Development and Application of Controllable Line-Commutated-Converter （CLCC）

China Electric Power Research Institute (CEPRI)

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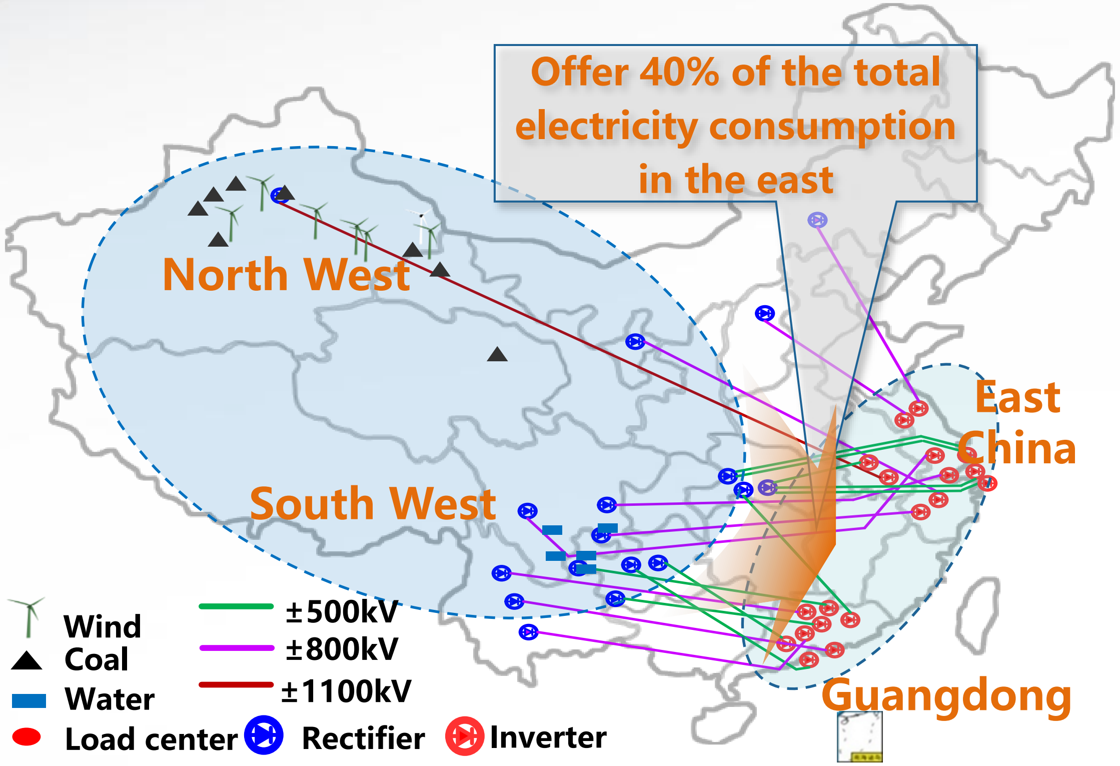
Contents

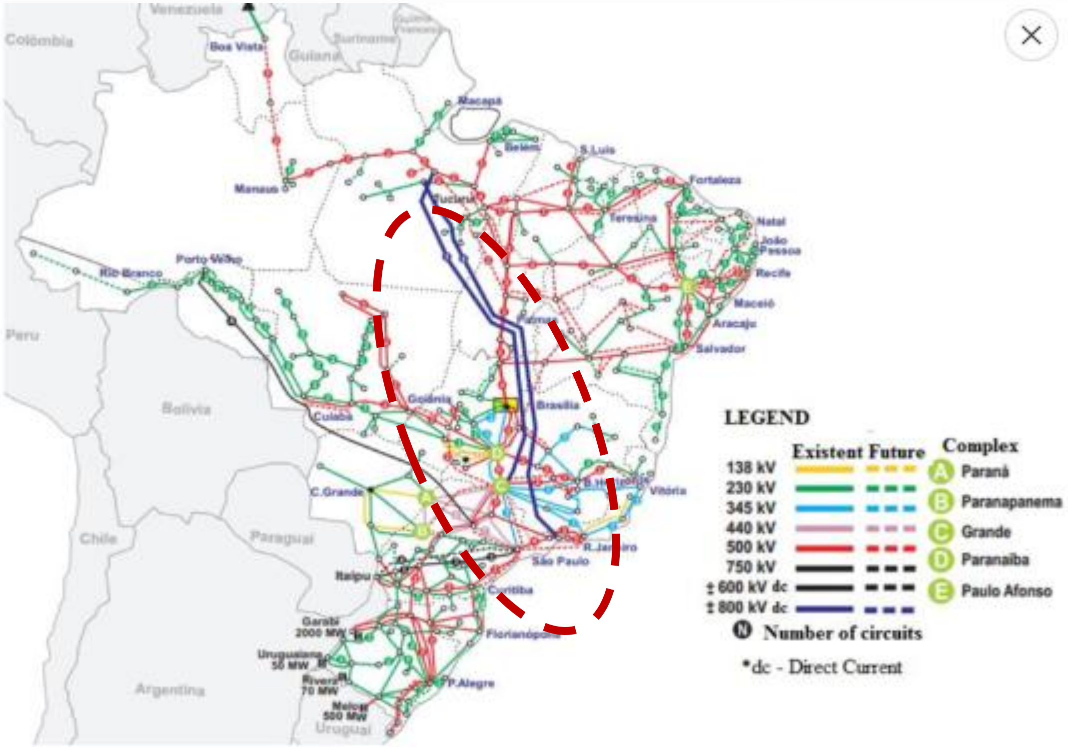
1. LCC-HVDC Technology

Advantages of LCC-HVDC

- Thyristor-based conventional LCC-HVDC technology has been widely used for bulk power transmissions due to its number of advantages, such as transmission with large capacity (5000MW and above), low cost (e.g. 40$/kW), low operating losses (less than 1%), high reliability, DC fault current extinguished capability and technical maturity.



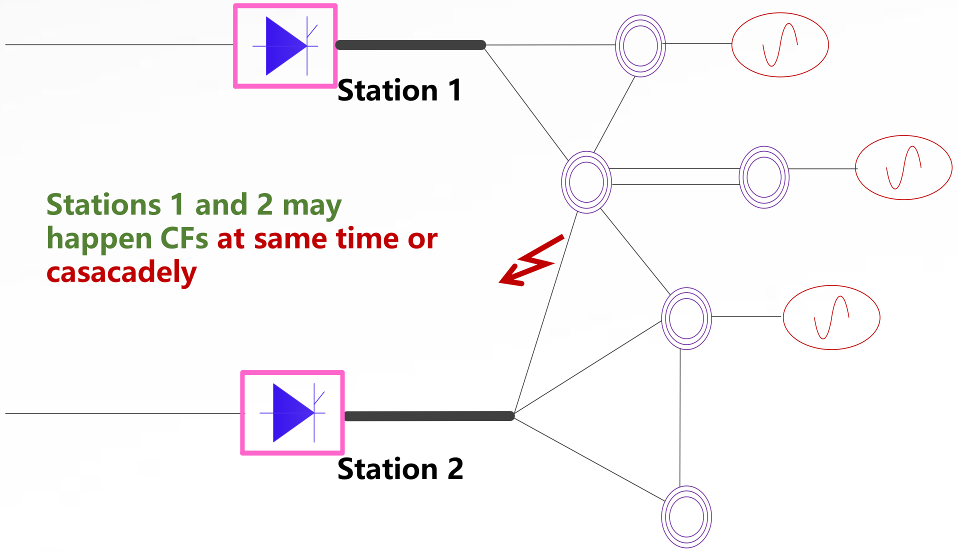
LCC HVDC projects in China



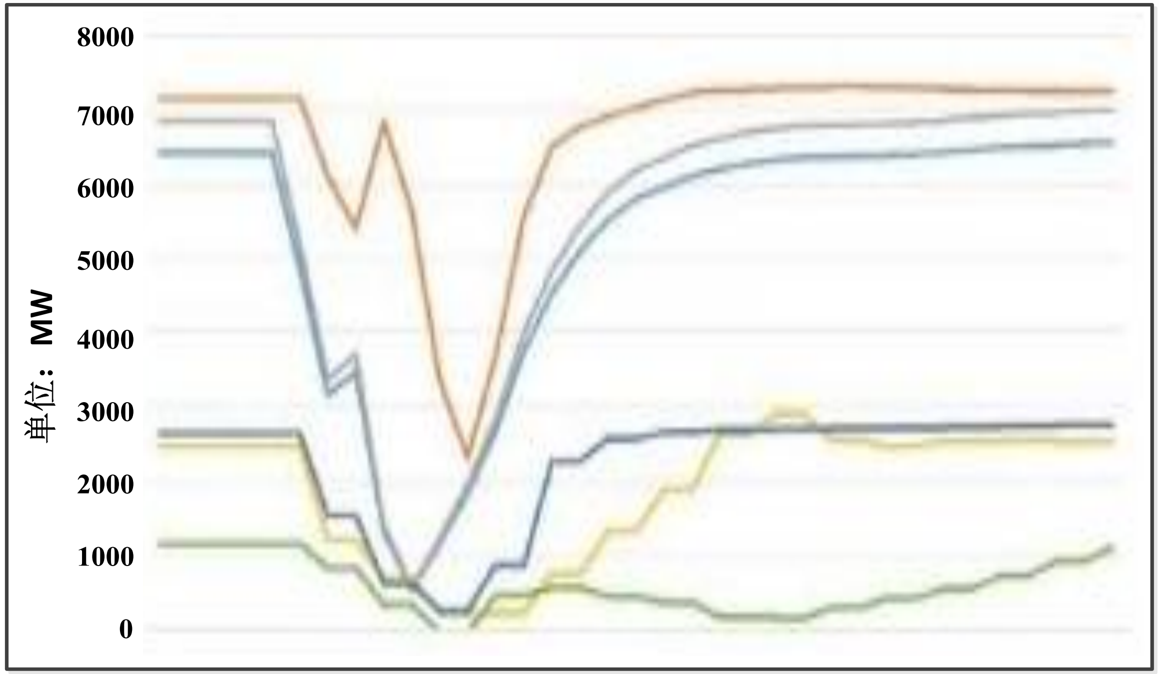
LCC HVDC projects in Brazil (to be confirmed)

Disadvantages of LCC-HVDC

- When a fault occurs on the AC system, it may cause the commutation fauilures (CFs) at Inverter station of LCC-HVDC projects.
- This may be a threat to the stability and safety of the power system.



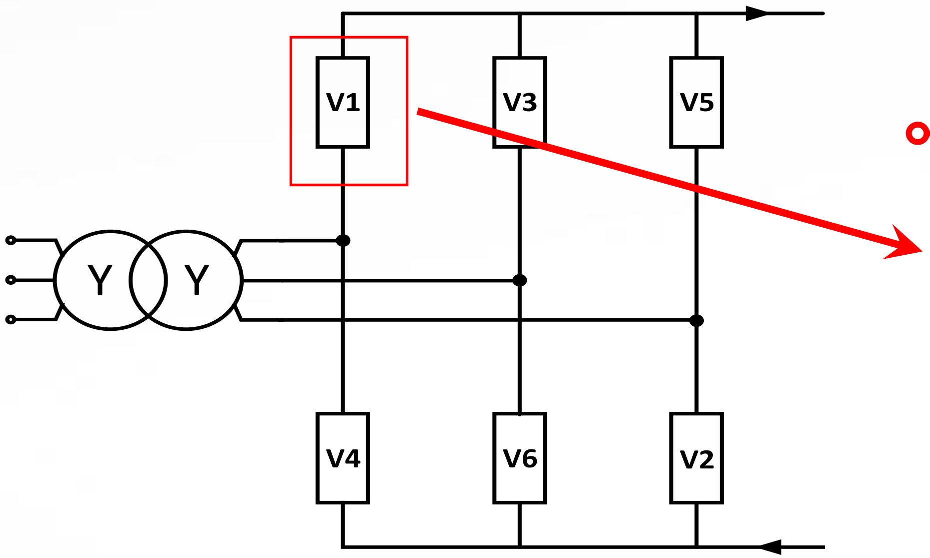
multi infeed HVDC sytem



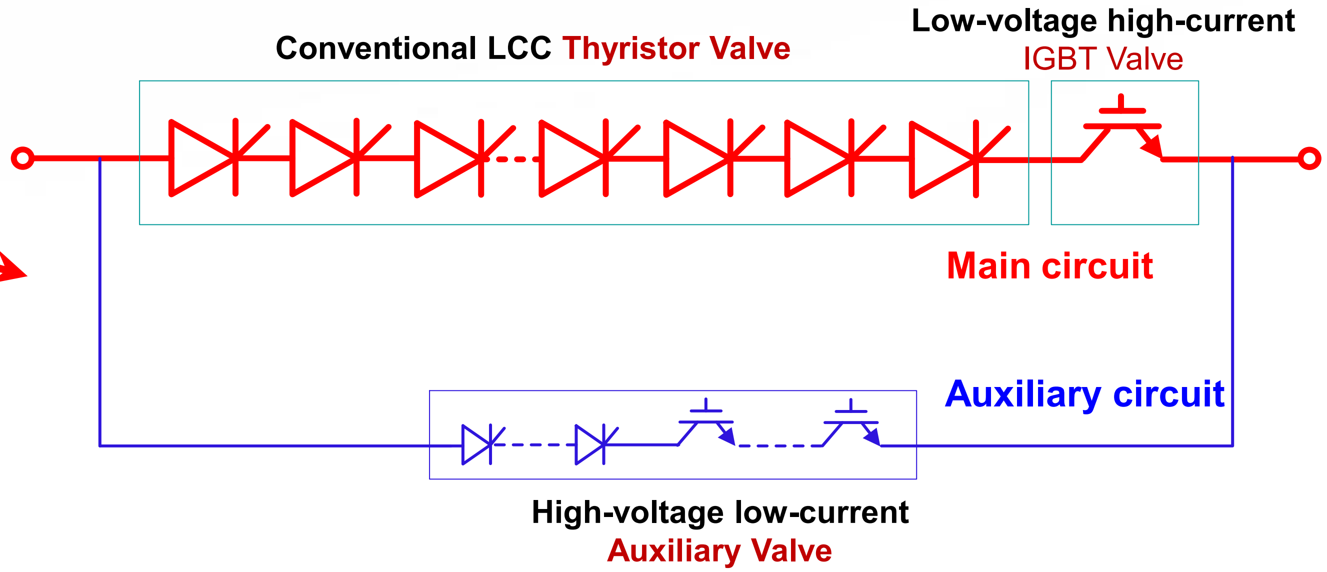
DC power changes in a multi-infeed HVDC system during CFs

Proposed a new type Converter - CLCC

- To solve the CF problem of the LCC, a new type of converter: Controllable Line-Commutated-Converter (CLCC) was proposed by Electric Power Research Institute (CEPRI).
- Each arm of the CLCC is structured with a main circuit (branch) and an auxiliary in parallel. Both branches are composed of thyristor valves and IGBT connected in series.
- The thyristor valve (same as the conventional LCC valve) used in the main branch is of high voltage and large current and in the auxiliary branch high voltage and low current.
- The IGBT valve used in the main branch is of low voltage and large current and in the auxiliary branch high voltage and low current.



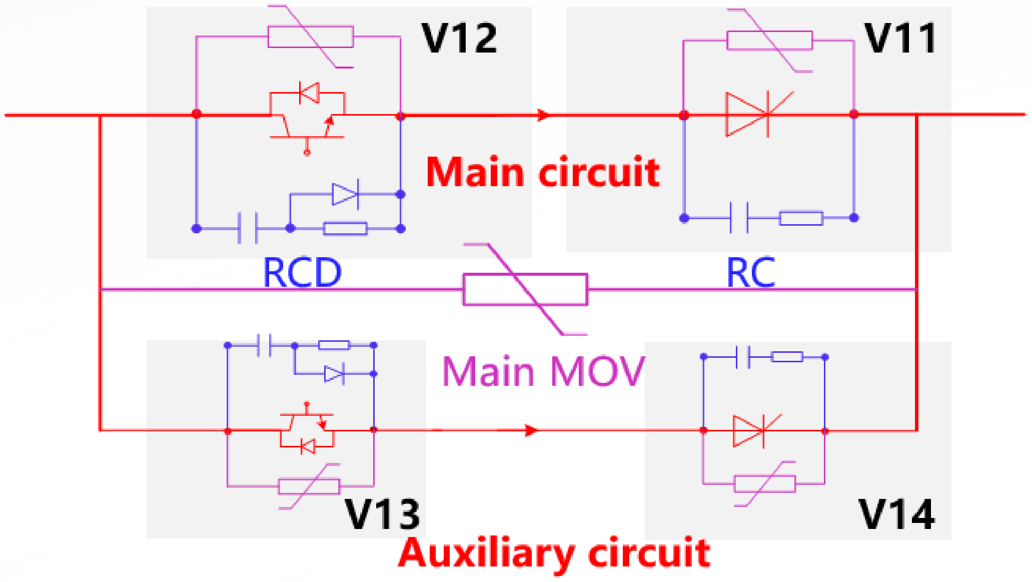
6-pulse bridge



V1 bridge arm circuit topology

Highlights of the CLCC

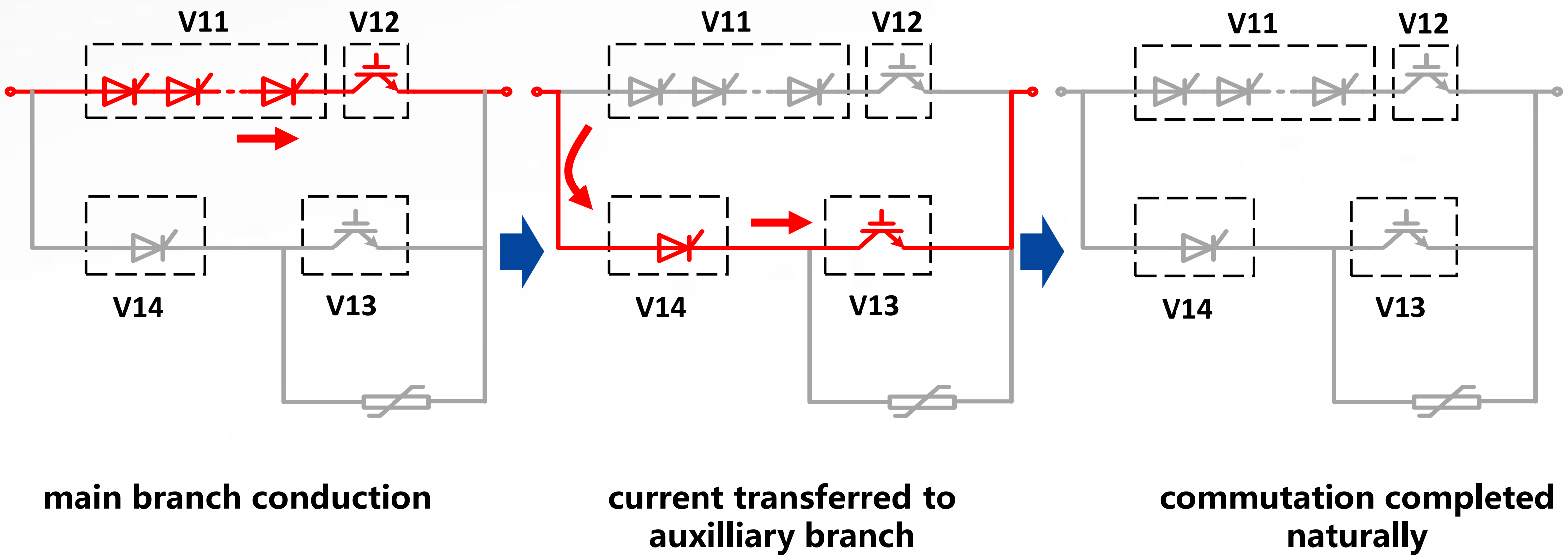
- Within the CLCC, the main circuit thyristor valve (V11) and MOV insulation coordination characteristics are retained as that of the LCC.
- The operating voltages and losses of the IGBT valves (V13) in auxiliary circuit can be reduced by connecting with thyristors (V14) in series.
- The IGBT valves (V12 and V13) are designed with a large RDC damping circuit in parallel to damp the peak and rate of rise of the switching voltages .



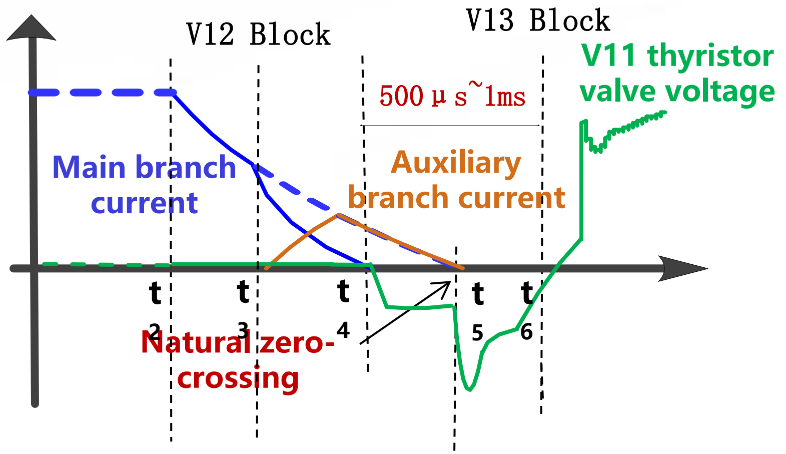
2. CLCC-HVDC Technology

Natural commutation of CLCC without fault

- In normal operation, the arm current firstly flows through the main branch, and then is transferred to the auxiliary branch during the commutation phase by turning off V12 and turning on V13 and V14.
- After a pre-defined time delay, the IGBT valve V13 is turned off at zero current after the commutation process finished naturally.



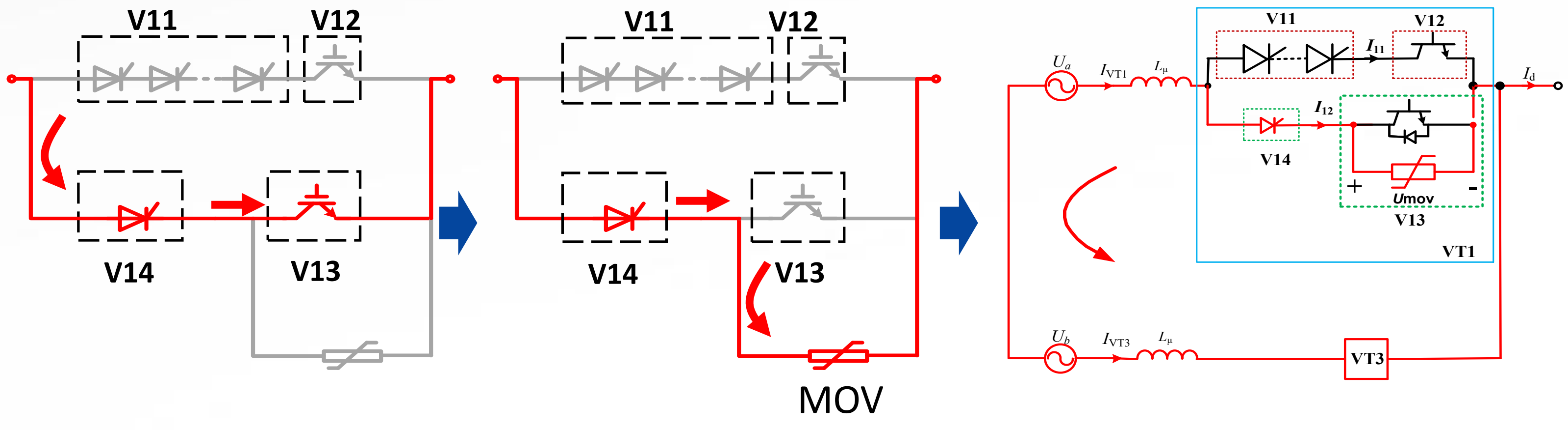
Current transfer process in normal operation



Switching sequence and waveform

Forced commutation of CLCC with fault

- When a AC fault happens, the switching sequence of each valve in the bridge arm is the same as the normal operation.
- However, the arm current may not be extinguished naturally due to the AC voltage drop, it will be interrupted and forced to commutate to the next bridge arm by switching-off of V13 valve. The V11 valve is able to recover to its blocking capability quickly due to zero current. So, the commutation failure can be avoided.

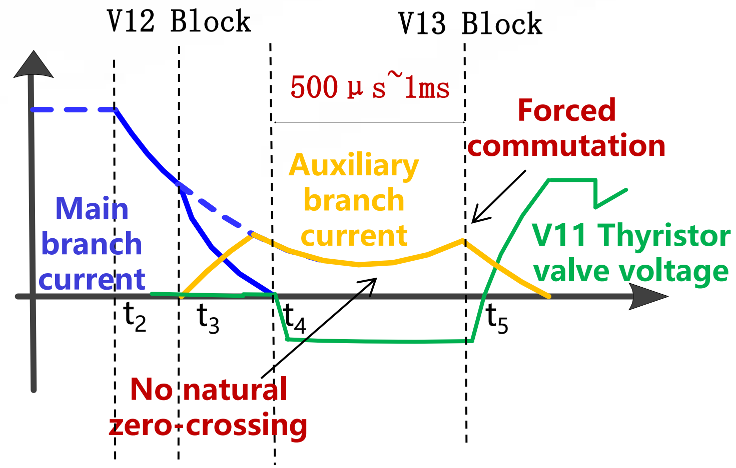


current transferred to auxilliary branch

current transferred to MOV

forced commutation process

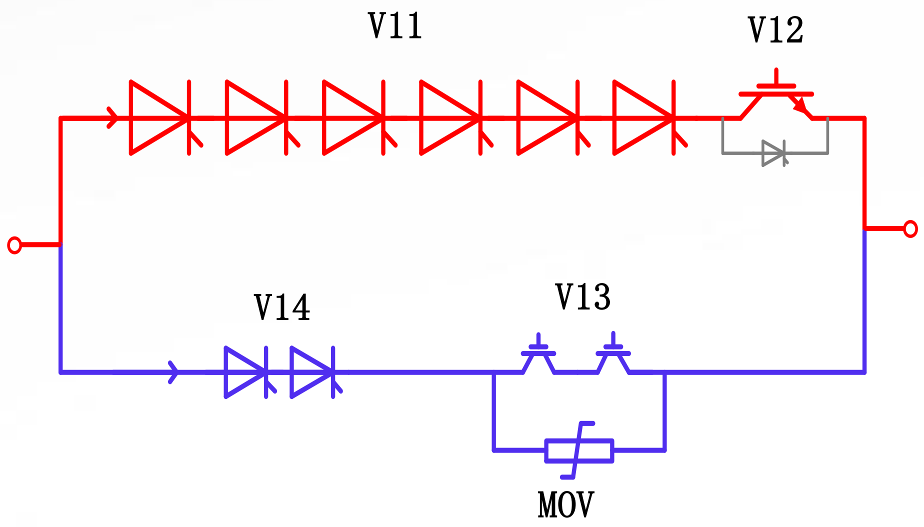
Current transfer process durig AC fault



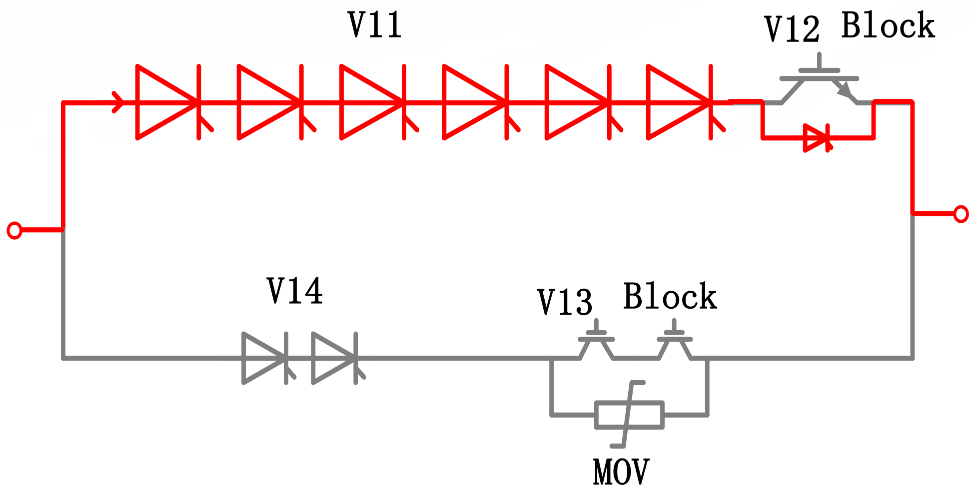
Switching sequence and waveform

Operating modes of CLCC

- Normally , the CLCC is operated in CLCC mode: the DC current in the main circuit is transferred to the auxiliary branch during the commutation.
- However, the CLCC will be switched to LCC mode by closing a thyristor valve paralleled with V12 when the IGBT valve V12 or V13 loses the redundancy.



Operated in CLCC mode

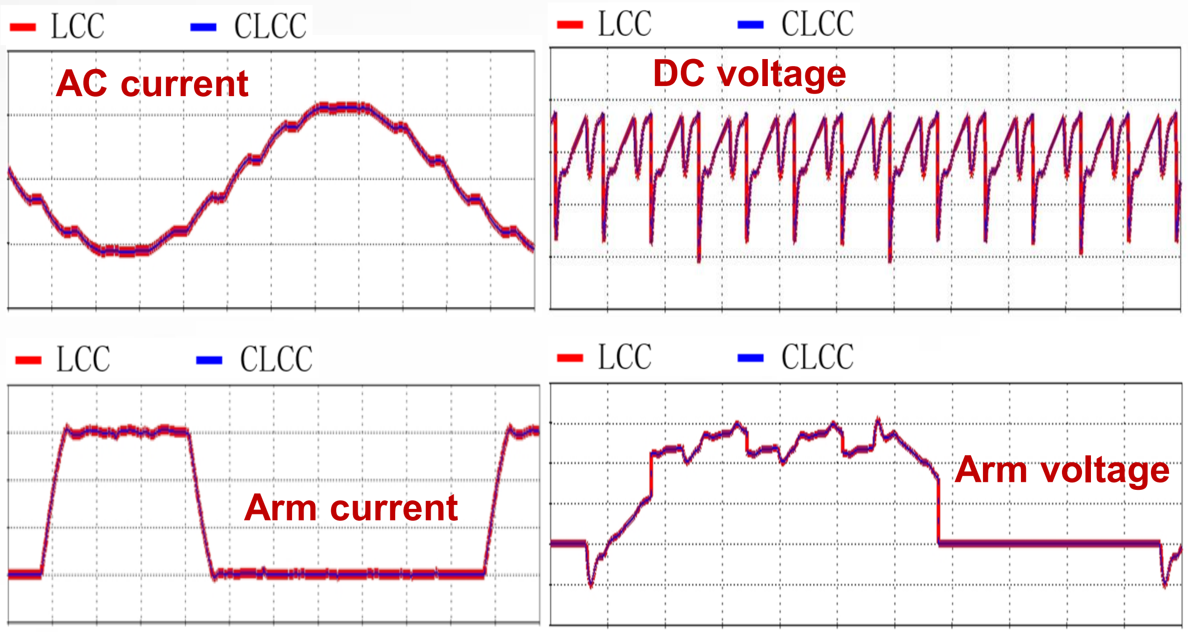


Operated in LCC mode

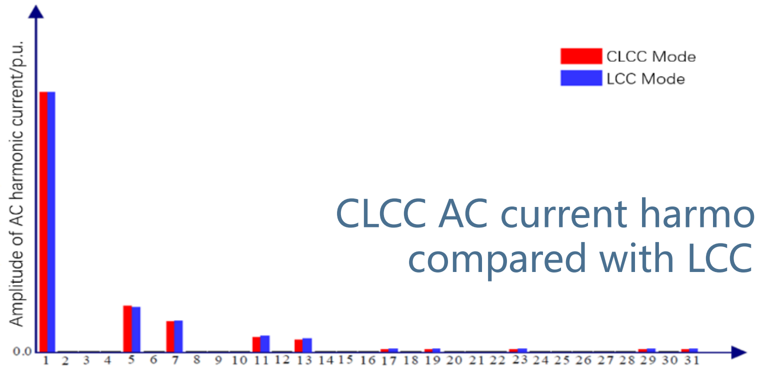
3. System Performances of the CLCC

Steady state – same as the LCC

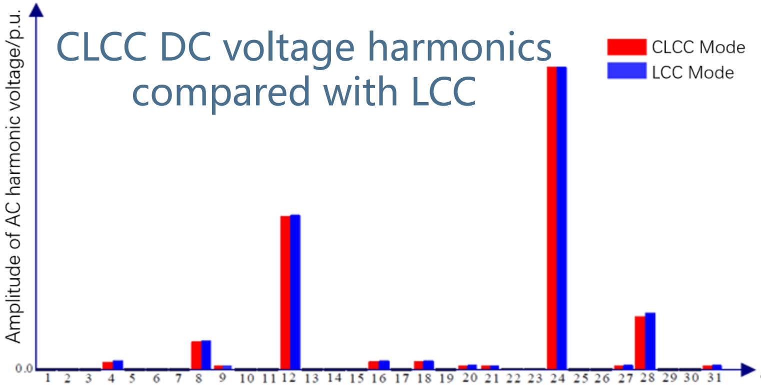
- Although the current in main branch of the CLCC converter is commutating to the auxiliary branch, the entired bridge arm voltage and current are unchanged. Therefore, the AC and DC harmonics and the active and reactive powers of the CLCC are retained and same as the LCC.



Voltage and current waveform comparison between LCC and CLCC modes



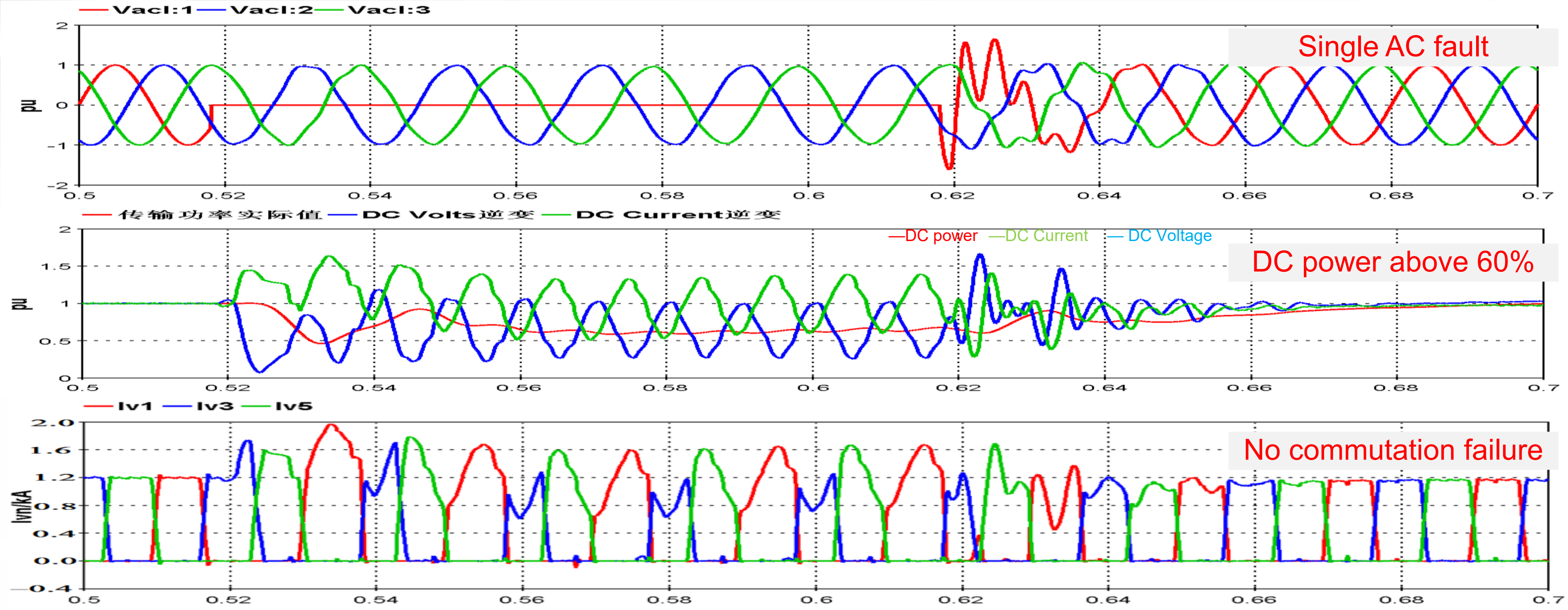
CLCC AC current harmonics compared with LCC



CLCC DC voltage harmonics compared with LCC

Transient – commutation failure eliminated

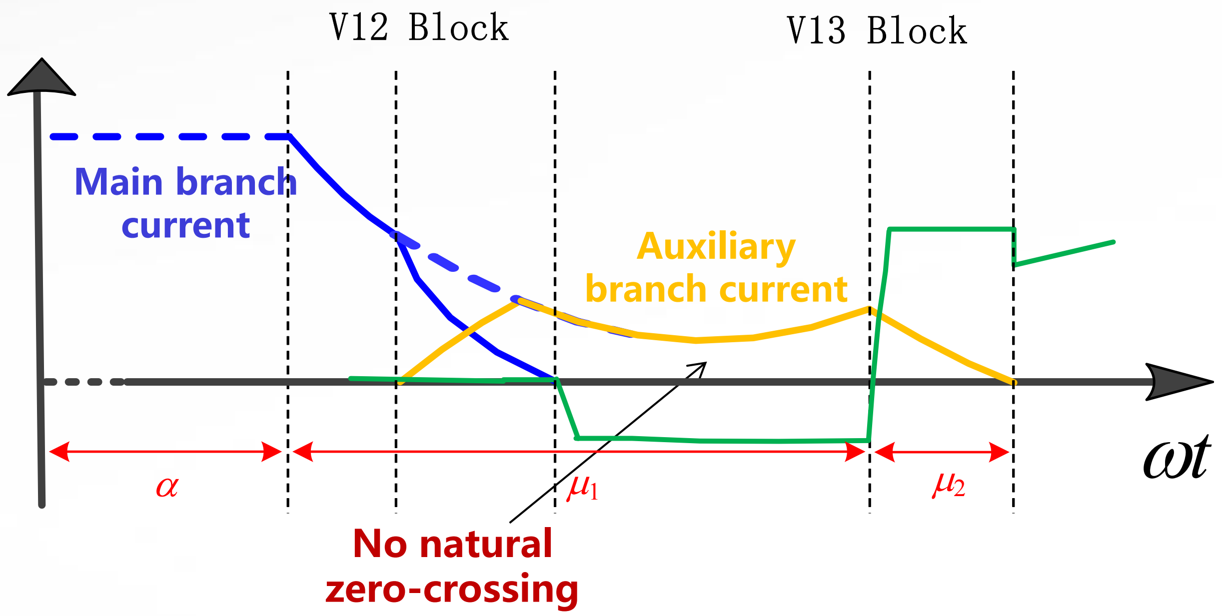
- During a transient AC fault, the CLCC can prevent CFs and maintain DC power above 60%, reducing power disturbance to the AC grid.



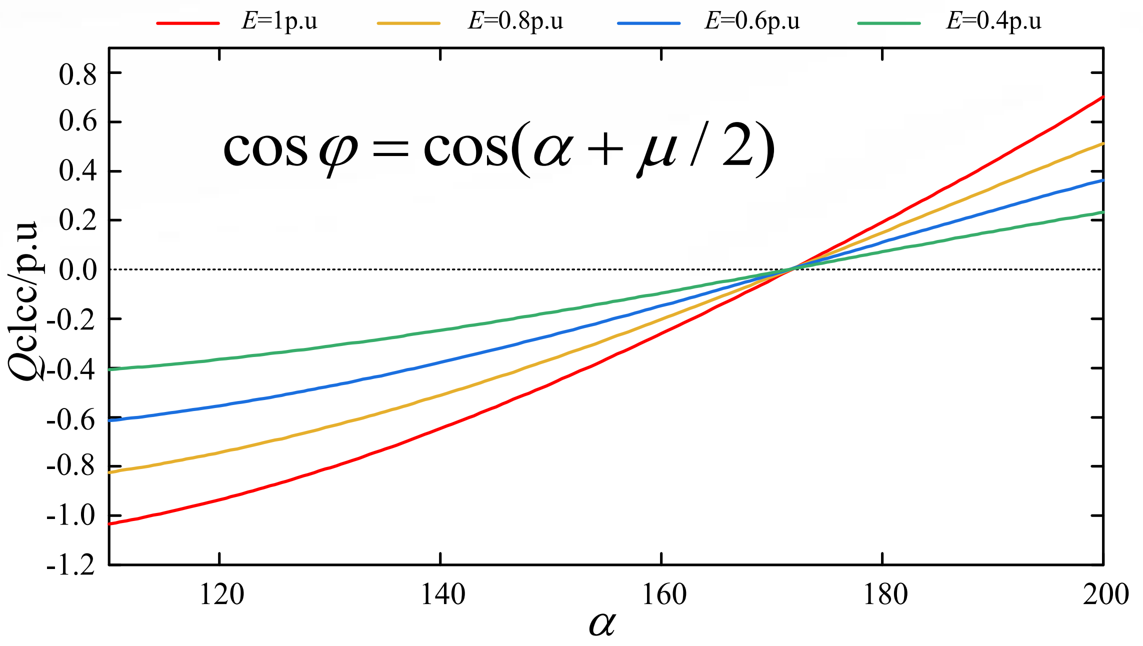
Transient process of the CLCC during a single-phase to ground AC fault

Dynamic – reactive power support

- Thanks to CLCC branch transfer function, theoretically, the CLCC can increase its firing angle temporarily and reduce its consumption of reactive power to supply dynamic reactive power support to the AC grid.
- In particular case, the CLCC can even output reactive power (power factor, cosφ<0) when the firing angle α exceeds a value (e.g. α>170 deg.) and α+μ/2 > 180 deg.



formula of reactive power



relationship between reactive power and AC voltage, firing angle (α)

Comparison of three types of Converter

Key indication	LCC	VSC	CLCC
Capacity of converter	8000MW	8000MW	**8000MW**
Cost of station	1 p.u	1.3 p.u	**1.07 p.u**
Converter losses	0.7%	1%	**0.74%**
CFs	Yes	No	**No**
2-hour overload capacity	1.25p.u.	1.05p.u.	**1.25p.u.**
Active power maintained level during transient AC fault	0	>60%	**>60%**
Dynamic reactive power support	Uncontrollable, - 0.5p.u.	Controllable, ± 0.1～0.3 p.u.	**temporarily Controllable** - 0.5～0.3 p.u.
DC fault current breaking capability	Yes	DC circuit breaker or full-bridge module is required	**Yes**

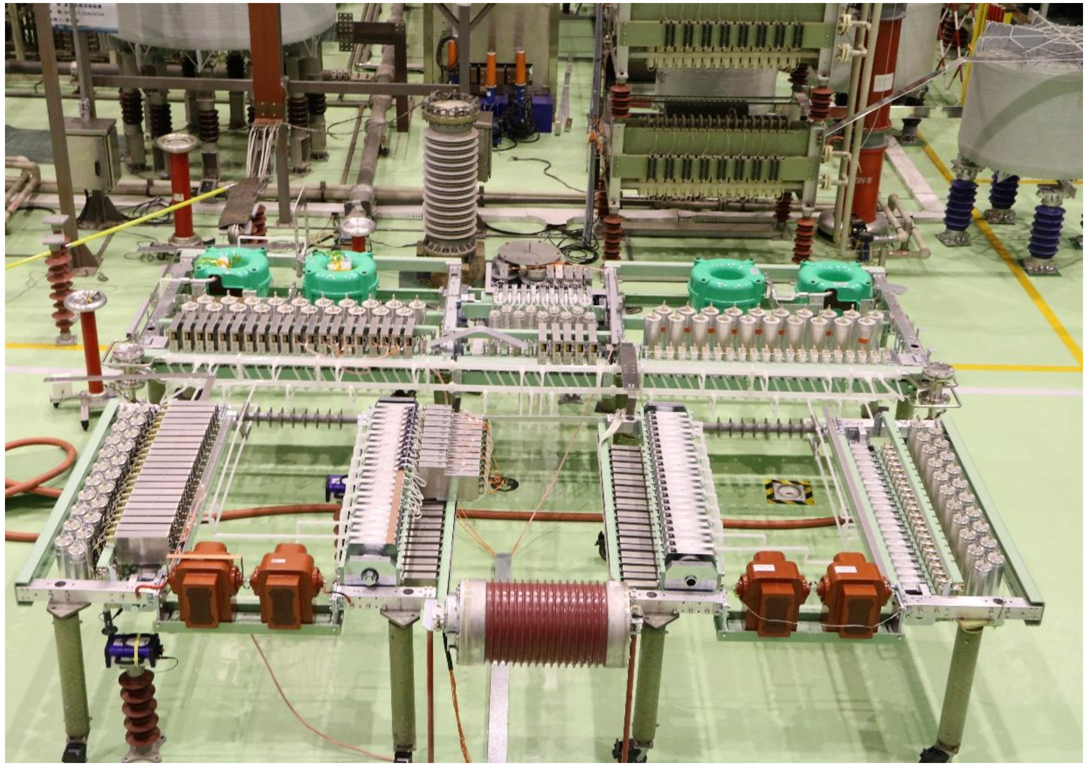
CLCC inherits both advantages of LCC and VSC!

4. Application of the CLCC

Prototype of the CLCC

- A valve module and a double valve tower prototypes of the CLCC were developed at CEPRI.
- To evaluate the electrical stress withstanding capability and designed operational function, a full set of type tests were conducted in the CEPRI laboratory.

Prototype of Valve Tower



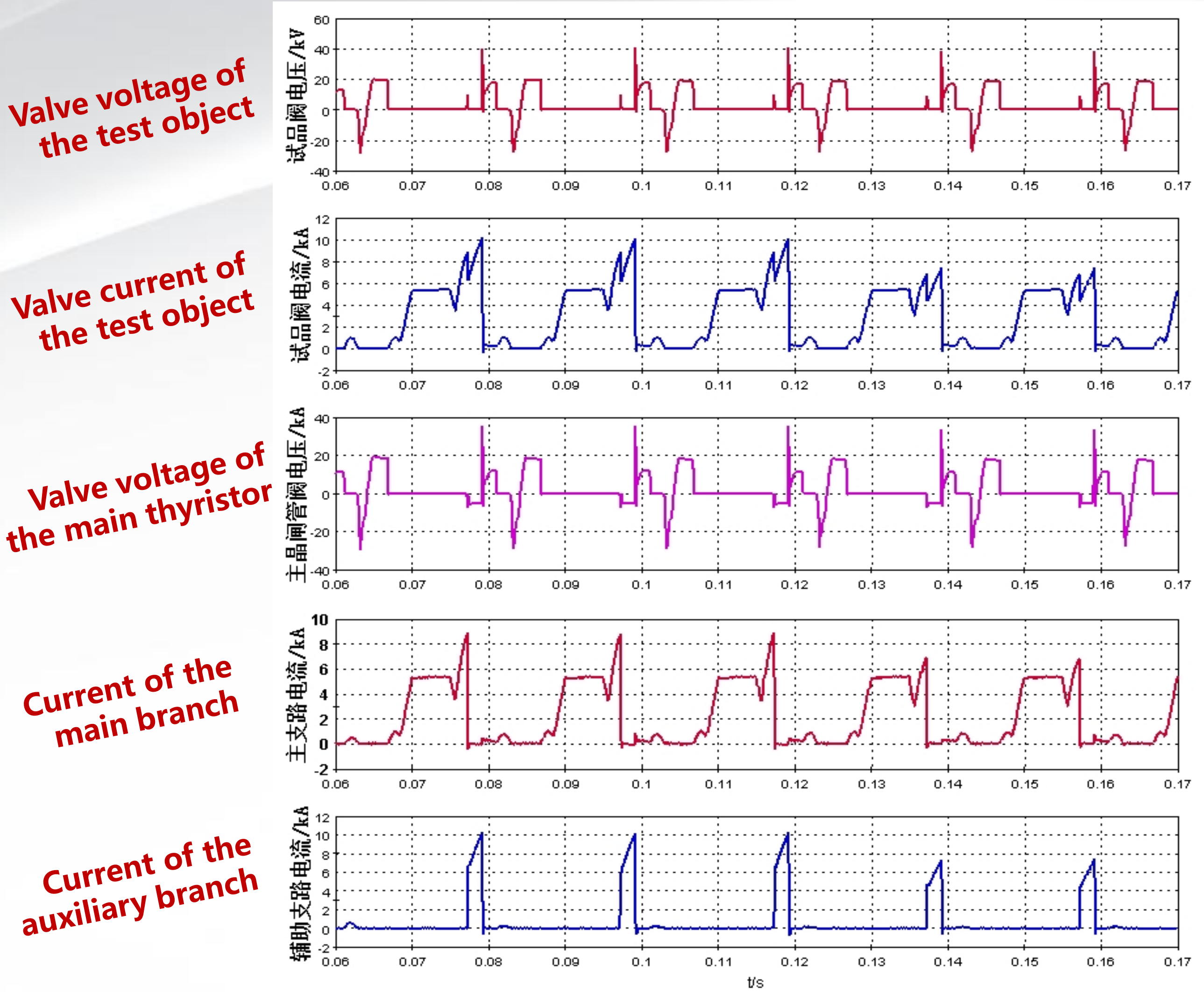
Valve Module in testing

Type tests of the CLCC

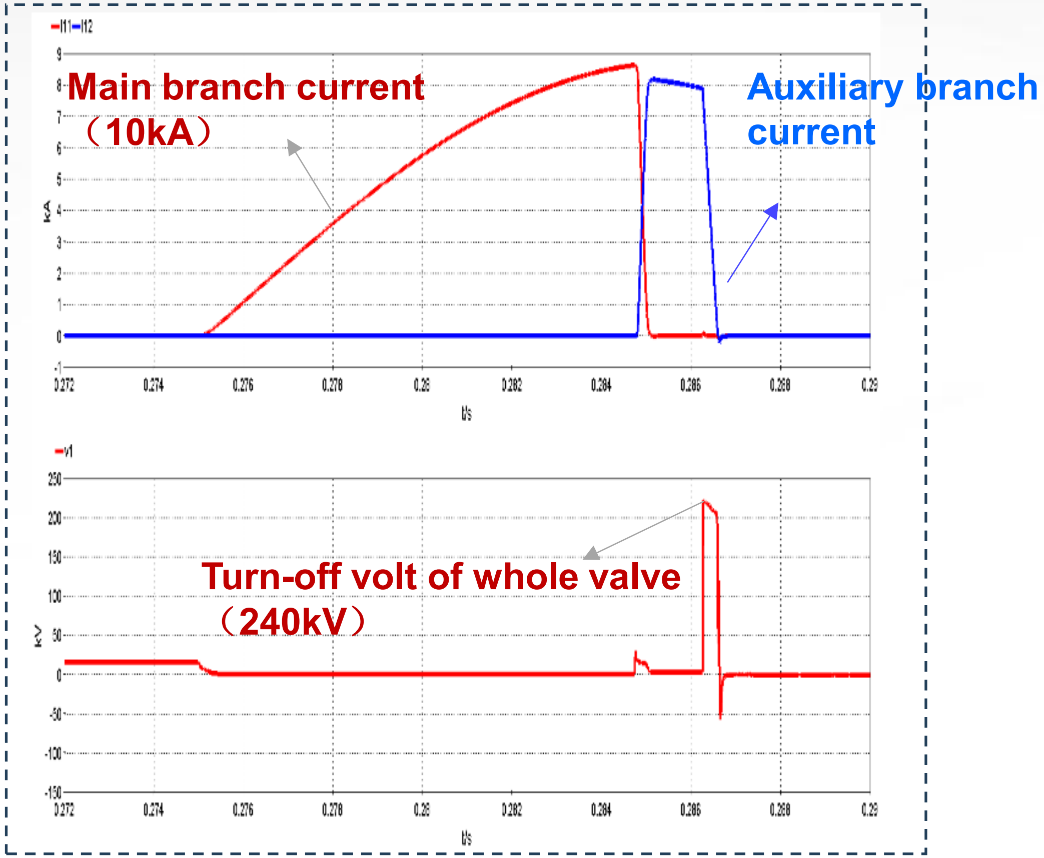
- A list of type tests of the CLCC has been carried out and passed successfully.

Item	Test	Parameter
1	Maximum continuous operating duty test	Test current：5300A；
2	Maximum temporary operating duty test（2s）	Test current：1575A；
3	Maximum temporary operating duty test（10s）	Test current：1575A；
4	CLCC/LCC operating modes changed-over test	Test current：5300A；
5	Controllable turn-off test	Test current：5300A; 5 cycles
6	Minimum firing angle test	Test current：5300A；
7	Minimum extinguish angle test	Test current：5300A；
8	Temporary low voltage test	Test current：1575A；
9	Discontinuous DC current test	Test current：≥100A；
10	Single short-circuit current test	Fault current：52kA；
11	Multiple short-circuit current test	Fault current：55kA；
12	Recovery positive voltage test	Test current：5300A；

Example of type testing results



High current turn-off test of the CLCC valve

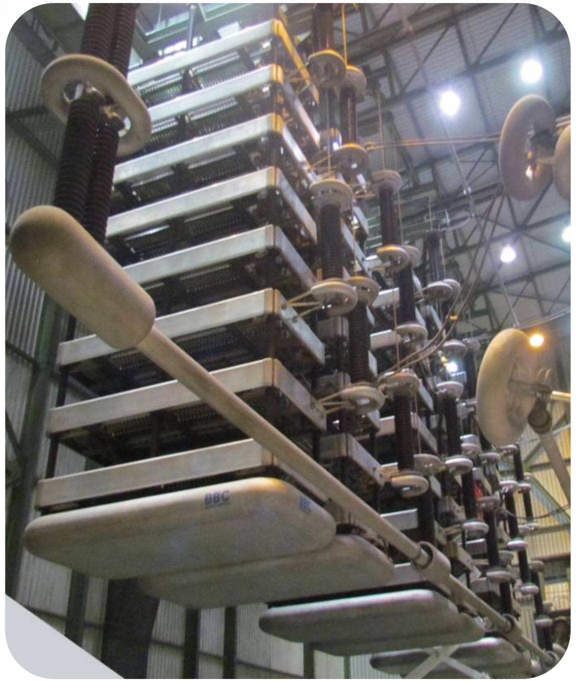


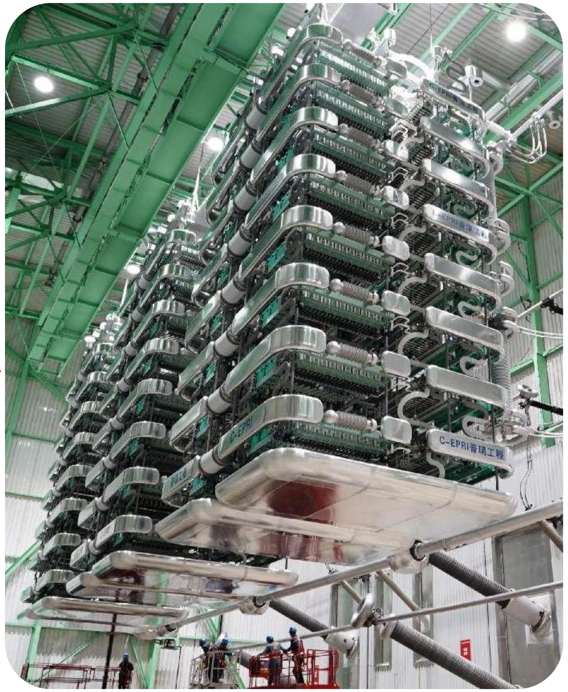
High current turn-off test of CLCC valve tower

Ge’nan 500 kV HVDC project converter valve refurbishment with CLCC

- Ge’nan LCC-HVDC project commissioned in1989 is the first ±500kV HVDC transmission project in China.
- The project at its inverter side Nanqiao station was refurbished with CLCC and commissioned on 18th June 2023 successfully.

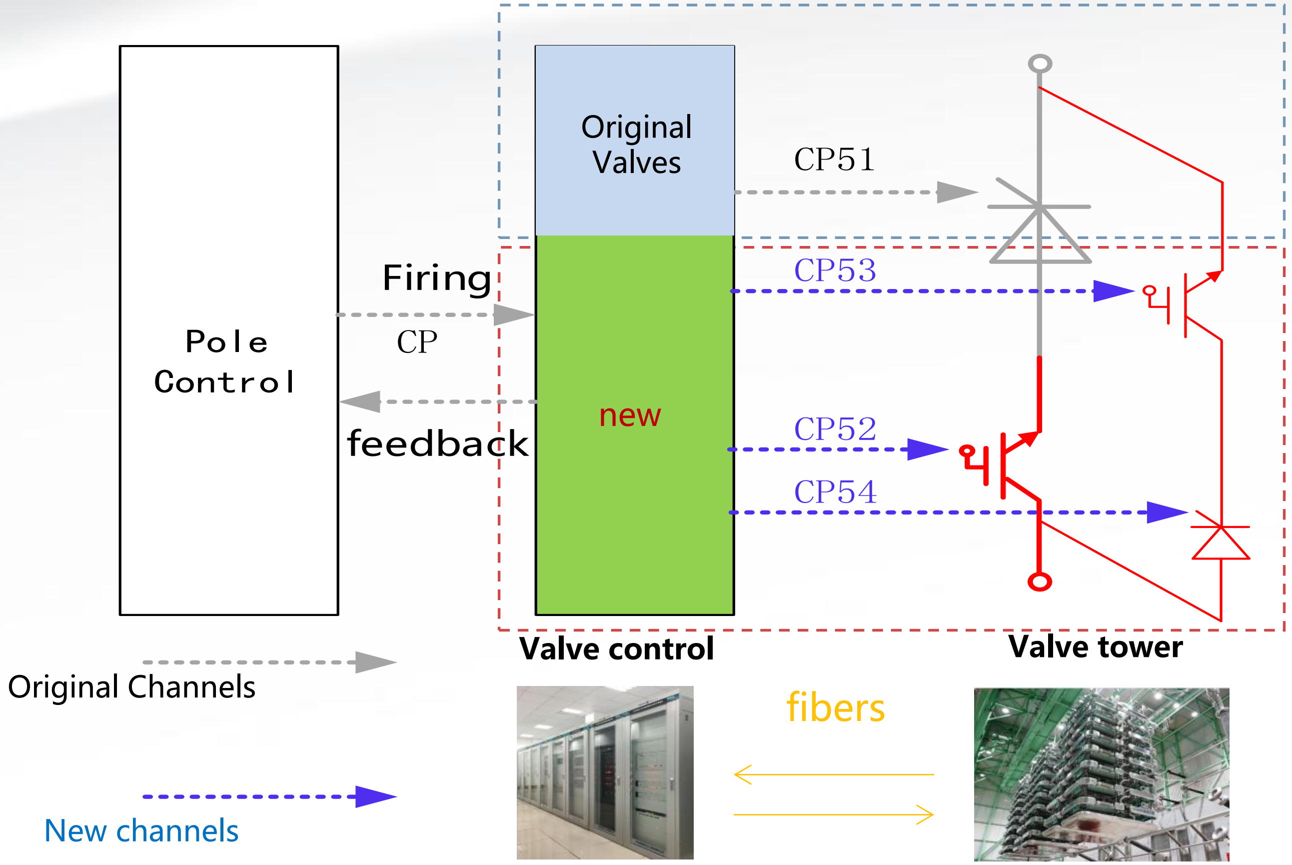
Geographical Map of GeNan Project





Converter before and after refurbishment

HVDC control and protection system are also refurbished with CLCC accordantly

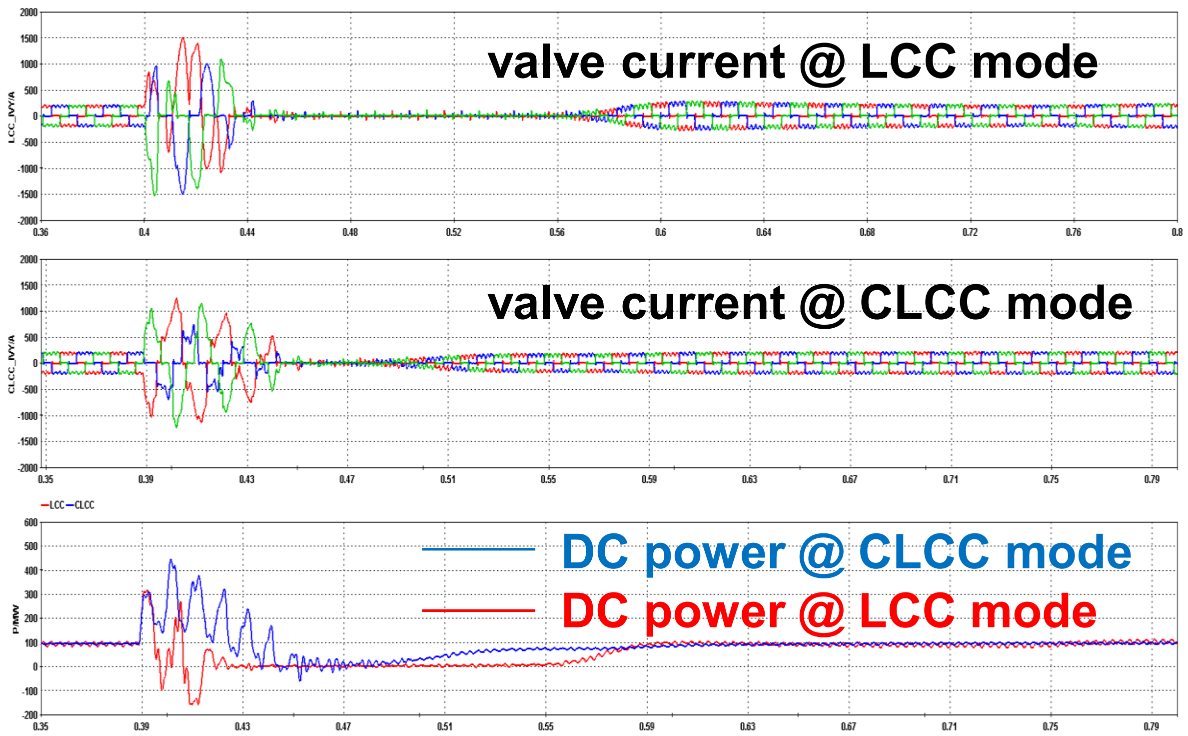


CLCC HVDC control and protection system

Artificial AC fault testing on site

- The CLCC has passed over 200 system commissioning tests, including a man-made artificial single-phase to ground AC fault on a 220 kV AC line near the converter station.
- Test results shows that no commutation failure occurred in CLCC mode and DC power level and recovery rate during fault are higher than LCC.

Artificial AC fault test on site



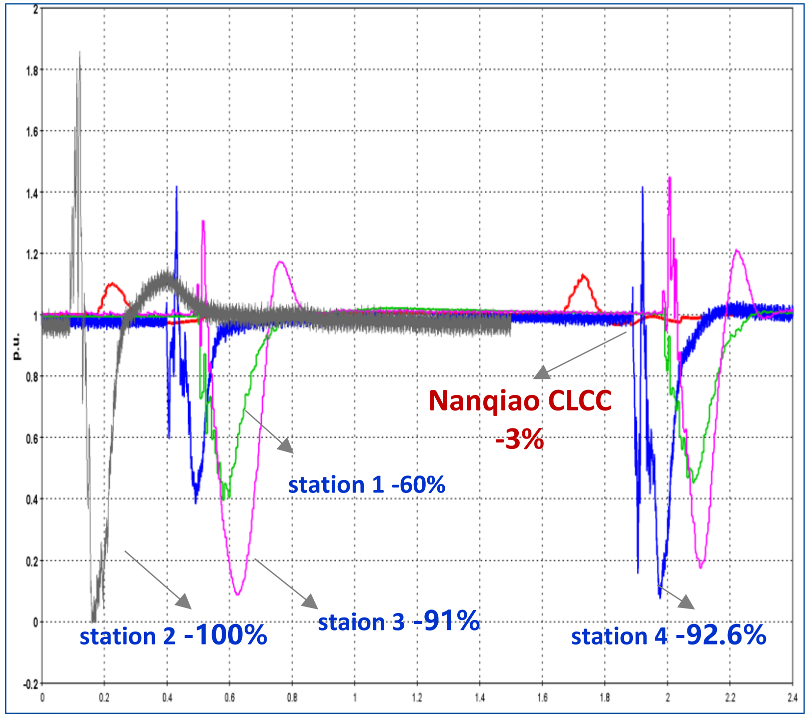
AC fault test waveforms

Operational performances of the CLCC

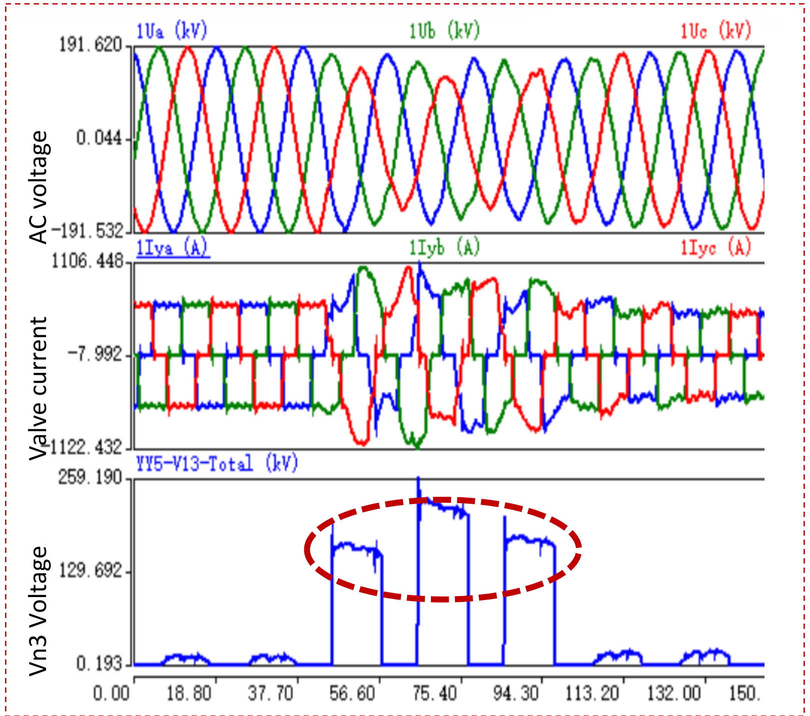
- Since Nanqiao station has been refurbished with CLCC and put into operation in June 2023, it has encountered 15 AC faults, but no CF.
- Particularly, on Sept. 10, 2023, an AC fault induced the commutation failures of four (4) HVDC converter stations nearby Nanqiao, resulting in large transient power disturbances. However, Nanqiao station has no CF and maintained a stable power transmission.

Date	AC fault and CF consequence
2023.8.3	AC disturbance， no CF in Nanqiao
2023.8.28	220kV AC fault， CF occurred in one another station, no CF in Nanqiao
2023.9.10	1000kV AC fault， resulting in CFs in 4 other stations， no CF in Nanqiao
2023.10.7	220kV AC fault ， resulting in CF in one another station, no CF in Nanqiao
2023.10.11	220kV AC fault ， resulting in CF in one another station, no CF in Nanqiao
2024.3.26	500kV AC fault ， resulting in CF in one another station, no CF in Nanqiao
2024.5.11	1000kV AC fault ， resulting in CF in one another station, no CF in Nanqiao
2024.6.21	500kV AC fault ， resulting in CF in two other stations, no CF in Nanqiao

AC fault events and CF consequences



Power curves of the converter stations



Recorded waveforms during AC fault

5. Conclusions and Outlook

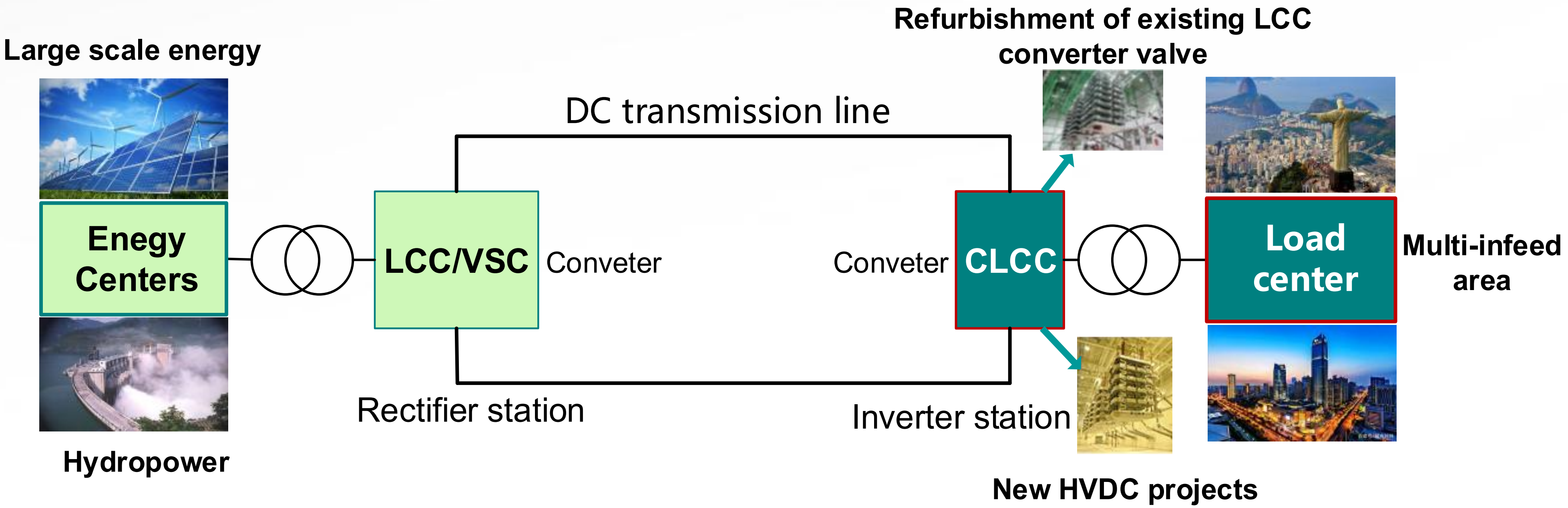
Conclusions

- **Practical CLCC-HVDC project shows that the CLCC technology is a good solution to against the CFs and with benefits of low power losses, low cost and high reliability.**

- **The existing LCC HVDC control and protection system and valve hall can be easily coordinated and integrated with CLCC.**

Outlook

- In the future, the CLCC can be applied to HVDC projects (including existing and new LCC projects) to solve the CF problem and also enjoy the advantages of low power losses, low cost, simple HVDC control and protection system compatibility and benefiting systems with high renewable energy penetration at the same time.



Thanks