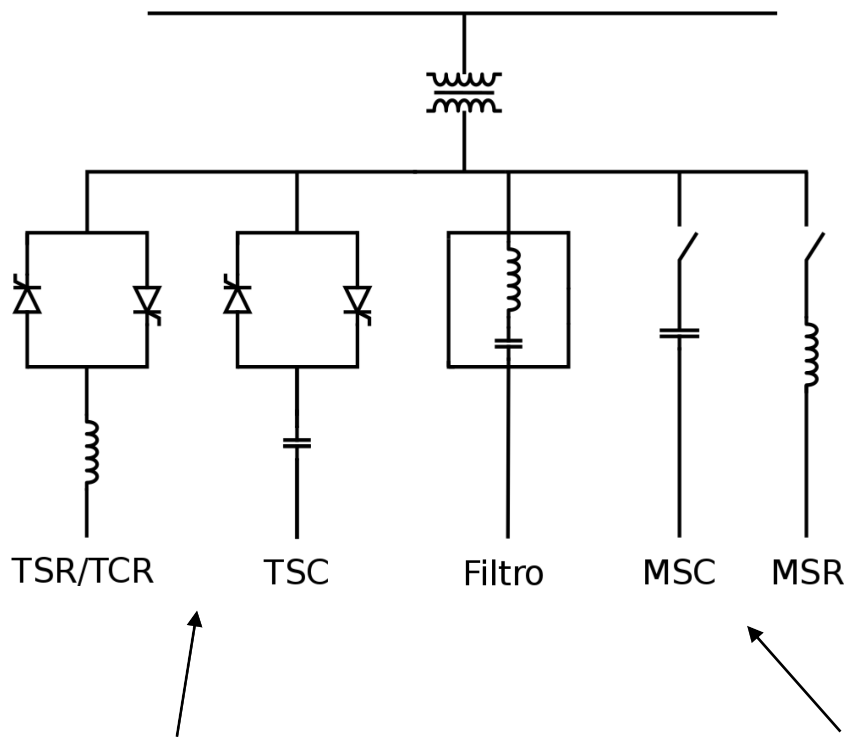
- **SVC**: Static VAR Compensator
- **STATCOM**: Static Synchronous Compensator

Analogy.



Shunt FACTS

Static VAR Compensator (**SVC**)



- **TCR**: Thyristor Controlled Reactor
- **Harmonic filters**
- **TSC**: Thyristor Switched Capacitor
- **MSC**: Mechanically Switched Capacitor
- **MSR**: Mechanically Switched Reactor

Response time: **2 – 3 cycles**

Response time: 5 – 7 cycles

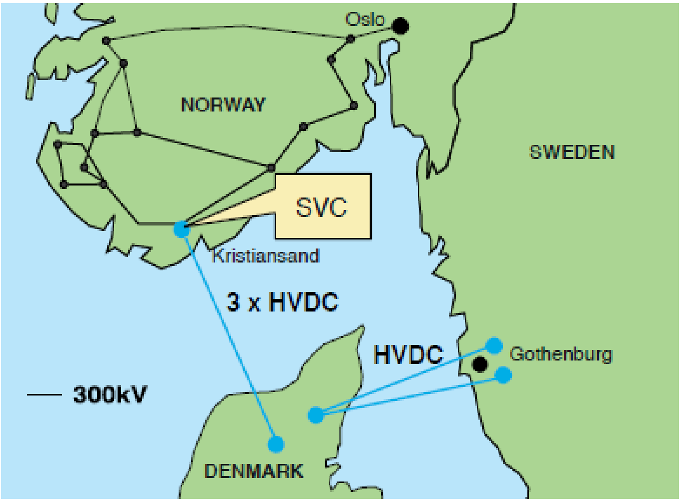
Shunt FACTS

- SVC substation layout

1. SVC transformer
2. Transformer cooling
3. TCR reactors
4. TSC capacitors
5. TSC reactors
6. Filter capacitors
7. Filter reactors
8. Filter circuit-breaker
9. Valve and control building
10. Valve cooling

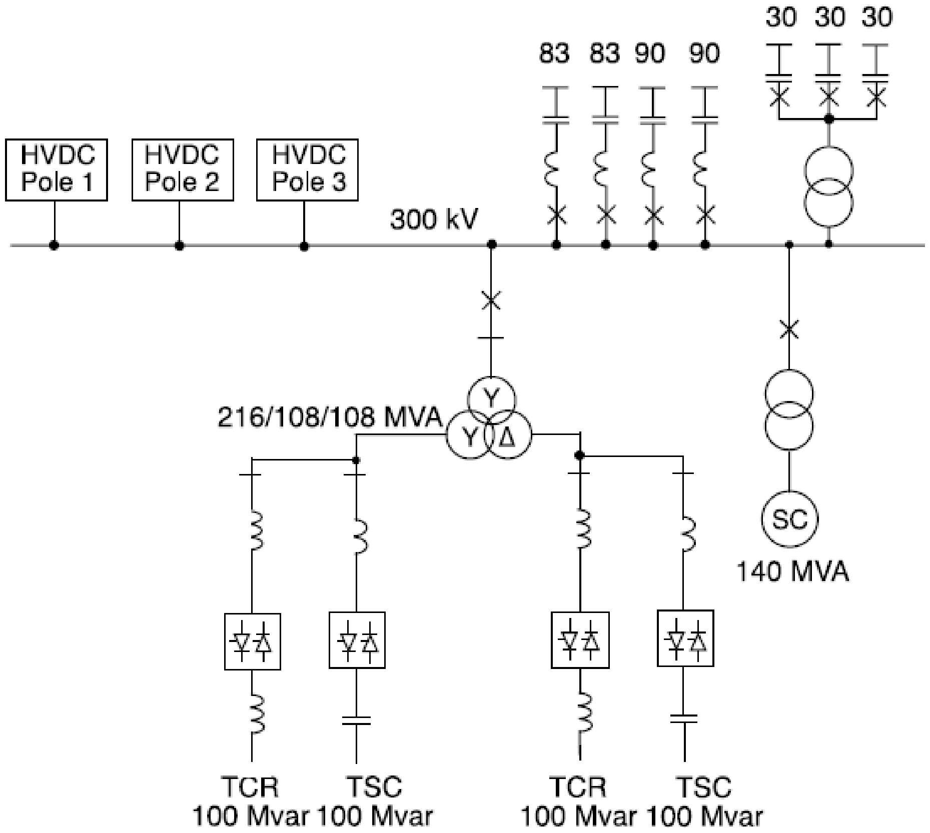
Shunt FACTS

- SVC – Example: Kristiansand (1995)



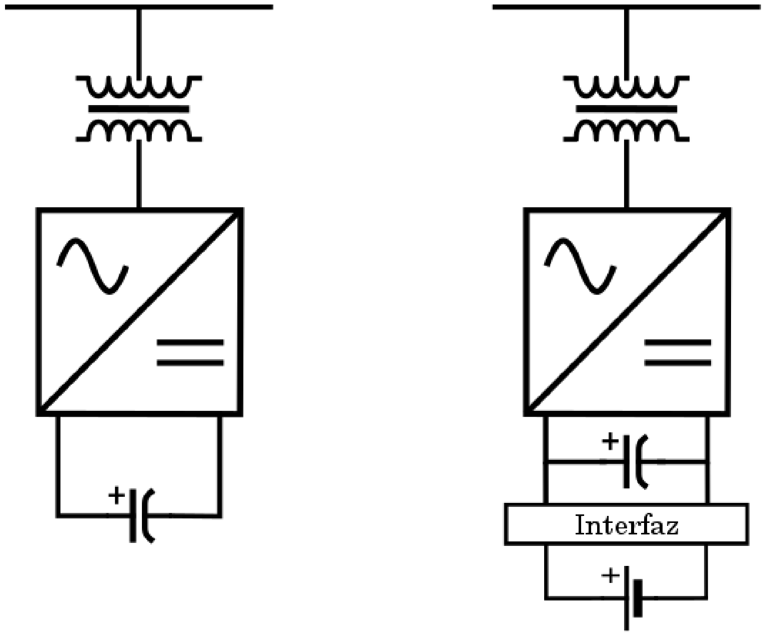
-200, +200 Mvar

Source: ABB



- Power transfer capability was limited by voltage dips and overvoltages during load rejection.
- 12-pulse via 3-winding transformer for minimizing harmonics.
- Load sharing with existing synchronous condenser.

Static Synchronous Compensator (**STATCOM**)



Response time: **1 – 1,5 cycles**

- **VSC** (Voltage Source Converter)
- **IGBT**, IGCT, GTO, GCT…
- Multilevel topology:
  - **NPC** (Neutral-Point Clamped)
  - **CHB** (Cascaded H-Bridge)
- Can be **combined** with other elements:
  - MSC
  - Filters (> 9º harmonic)
- Can include **ESS** (Energy Storage System)

Comparison **STATCOM** vs **SVC**

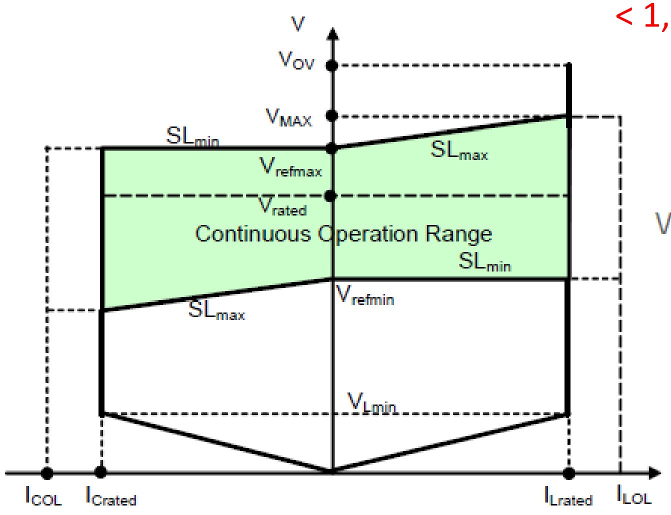
STATCOM

- Controllable voltage source behind a reactor
- \+ More Compact
- \+ Faster speed of response
- \+ Better overload capability during under voltages
- \+ Independent of line impedance (weak networks)
- — Rating is current-limited

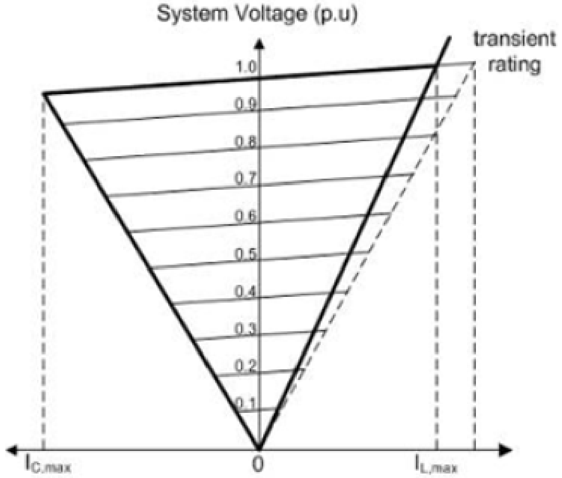
SVC

- Switched shunt impedance
- \+ Low-cost, well proven
- \+ Better overload capability during overvoltages
- — Rating is impedance-limited

< 1,3 pu



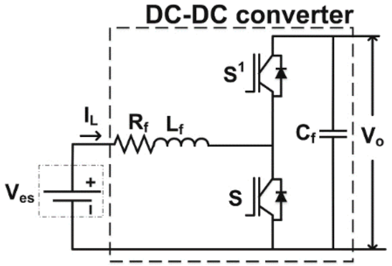
V-I – characteristics of STATCOM (left) and SVC (right)

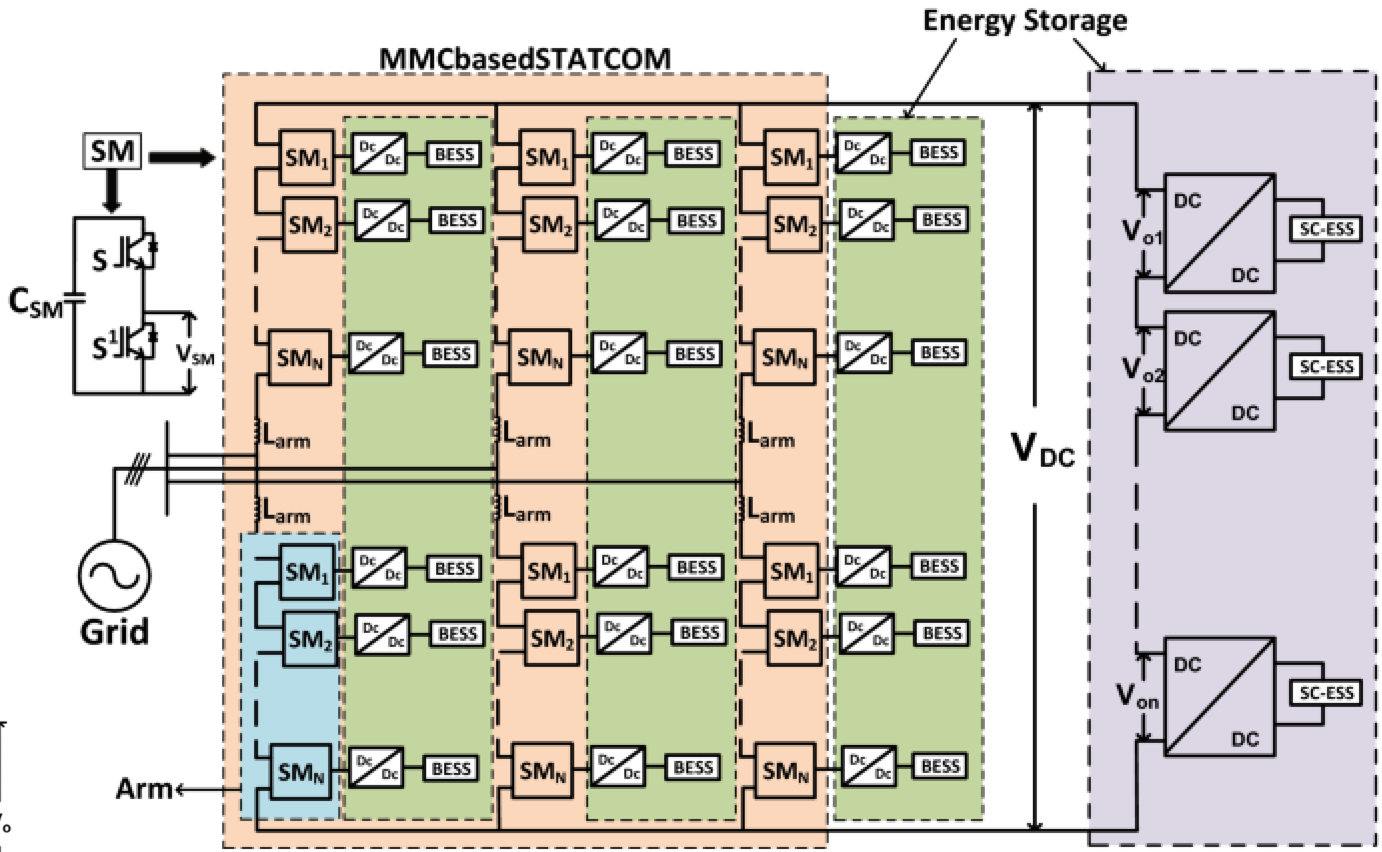


Utility STATCOM- 03.07.2014 – P 15

STATCOM + storage system

- **Active power** exchange possible: frequency support, inertia emulation, **renewable generation forecast correction**
- Sodium-nickel battery: high voltage cells , but no current peaks
- Lithium battery: low voltage cells, but high transient current peaks
- Supercapacitors: high transient current peaks

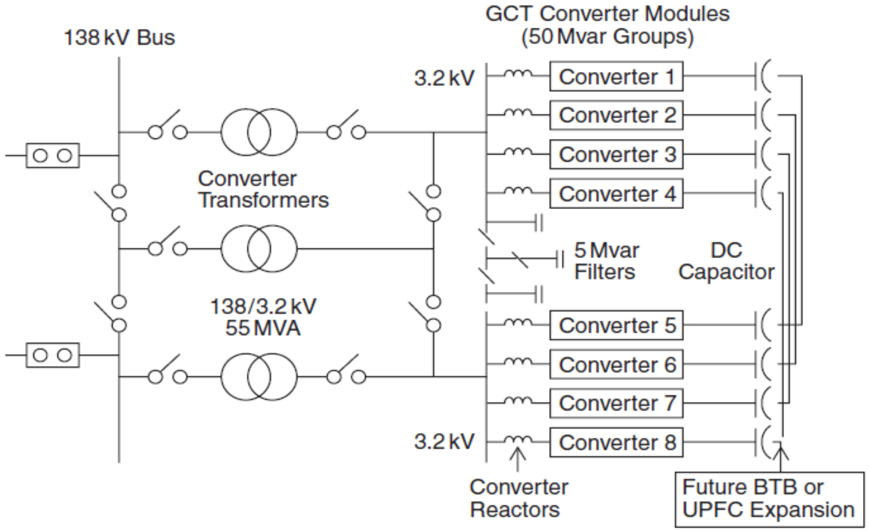




Source: Bharadwaj, A., Maiti, S., Dhal, N., & Chakraborty, S. (2019). Control and sizing of modular multilevel converter-based STATCOM with hybrid energy storage system for large-scale integration of wind farms with the grid. Electrical Engineering, 101, 743-757.

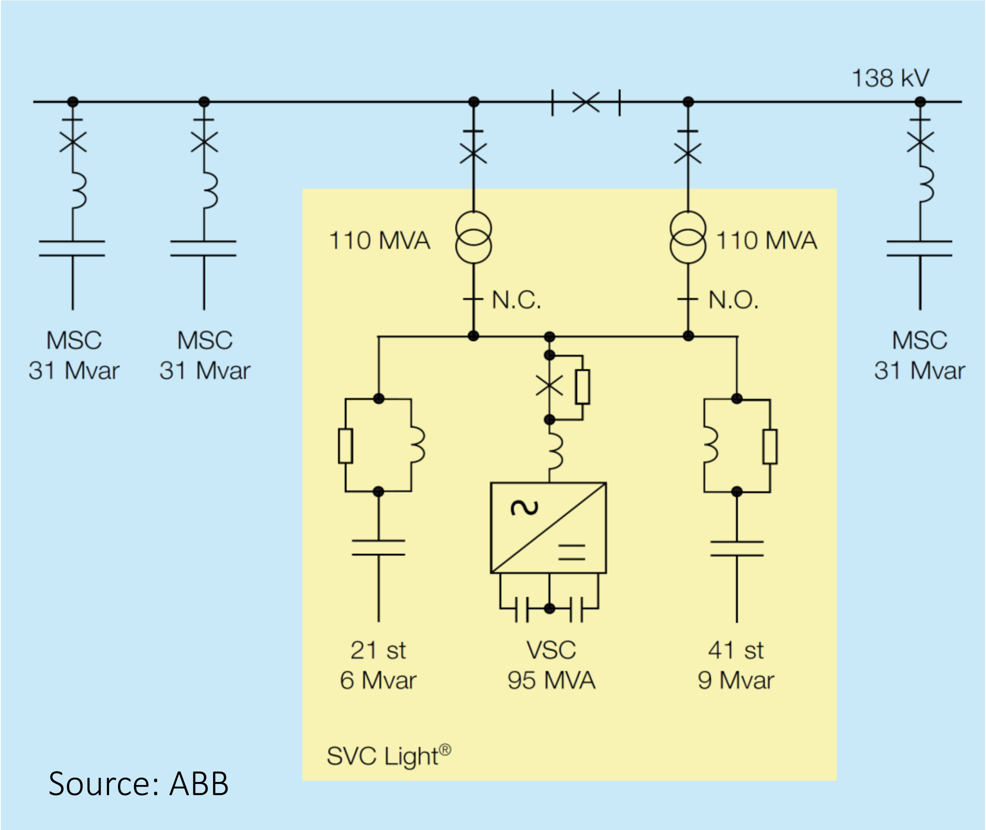
Shunt FACTS

STATCOM – Example 1: Talega (2003)



- Fast voltage support during critical contingencies.
- Smooth control of AC voltage over a wide range of operating conditions.
- Modular design (redundancy) and future B2B/UPFC expansion.

Example 2: Holly (2005)



- Fast reactive power source.
- Small space available and noise restriction.

Series-Shunt FACTS

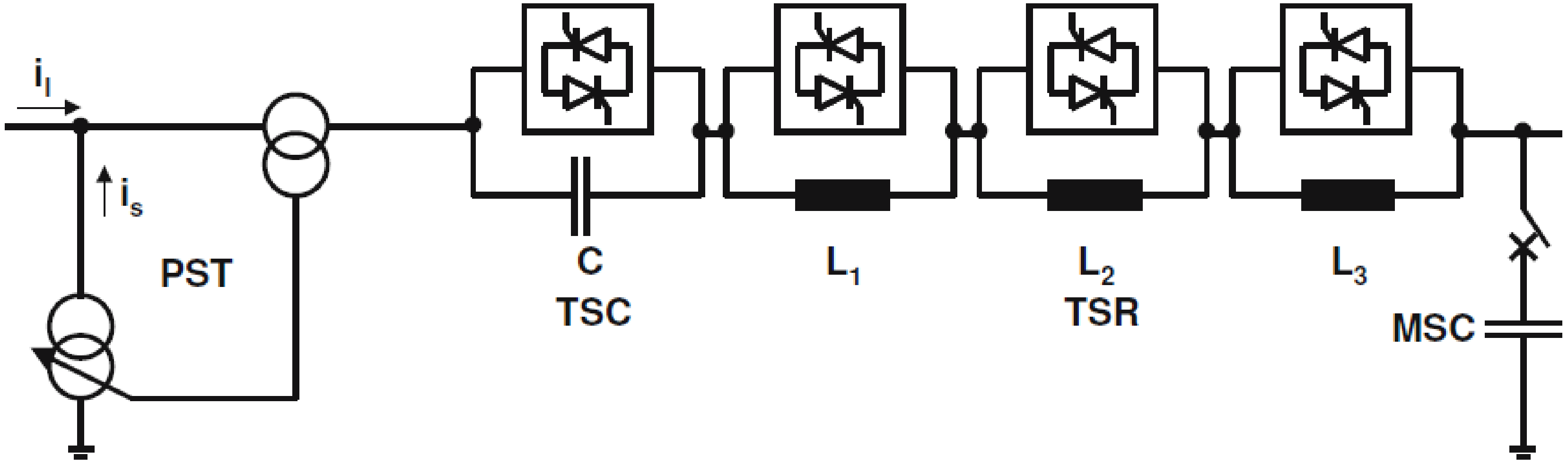
- Series-Shunt

	Series	Shunt	Series-shunt
Conventional	L, C	L, C	Phase Shifting Transformer (PST)
Thyristor valve	Thyristor Switched/ Controlled Series Capacitor (TSSC/TCSC)	Static VAR Compensator (SVC)	Dynamic Power Flow Controller (DPFC) HVDC-LCC Back to back
VSC	Static Synchronous Series Compensator (SSSC)	Static Synchronous Compensator (STATCOM)	Unified/Interline Power Flow Controller (UPFC/ IPFC) HVDC-VSC Back to back

Series-Shunt FACTS

- Technologies
  - **PST**: Phase Shifting Transformer
  - **DPFC**: Dynamic Power Flow Controller
  - **HVDC-LCC**: Line Commutated Converter (B-to-B)
  - **UPFC**: Unified Power Flow Controller
  - **IPFC**: Unified Power Flow Controller
  - **GUPFC**: Generalized Unified Power Flow Controller
  - **HVDC-VSC**: Voltage Source Converter (B-to-B)

Dynamic Flow Controller (**DFC**)



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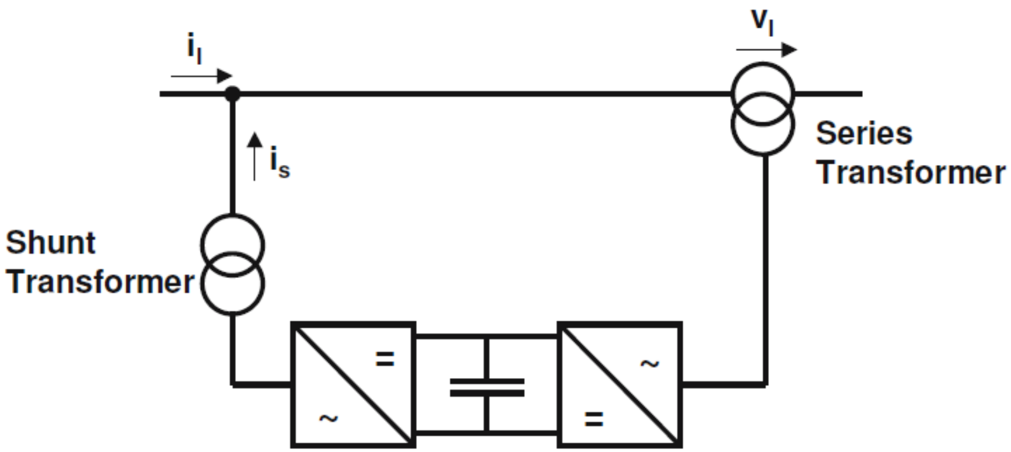
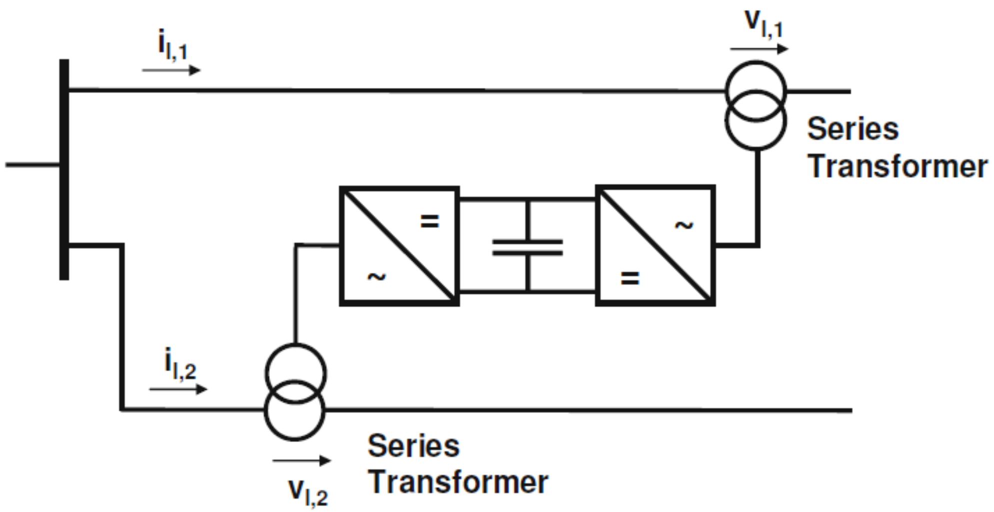
Series-Shunt FACTS

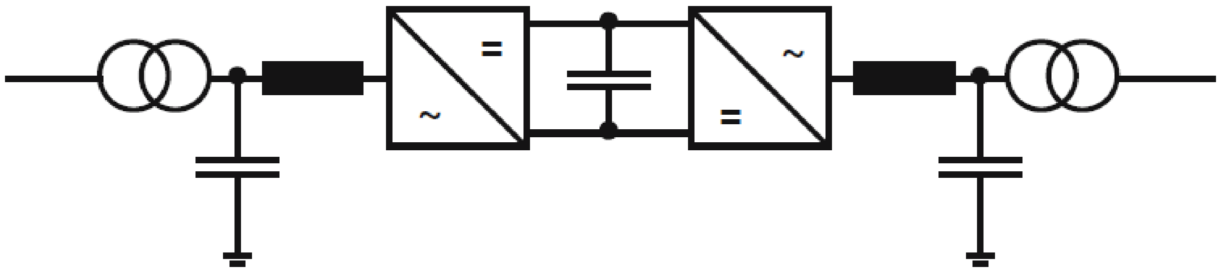
Unified Power Flow Controller (**UPFC**)



Interline Power Flow Controller (**IPFC**)



Back-to-back



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Electric Energy Conversion

10. Applications of electric energy conversion

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