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IEEE PES Distinguished Lecture

Developments in HVDC Technologies for Renewable Energy Interconnection

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Hungarian Chapter, IEEE Power and Energy Society

Hungarian PES/IAS Student Branch Chapter

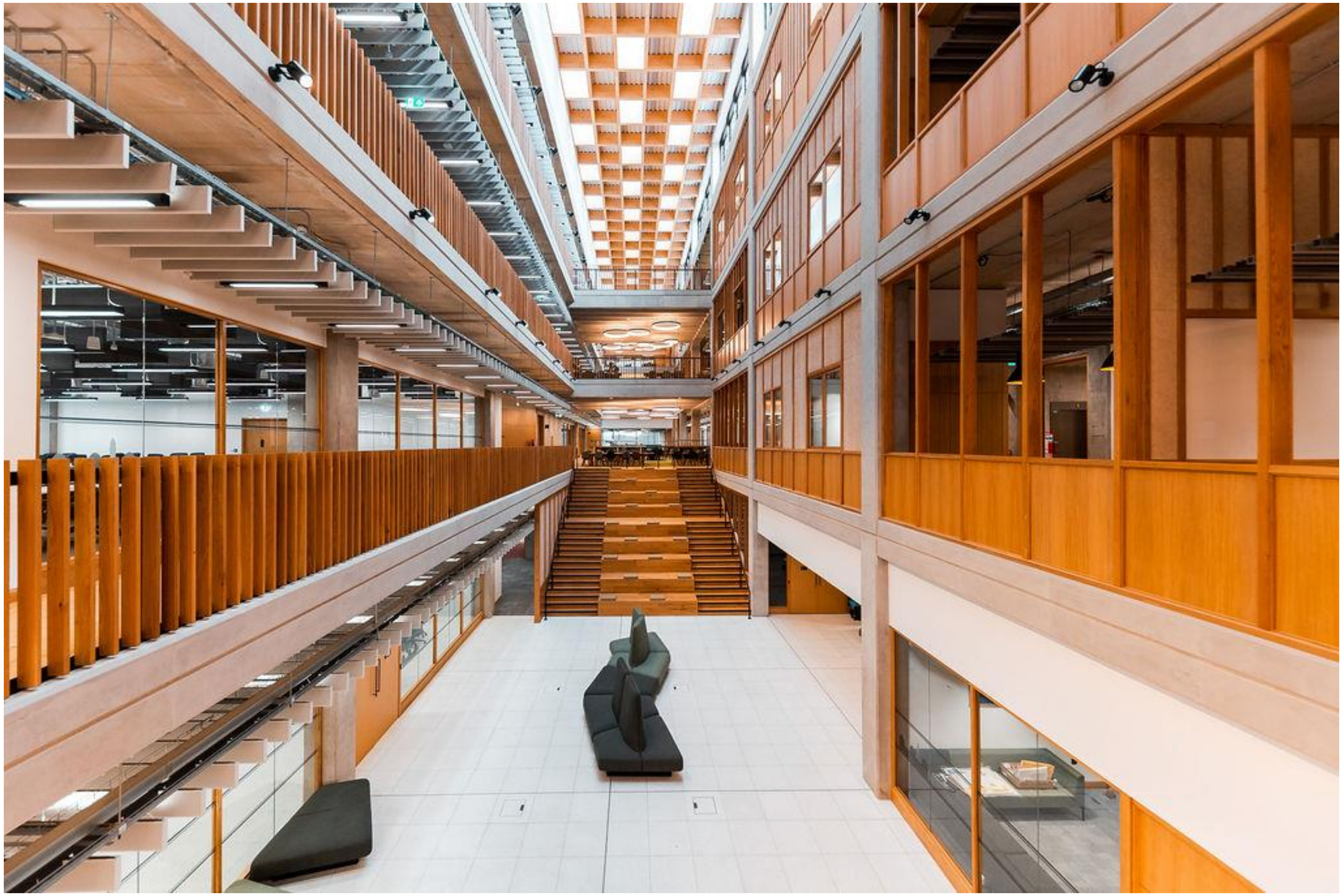
Thursday 5th Oct 2023

Founded 1900, 10 Nobel Prize Winners of our alumni and staff

Premiere Centre for Science & Engineering

Two Prime Ministers

School of Engineering,
College of Engineering and Physical Sciences



Where is Birmingham?

- **Midland of England**
- **High Speed Railways Centre**
- **Energy Centre (Energy Capital)/Energy Valley**
- **Manufacturing Centre**
- **1st Industrial Revolution: Watt's factory for steam engines**

Introduction

- **Engineering Programme: Top 10 (2021 REF)**
- **Birmingham Energy Institute: Smart Grid**, Energy Storage, Hydrogen, Railways, Energy Material, etc
- **Smart Grid Research Focus: Digitalised Energy System** - making renewable energy integration more efficient, reliable and flexible
- **Electrical Power and Control Systems Group: 7** staff + **20** PhD students
- **Two MSc Programmes in Electrical Power Systems:** a cohort of **100+** students annually
  - – one-year taught MSc programme
  - – two-year mixed taught/research programme

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- Framework for Future Energy Interconnection
- Transforming LCC HVDC into Flexible LCC HVDC
- Major Technological Developments in Flexible LCC HVDC
- Economic Analysis of Flexible LCC-HVDC Systems
- Conclusions

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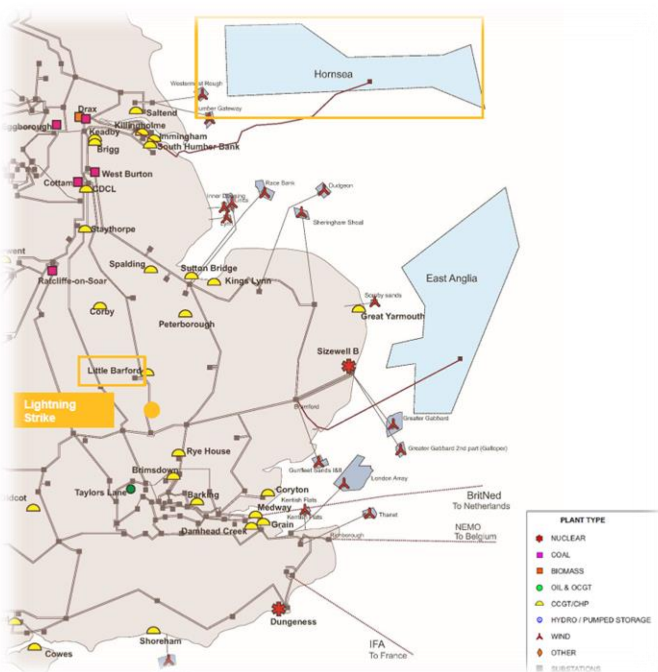
Grand Challenges and Solutions

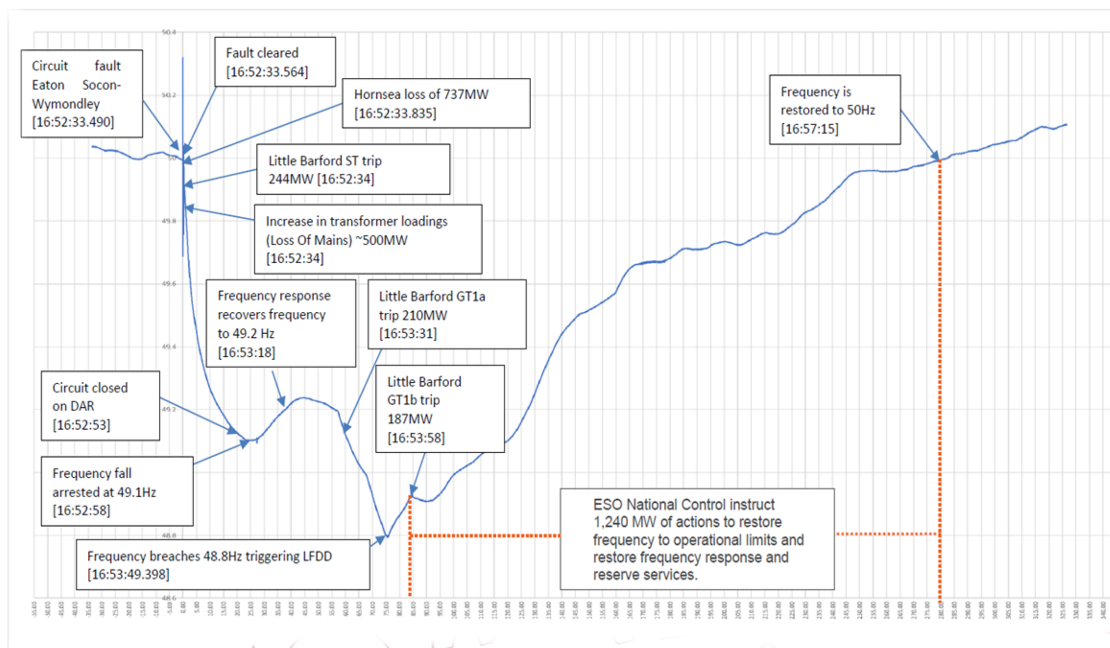
- **Increase in population by 25**% from 2010 to 2040 (6B -> 9B)
- Massive integration of renewable energy sources (wind, solar and wave) far away from load centres: **low inertia system = Gone with wind is happening**
- Massive integration of electric vehicles : **very soon gone with EVs**
- Distributed generation/micro-grid/demand response: **Big hope is that demand would follow generation**
- Systematic grid interconnections between existing power grids: **bring benefits and trade opportunities**
- Complex coupling between electricity, transport, gas & heat
- The key is to bring flexibility to source, grid and load:
  - System interconnection: HVDC, FACTS, and other emerging technologies
  - Energy storage
  - Data analytics and Artificial Intelligence

Challenge of Low Inertia Power Systems

□ Blackout in Great Britain Power Grid on August 9th, 2019

- At 16:52 a series of events happened on the electricity system, resulting in the disconnection of approximately 1 million customers, 1GW loss of load.
- Revealing the problems of poor performance of offshore wind power, inappropriate protection setting of distributed PV, system risks because of reduced inertia.





Challenge of Energy Market Balancing and Costs

Coinciding with the reduced demand due to the COVID-19 pandemic and high level of renewables output,

the GB electricity system has seen a balancing cost of £718 million this spring and summer 2020, which is 39% higher than the expected cost in this period.

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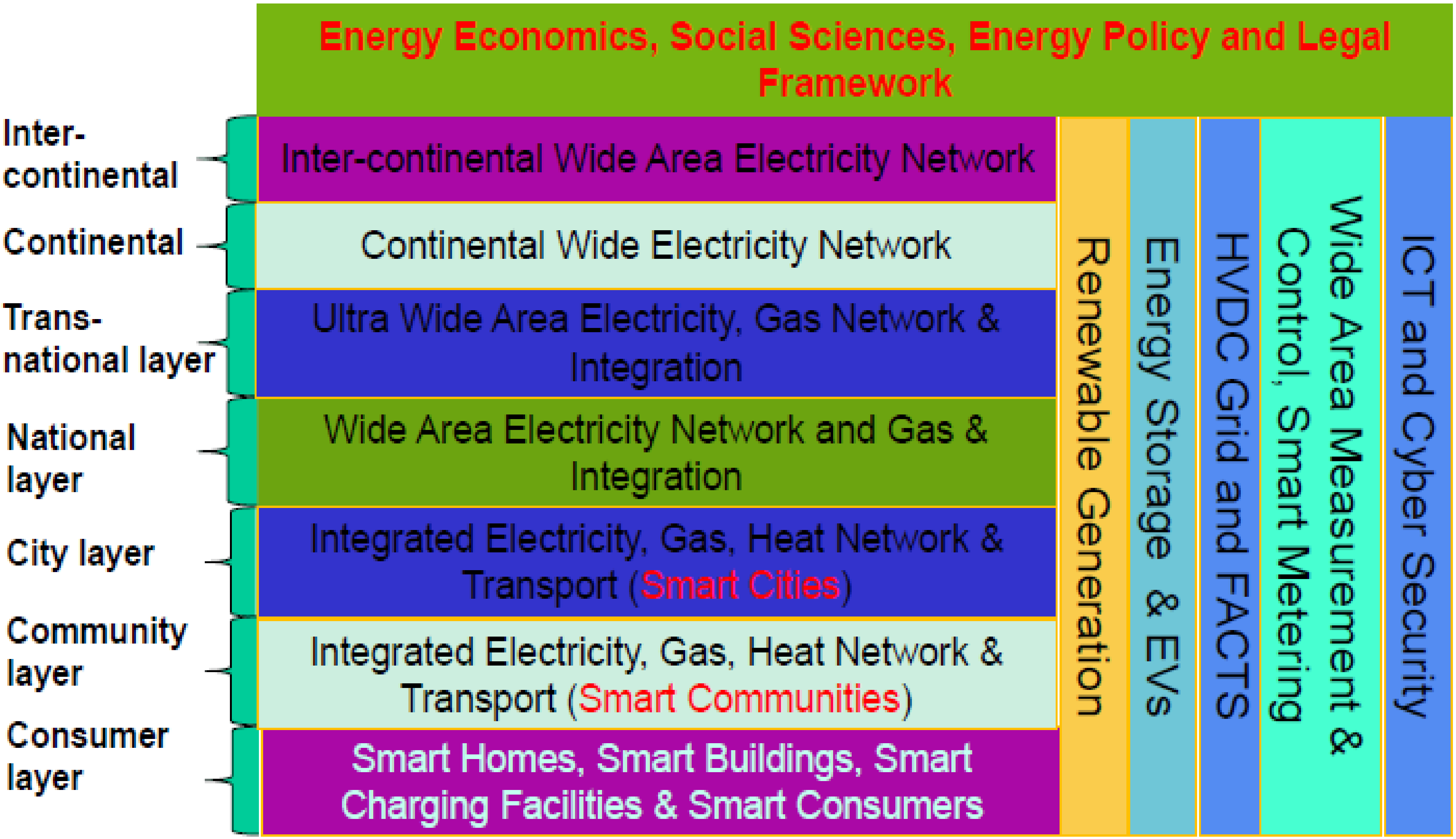
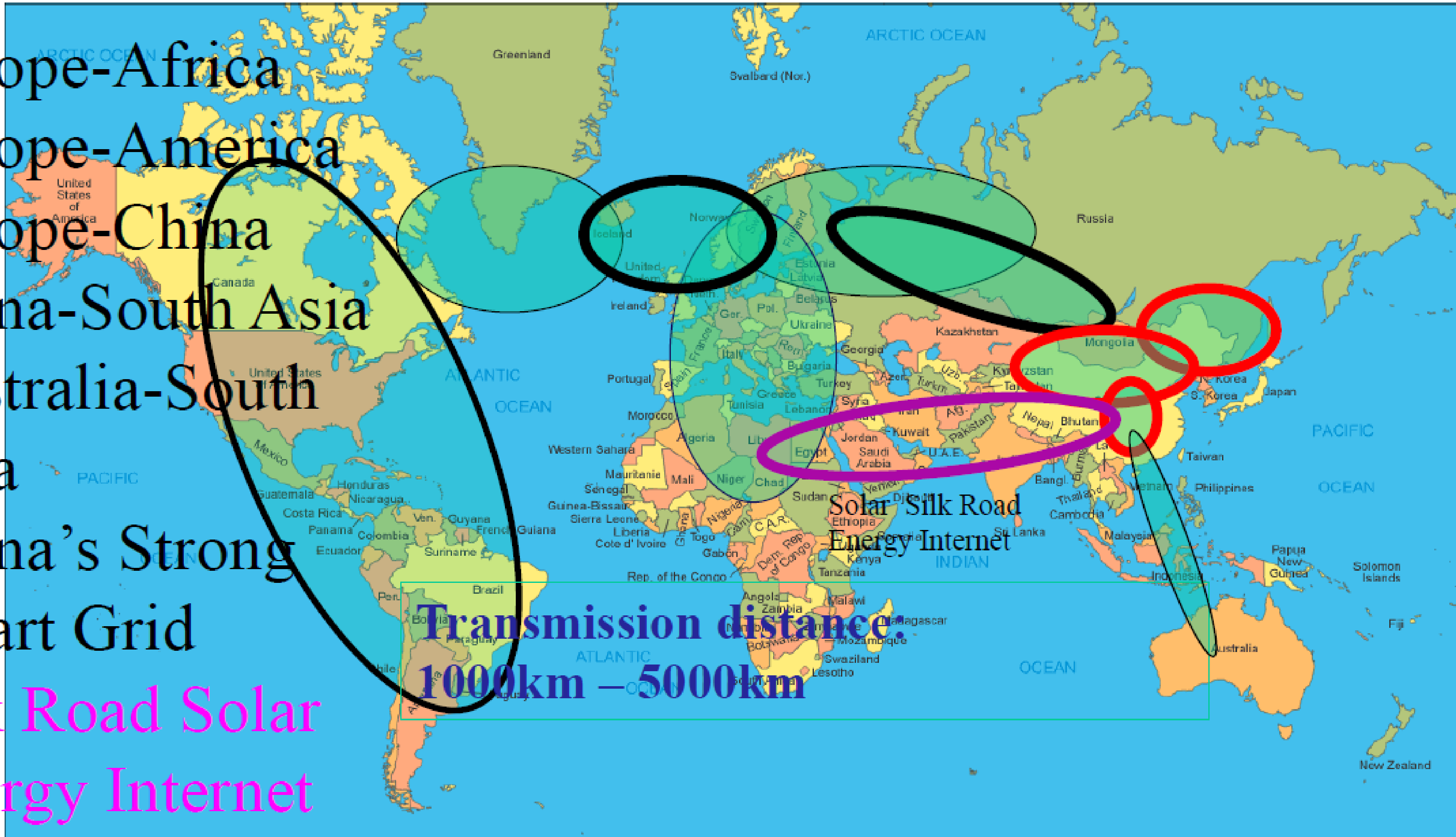
Framework for Future Energy Interconnection

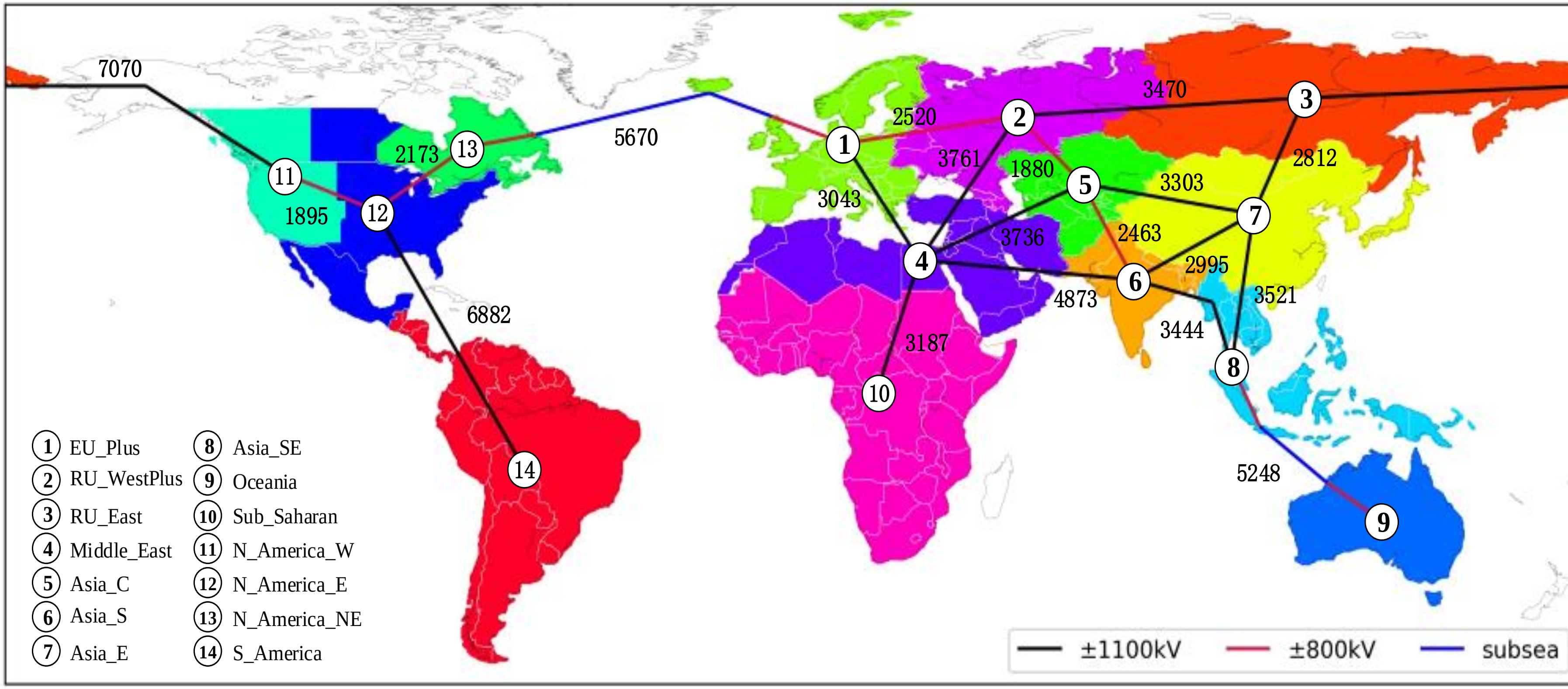


Framework for Future Energy Integration: Energy Internet/Interconnection

Europe-Africa
Europe-America
Europe-China
China-South Asia
Australia-South Asia
China's Strong Smart Grid
Silk Road Solar Energy Internet



Framework for Future Energy Interconnection



Global 14 regions and 20 potential interconnection routes

Global electricity grid with 100% renewable energy can bring 20% investment savings

Flexibility is critical for Energy Integration/Interconnection

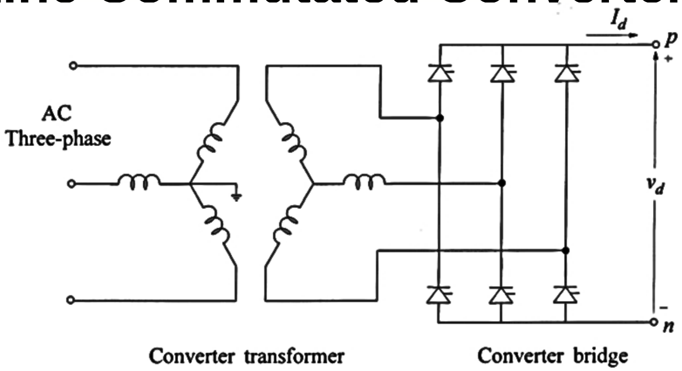
- ***The key is to bring flexibility to source, grid and load***
- **Flexible AC Transmission Systems**: Change impedance, control power flow/voltage/stability
- **High Voltage DC Transmission Systems**
  - *LCC HVDC (Thyristor)*
  - *VSC HVDC (IGBT)*
  - *LCC/VSC (Hybrid)*
- **Power Electronic Interface** for Renewable Generation/Energy Storage/Electrical Vehicles/Demand

Historic Development of HVDC

- 1920s: the mercury arc rectifier emerged
- 1954: the mercury arc valve technology used in a commercial **LCC HVDC** project, Gotland 1
- 1970: The thyristor valve first came into use in **LCC HVDC** applications and from that time forward the limitations of LCC HVDC were largely eliminated
- 1997: **VSC HVDC** (using IGBT), known as HVDC Light, introduced by ABB, with transmission not more than 50 MW, very high power loss
- 2010: 1st ±800kV, 6.4 GW **LCC UHVDC** commissioned by State Grid Corporation of China, > 2000 km
- 2010: Trans Bay Cable project was the first HVDC system to use the **Modular Multi-Level Converter (MMC) HVDC** system. 53 mi (85 km) cable, 400MW, DC voltage of ±200 Kv
- 2020: Multiterminal ±500kV MMC HVDC Grid with DC Circuit Breakers

LCC HVDC vs VSC HVDC

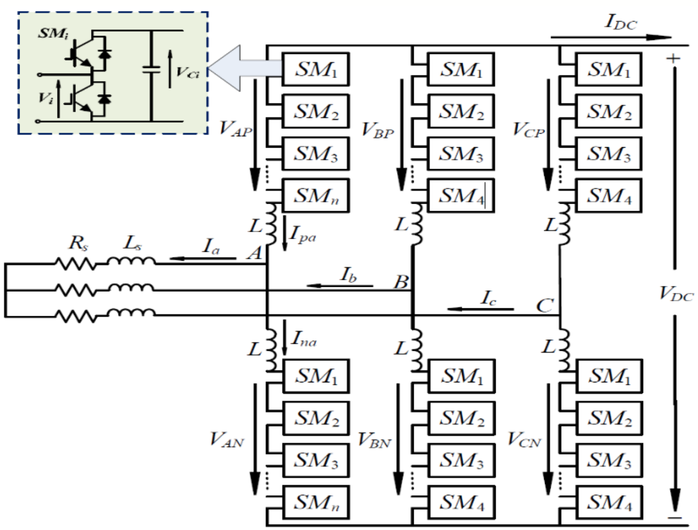
- **Line Commutated Converter (Thyristor Valve)** ➡ **LCC HVDC**

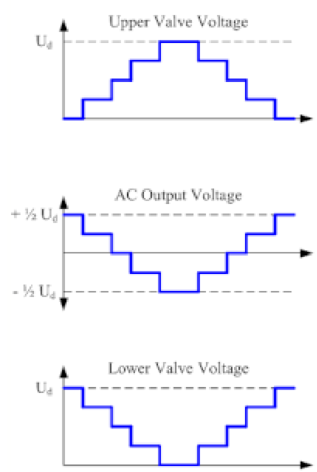


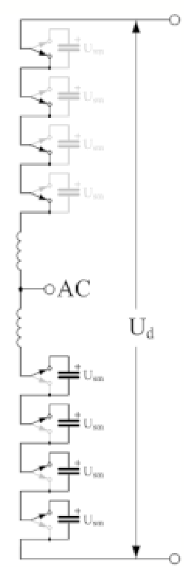
±1100kV, 12GW

"Train"

- **Voltage Sourced Converter (IGBT Valve)** ➡ **VSC HVDC**







±500, 2 - 3GW

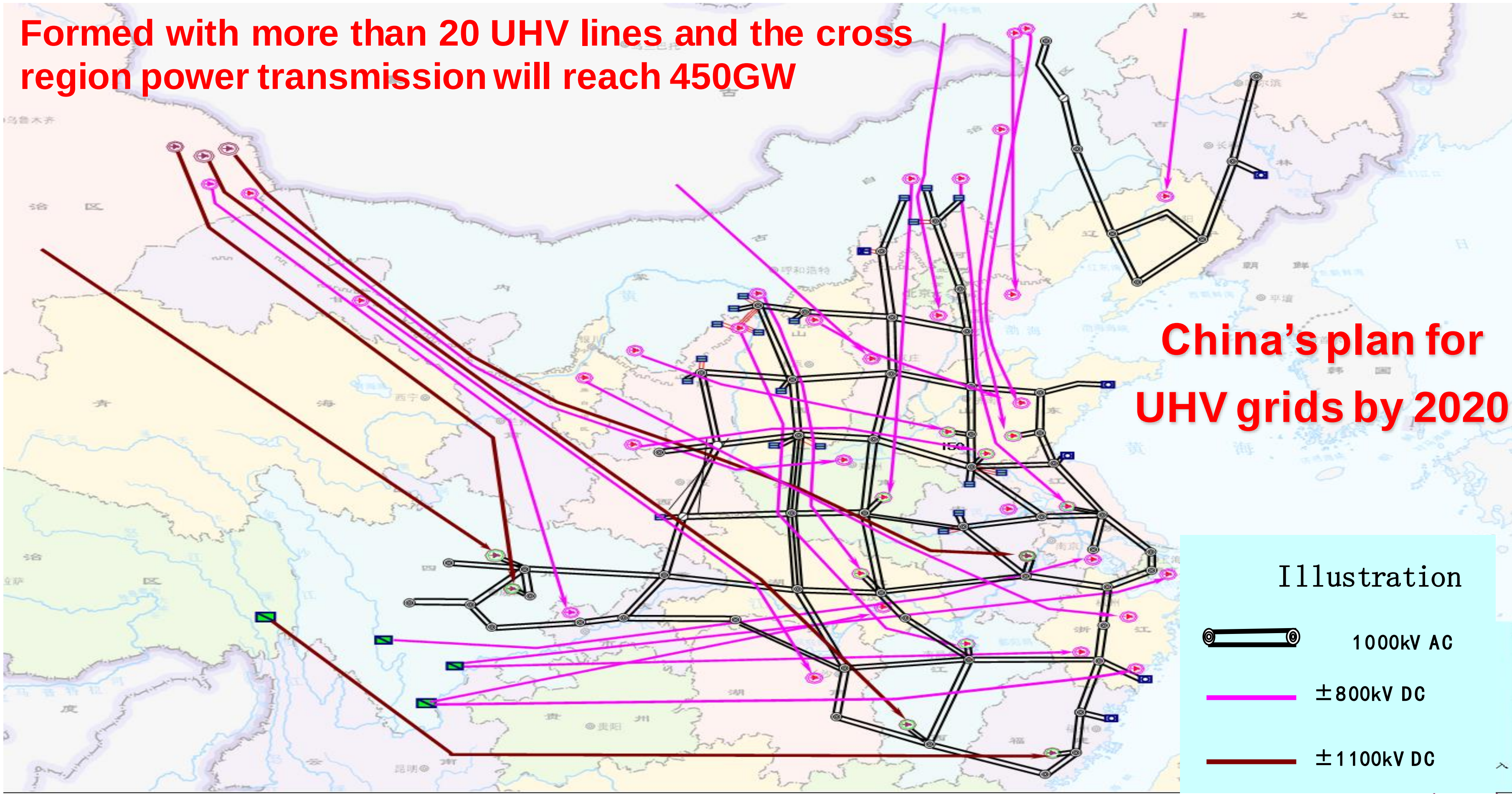
"Bus"

Comparison of DC and AC Transmission

TYPE	VOLTAGE LEVEL	TRANSMISSION DISTANCE	ECONOMIC CAPACITY
AC	500kV	300~500km	1GW
AC	1000kV	1000~2000km	5GW
DC	±500kV	500~1500km	3GW
DC	±800kV	1000~2000km	8GW
DC	±1100kV	1500~3000km	12GW

Long distance bulk power transmission in favor of DC transmission

HVDC/UHVDC Projects in China



UHVDC in China: ±800 kV, 5GW Converter Station

VSC/MMC HVDC Projects in China

Project	Time in operation	Basic profile
Nanhui HVDC project (SGCC)	2011.07	• MMC • Transmission capacity: **20MW** • DC voltage: **±30kV** • DC cable length: **8.6km**
Nanao 3-terminal HVDC project (CSG)	2013.12	• MMC • Transmission capacity: **200MW** • DC voltage: **±160kV**
Zhoushan 5-terminal HVDC project (SGCC)	2014.07	• MMC • Longest distance: **40km** • DC voltage: **±200kV**
Xiamen HVDC project (SGCC)	2015.12	• MMC • Distance: **10.7km** • Transmission capacity: **1000MW** • DC voltage: **±320kV**
Zhangbei 4-terminal MMC HVDC Grid project with DC Circuit Breakers (SGCC)	2020.06	• MMC • Longest distance: **648 km** • Transmission capacity: **4500MW** • DC voltage: **±500kV**

There are demonstration projects in MV and LV DC applications globally

HVDC Interconnectors in EU

UK's HVDC Interconnectors

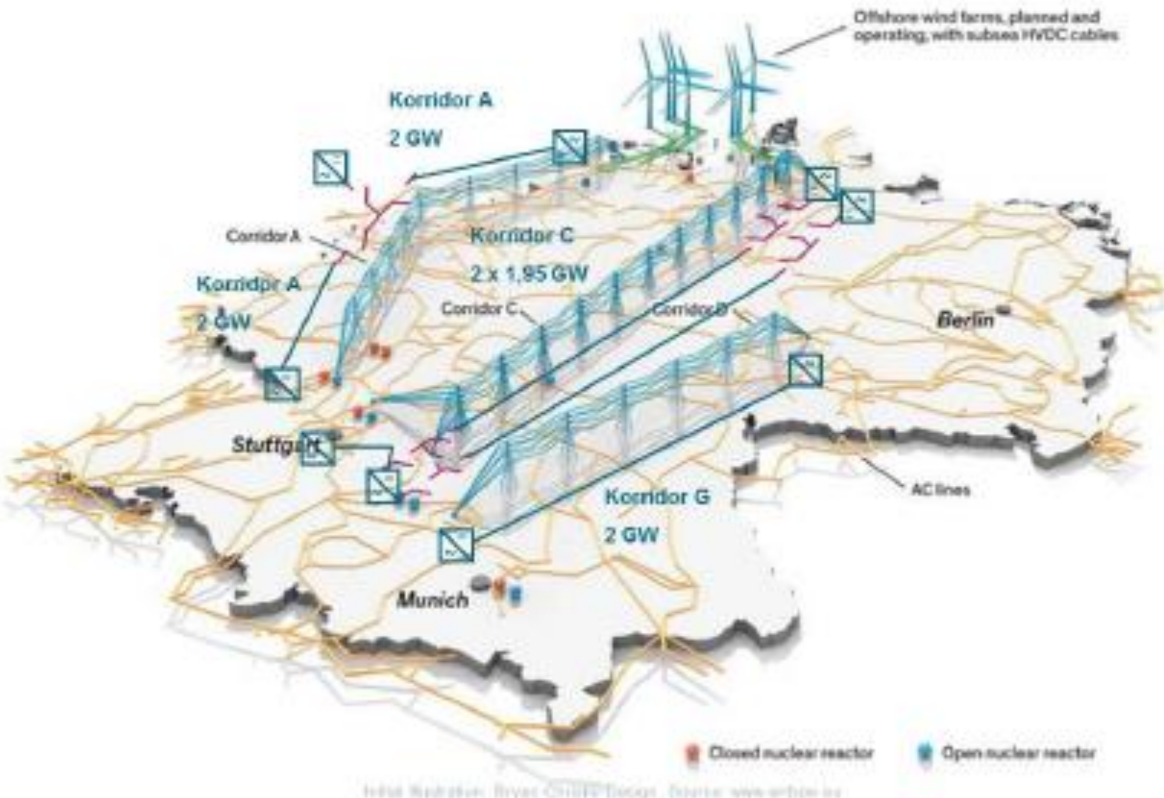
- Operational: 8GW, 7 projects
- Construction: 4.8GW, 4 projects
- Planning: 23.7GW, 18 projects

UK’s HVDC Interconnectors

- The UK government plans to develop 40 GW of offshore wind capacity by 2030, whilst the Dutch are targeting 11.5 GW by 2030 and another increase of 20-40 GW by 2050

- Multi-Purpose Interconnectors have the potential to act as a key enabler for new offshore wind projects

HVDC Corridors in Germany



Potential HVDC Grid

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Classic LCC (Line Commutated Converter) HVDC vs MMC VSC (Voltage Sourced Converter) HVDC

Main advantages

- Lower power loss
- High power
- Manageable DC fault current
- Mature technology
- Lower costs

Main Disadvantages

- Vulnerable to AC faults
- Commutation failure at inverter side
- Large Q consumption of converter stations
- Inability of fast dynamic reactive power and AC voltage control
- Bigger footprint

Consequences of Commutation Failure

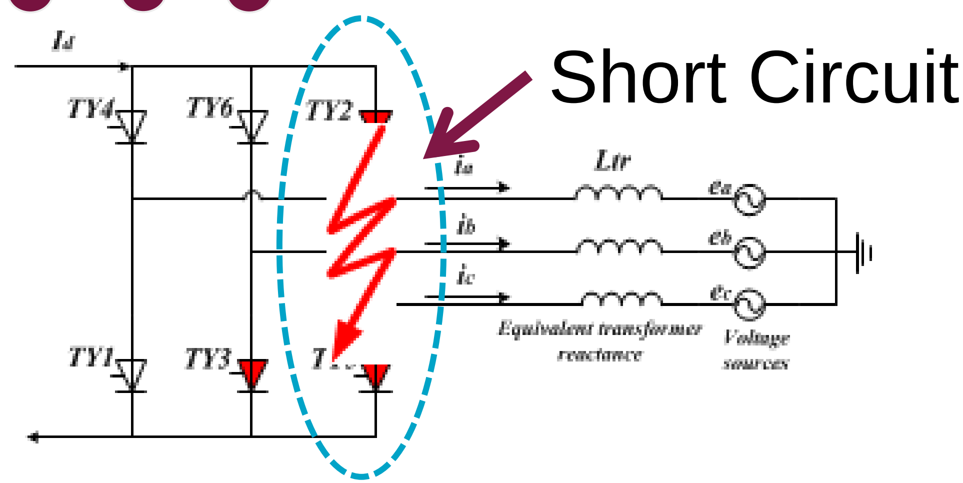
Disruption of P transfer (up to tens of GW)

Frequency **increase** at sending end

Generator **tripping**

Frequency **drop** at receiving end

Activation of spinning reserve



Existing Solutions to Commutation Failure

- Existing solutions only focused on reducing commutation failure probability
- No solution is able to eliminate commutation failure
- Existing solutions into 3 categories
  - Capacitor-commutated converter (CCC) based HVDC
  - Reducing DC current
  - Installation of additional reactive power compensation devices (SVC, STATCOM, Synchronous Condenser)

Transforming Classic LCC HVDC into Flexible LCC HVDC

Main advantages

- Lower power loss
- Higher/moderate power
- Not vulnerable to DC fault current
- Smaller footprint
- Lower costs
- Not vulnerable to AC faults
- No commutation failure at inverter side
- Provide Q control of converter stations
- Provide fast dynamic reactive power and AC voltage control

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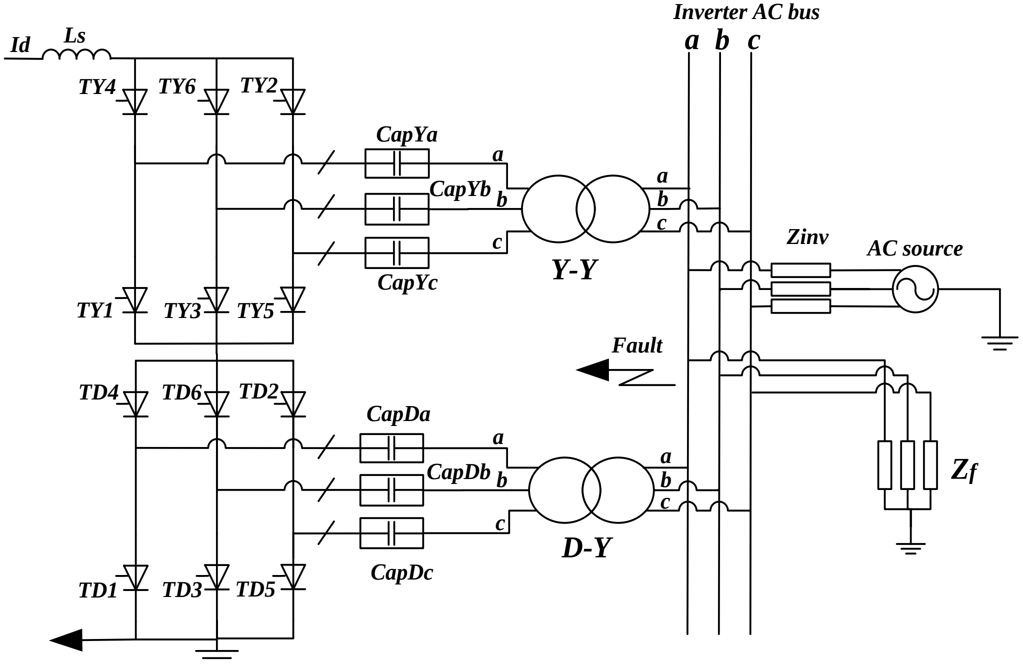
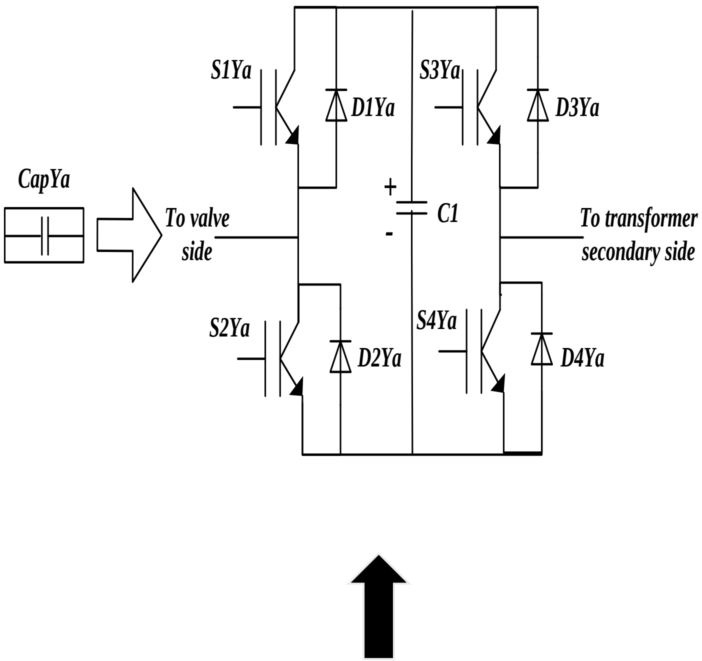
Major Technological Developments in Flexible LCC HVDC

- **Basic Topology**: Elimination of Commutation Failure
- **Basic Topology**: Reactive Power and AC Voltage control
- **Enhanced Topology:** Elimination of AC Filters
- **Further Enhanced Topology:** Series Capacitor Compensation with reduced costs
- **Special Topology:** Application in UHVDC Systems

Basic Topology: Commutation Failure Elimination



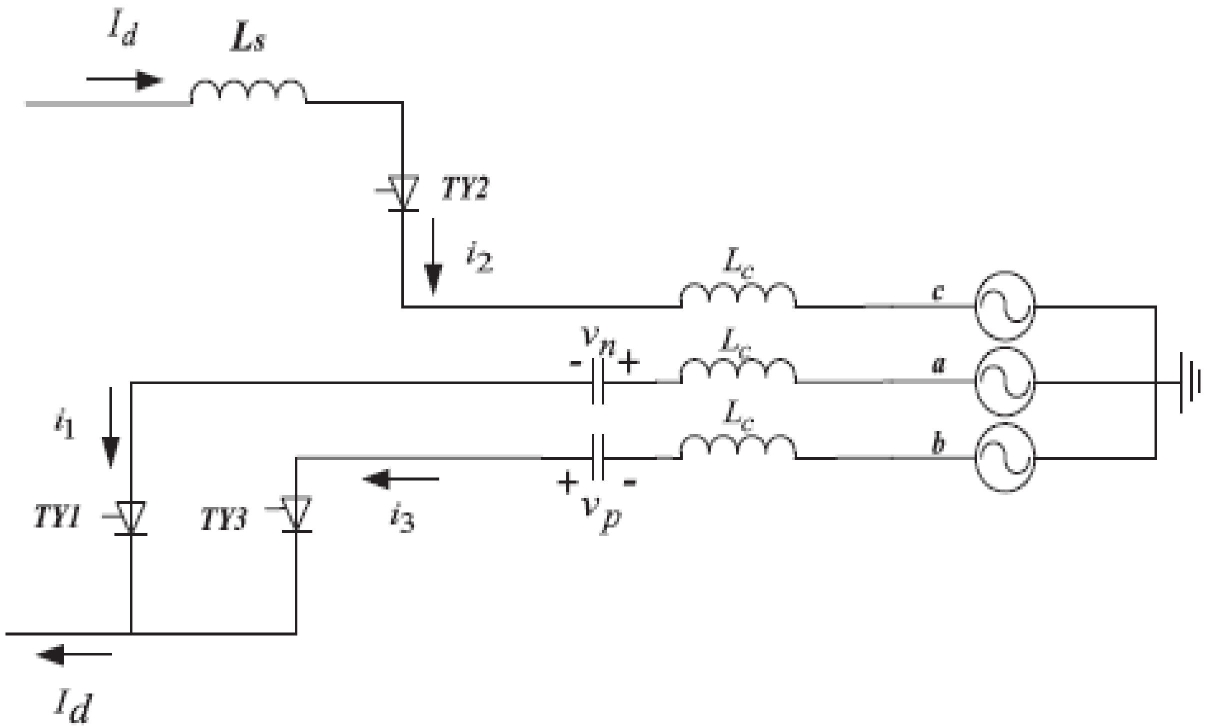


LCC HVDC with Controllable Capacitor

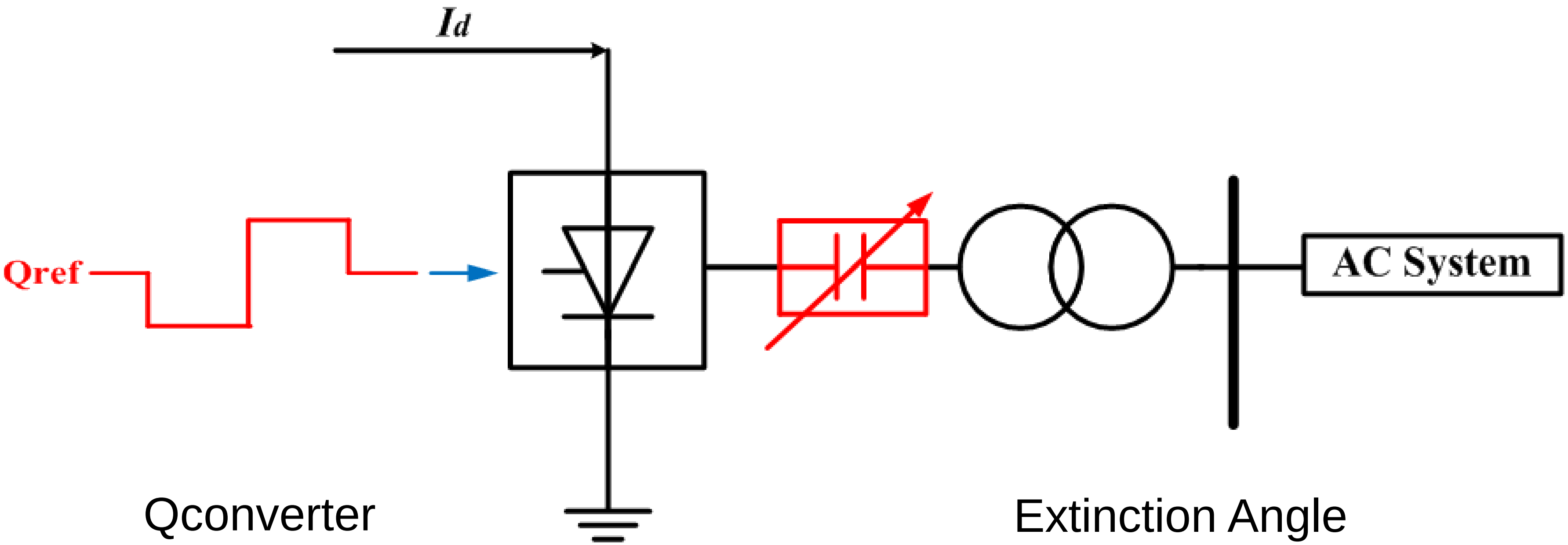
Controllable Capacitor module configuration

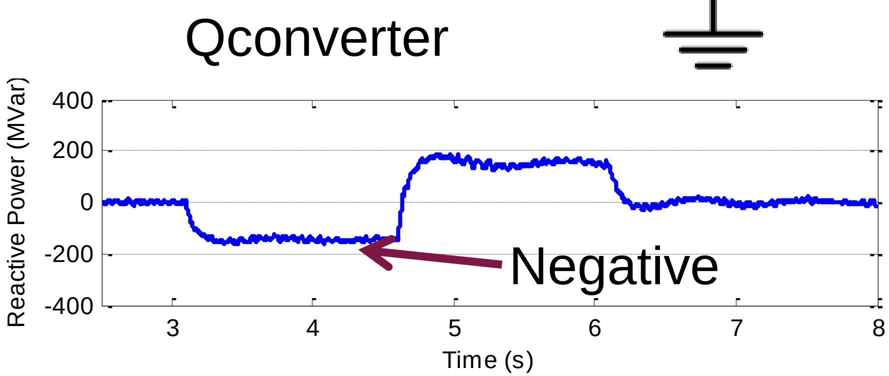
Basic Topology: Flexible LCC HVDC

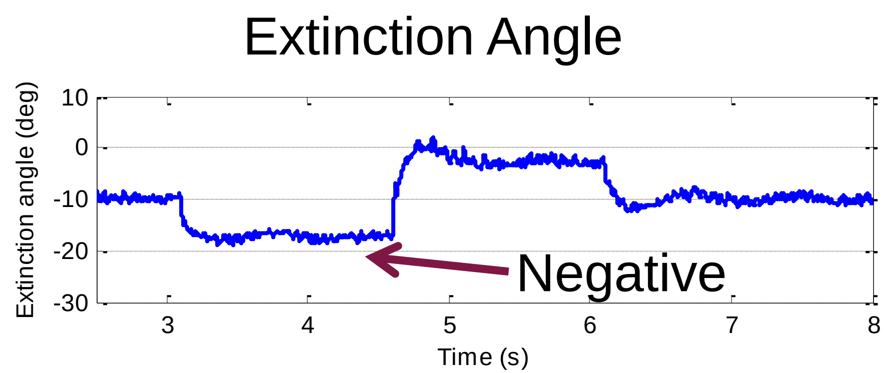
- **LCC HVDC + Controllable Capacitor**
- **Commutation from TY1 to TY3**
  - **with increased effective commutation voltage;**
  - **i_1 will reduce from I_d to zero;**
  - **i_3 will increase from zero to I_d;**



Basic Topology:
Reactive Power and Vac Control







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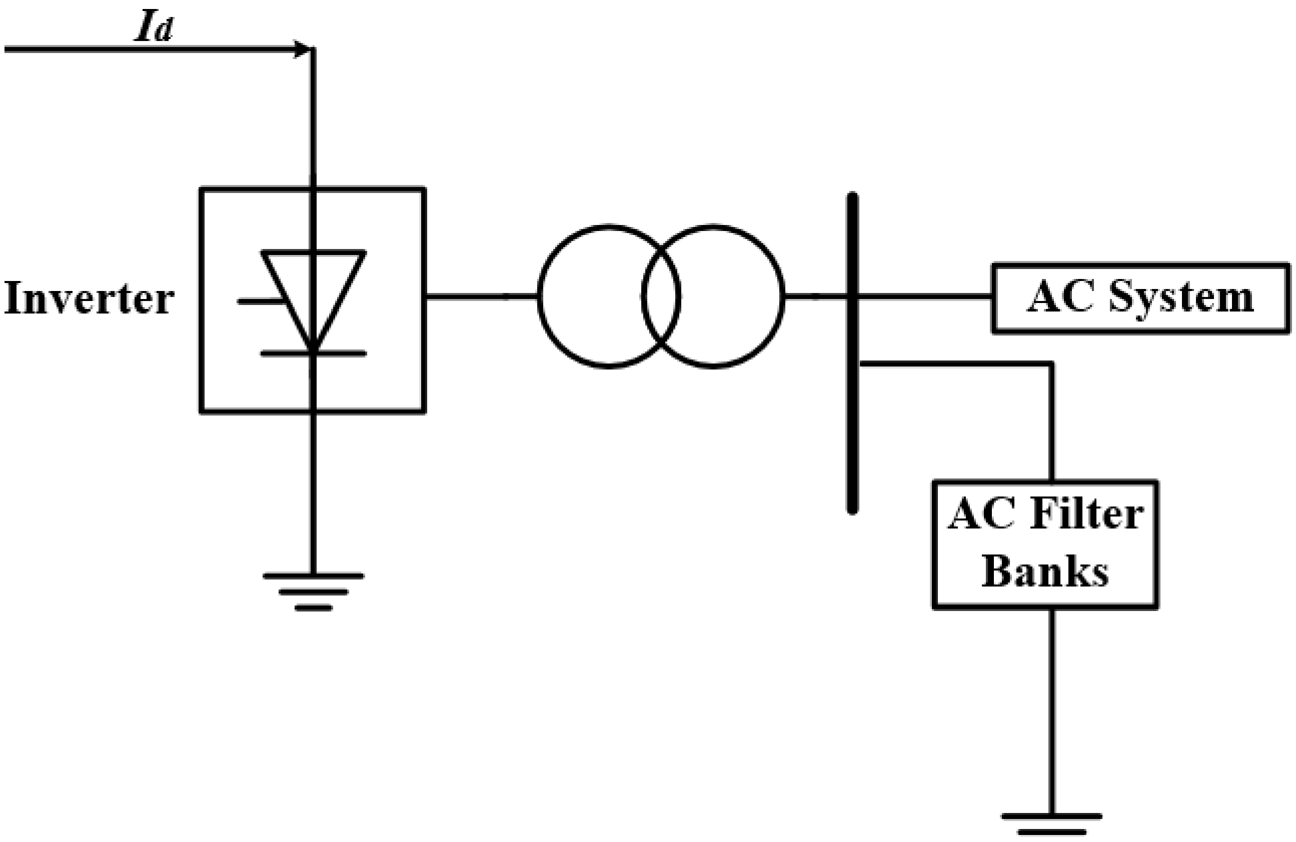
Y. Xue and X. P. Zhang, "Reactive Power and AC Voltage Control of LCC HVDC System With Controllable Capacitors," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 753-764, Jan. 2017.

Enhanced Topology:
Elimination of AC Filters (1 of 3)



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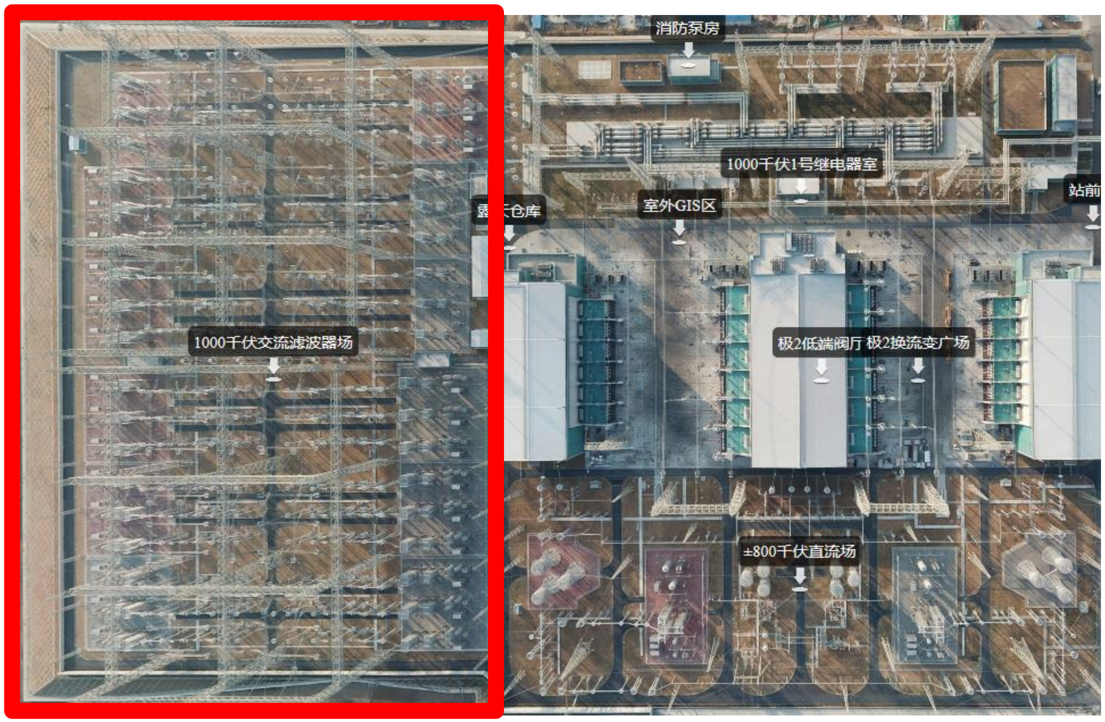
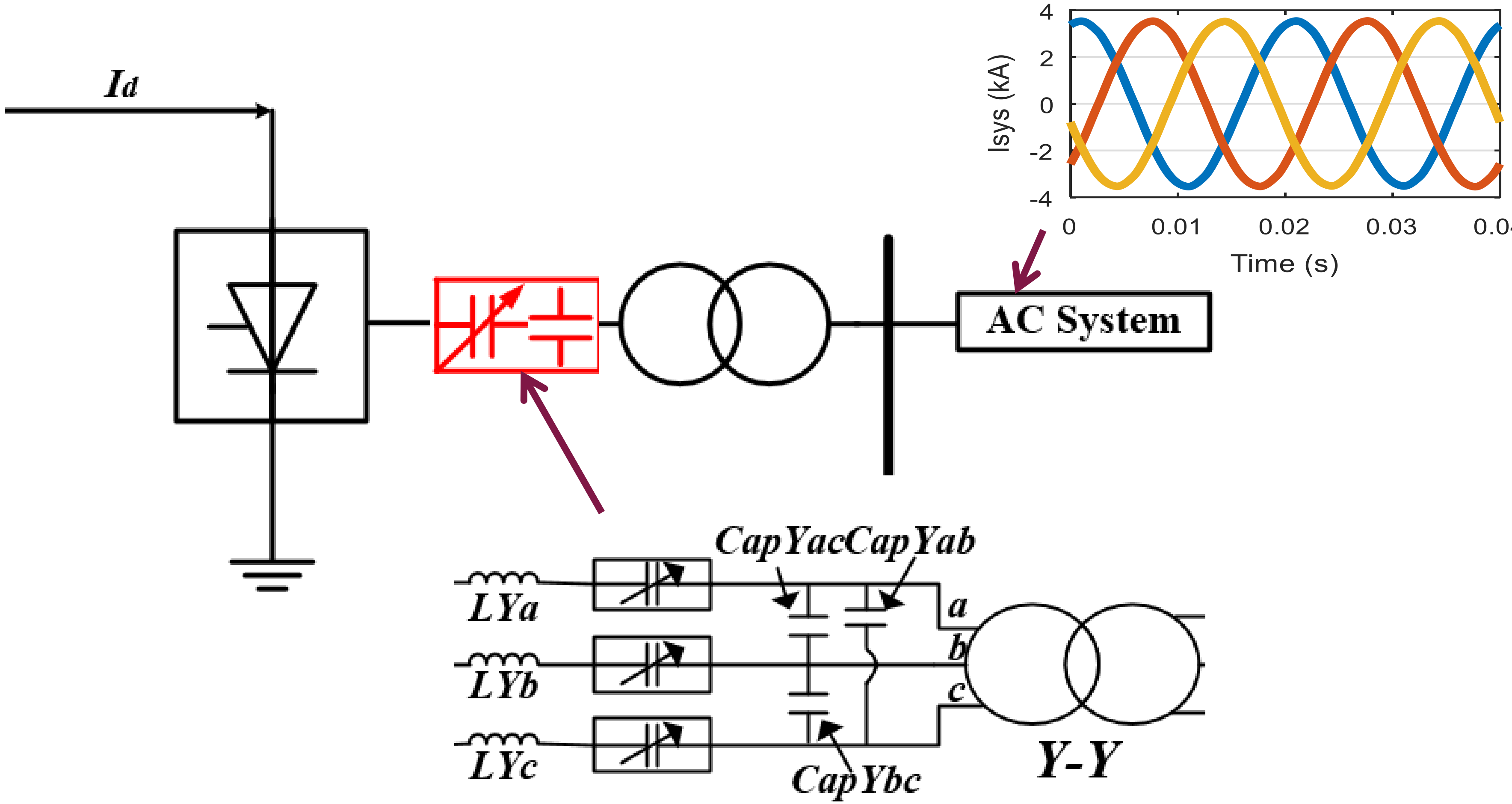
Y. Xue, X. P. Zhang and C. Yang, "AC Filterless Flexible LCC HVDC with Reduced Voltage Rating of Controllable Capacitors," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5507-5518, Sept. 2018, doi: 10.1109/TPWRS.2018.2800666.

Enhanced Topology:
Elimination of AC Filters (2 of 3)

- AC filters
  - Space (around 50% of the converter station footprint)
  - Costs (up to 10%)
  - Losses (9% per station)



Enhanced Topology:
Elimination of AC Filters (3 of 3)



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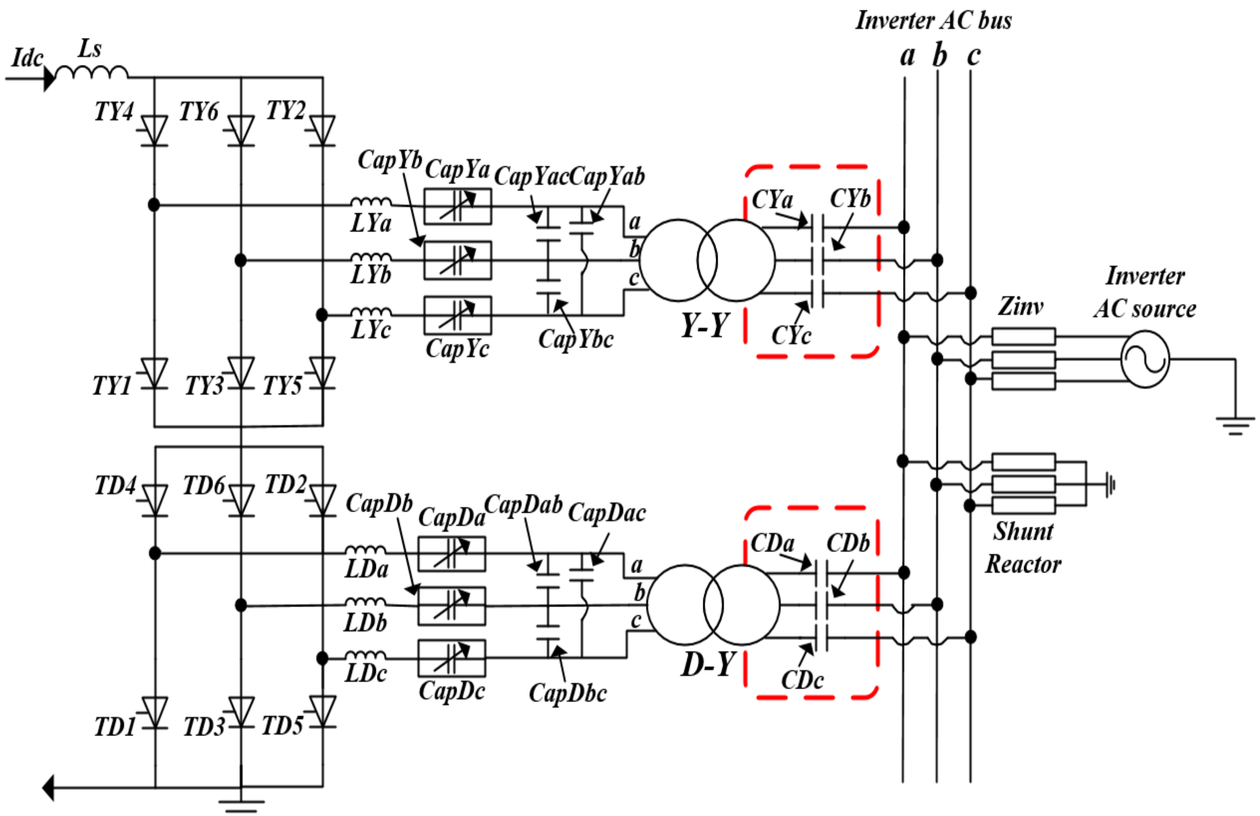
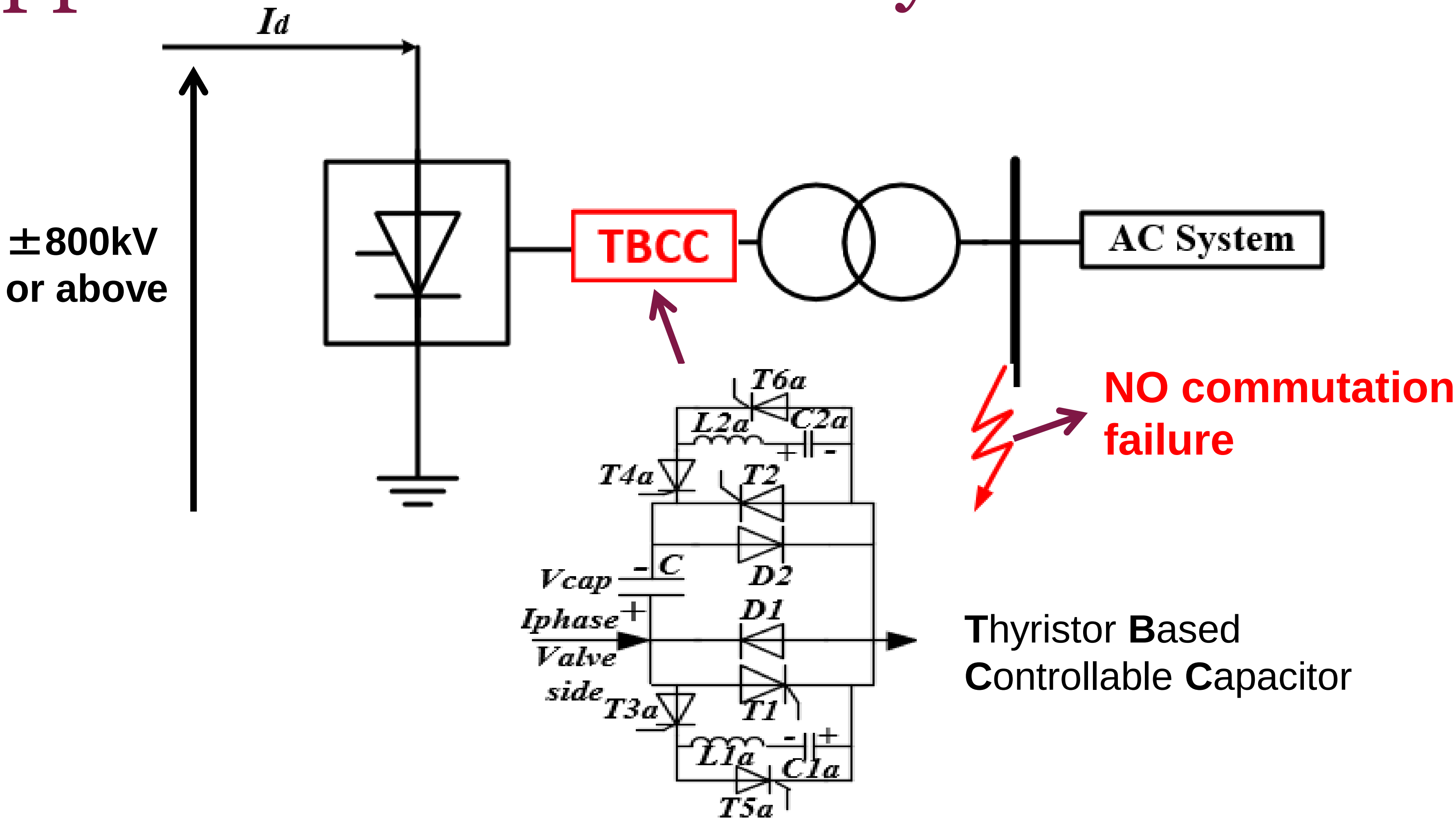
Further Enhanced Topology:
Series Capacitor Compensation with reduced costs



- **reduced equipment cost due to the reduced numbers of controllable capacitors**
- **reduced capitalized cost of losses due to the reduced numbers of controllable capacitors**

Y. Xue, X. Zhang and C. Yang, "Series Capacitor Compensated AC Filterless Flexible LCC HVDC With Enhanced Power Transfer Under Unbalanced Faults," *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 3069-3080, July 2019, doi: 10.1109/TPWRS.2019.2899065.

Special Topology:
Application in UHVDC Systems



Thyristor **B**ased **C**ontrollable **C**apacitor

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Y. Xue, X. P. Zhang and C. Yang, "Commutation Failure Elimination of LCC HVDC Systems using Thyristor-Based Controllable Capacitors," *IEEE Transactions on Power Delivery*, vol. 33, no. 3, pp. 1448-1458, June 2018, doi: 10.1109/TPWRD.2017.2776867

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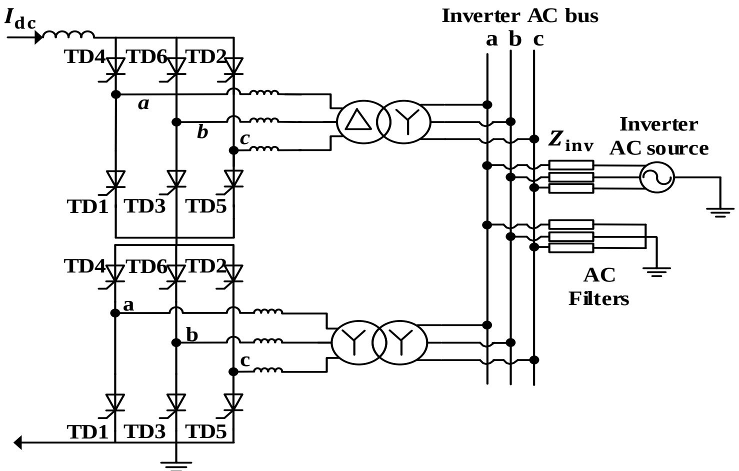
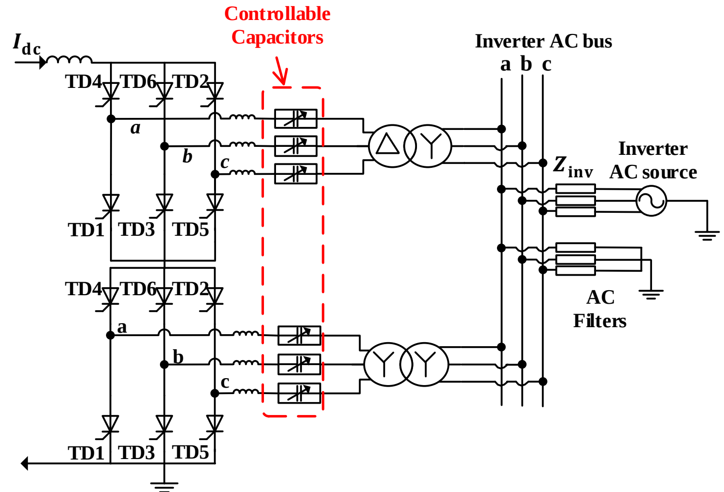
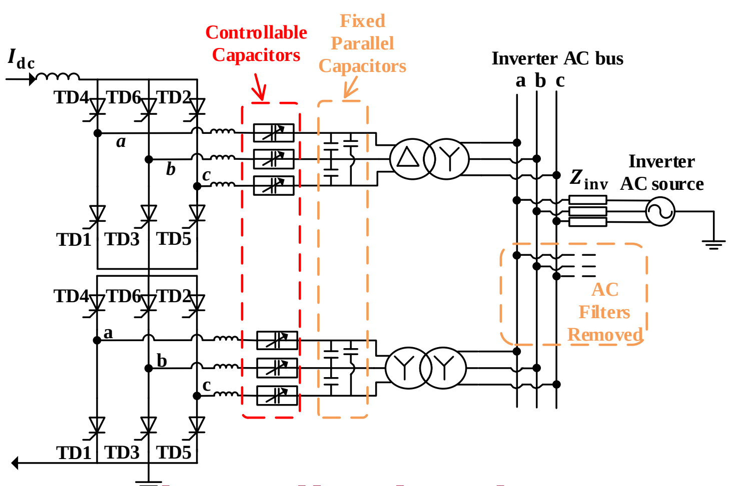
LCC HVDC & 3 Flexible LCC HVDC



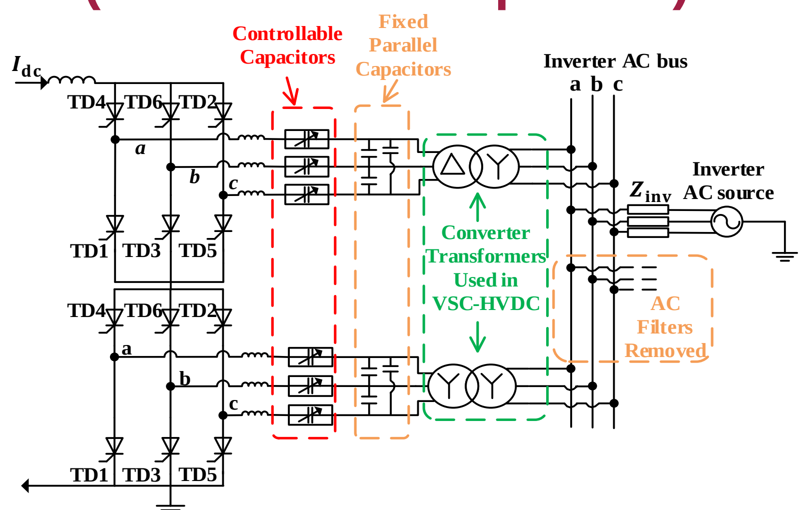
Classic LCC



CC (Controllable Capacitor) LCC



ACFL(AC Filterless)-CC LCC



Improved ACFL-CC LCC

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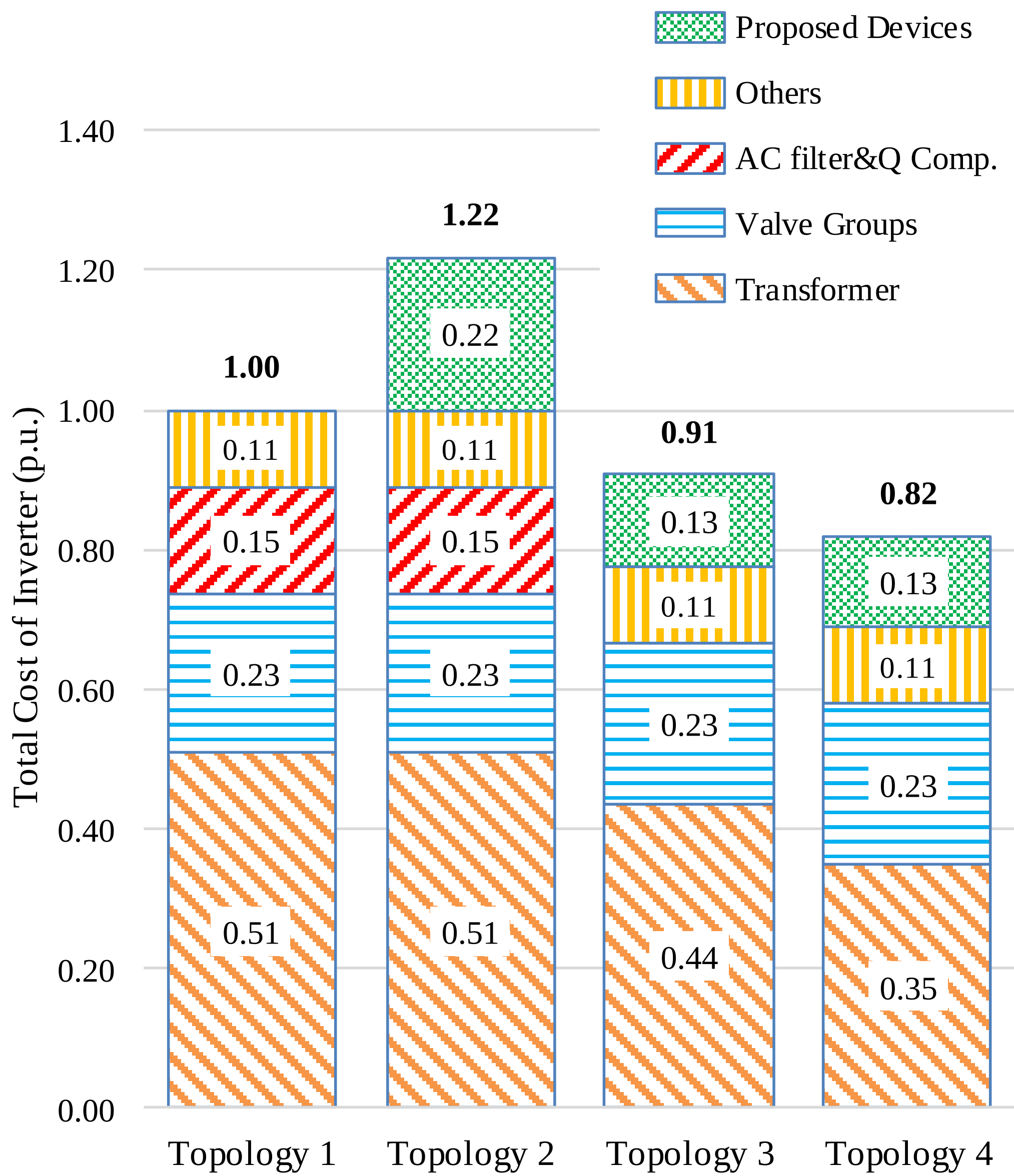
Comparison of Investment Costs



Topology 1:
Classic LCC

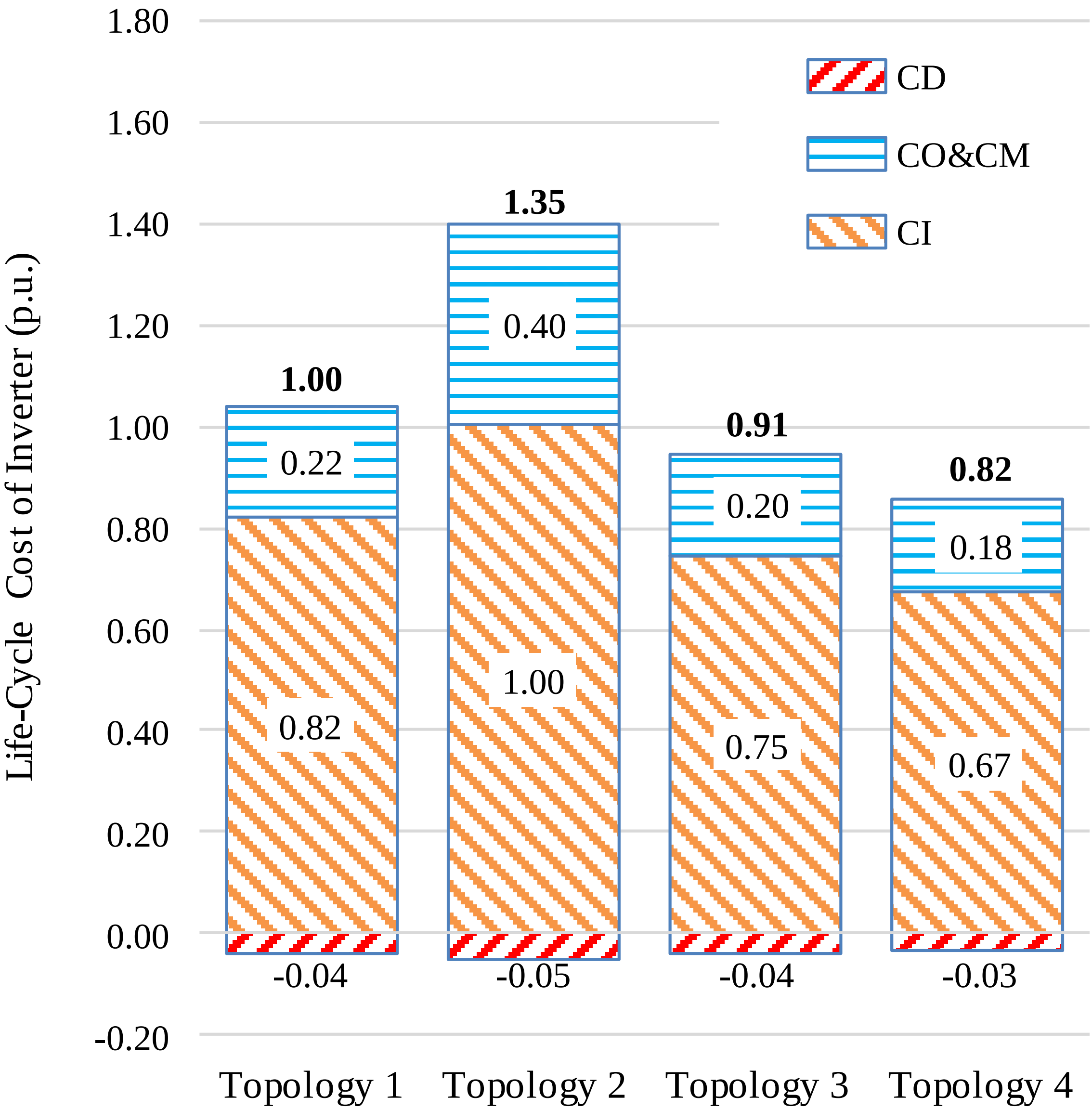
Topology 2:
CC LCC

Topology 3:
ACFL CC LCC

Topology 4:
Improved ACFL CC LCC

CI: investment cost;
CO: operating cost;
CM: maintenance cost;
CD: disposal cost.

Comparison of Life-cycle Costs



Topology 1:
Classic LCC

Topology 2:
CC LCC

Topology 3:
ACFL CC LCC

Topology 4:
Improved ACFL CC LCC

CI: investment cost;
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Conclusions

- **Flexible LCC HVDC** has overcome all the major disadvantages of LCC-HVDC, and can
  - Eliminate commutation failures of multi-infeed systems
  - Provide fast dynamic reactive power control (P, Q control)
  - Work with weak AC system
  - Reduce footprint by removing AC filters

Conclusions

- Commercially Flexible LCC HVDC as Next Generation LCC HVDC becomes attractive for upgrading existing LCC HVDC or new HVDC projects
  - Modular design
  - Easy implementation
  - Cost effective solution
- IGBT/IGCT can be used for the controllable capacitors
- Based on the economic analysis, Flexible LCC HVDC is a very efficient, reliable and flexible

Best Paper Award from the IEEE Transactions on Power Systems

Best Paper Award

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Nikos Hatziargyriou, Editor-in-Chief

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Much smaller, more reliable and cheaper

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