IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2016.
This plenary presentation A32 was given at ACASC 2015 (The 8th Asian Conference on Applied Superconductivity and Cryogenics).

The Possible Applications of HTS for Future DC Power Grid

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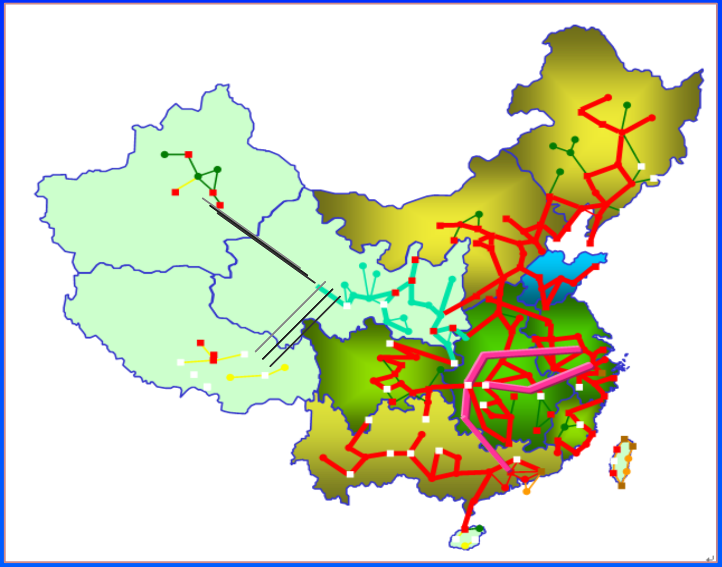
Content

- The Future power grid—DC power grid
- Superconducting DC cable/energy pipeline
- Superconducting DC fault current limiter
- Superconducting DC power electronic transformer

Future power grid—DC power grid

1、AC mode causes some problems with the development of power grid



- With the increasing of the scale of the power grid, the stability of AC power grid is becoming more and more serious;

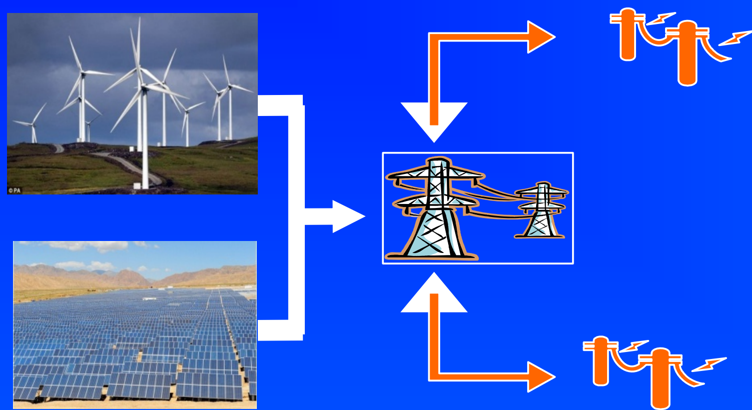
$$P = \frac{U^2}{X_L} \sin \delta_L$$

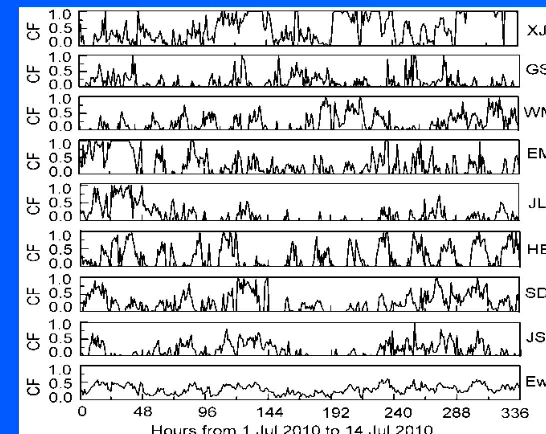
- The transmission capacity is limited over long distance intrinsically.

AC mode can causes possible blackout disaster such as the US-Canada's blackout at August 14, 2003, and India's power blackout in July 2012, etc.

Future power grid—DC power grid

2、RE connected to the AC power grid is a big challenges





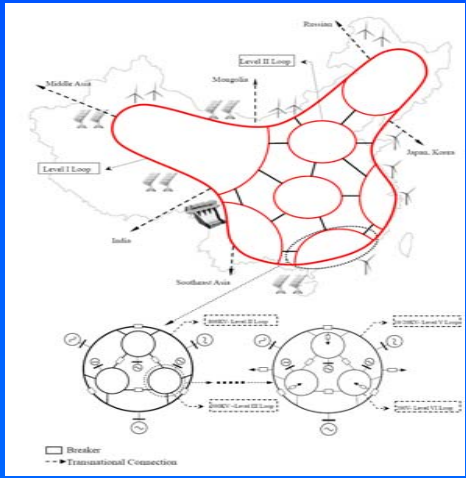
- Solar and wind energy: non scheduling (randomness, volatility, uncontrolled), no inertia or inertia is much smaller than conventional power machines.

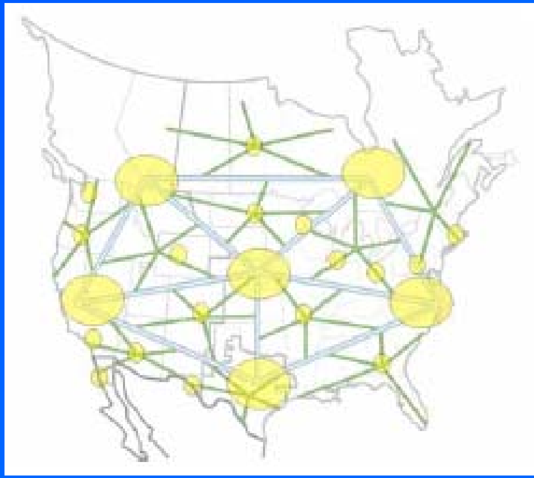
- The connection of remote intermittent energy source is in the absence of strong support from the AC power grid;
- Bidirectional flow control is not flexible;
- The stability problem of AC grid is more serious.

Future power grid—DC power grid

3、 DC power grid is a very effective solution to the above problems

- For DC power grid, no stability problems as AC power grid has;
- DC power transmission: long distance with high efficiency and high transmission capacity ;
- DC mode is more suitable for connection of renewable energies;
- DC mode is flexible to achieve bidirectional flow control ;

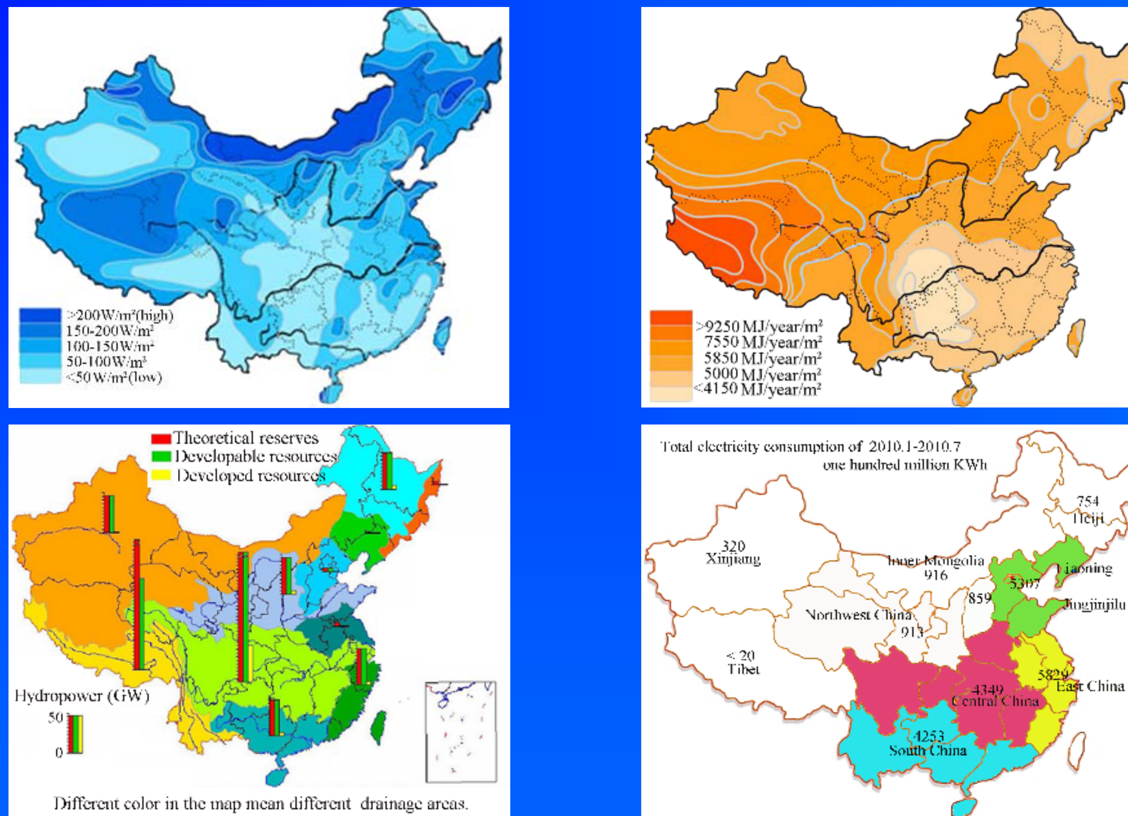




What can be used for HTS in Future DC Power Grid?

- Superconducting DC transmission cable/energy pipeline
- Superconducting DC fault current limiter
- Superconducting DC power electronic transformer

The Distributions of RE and Load Centers of China

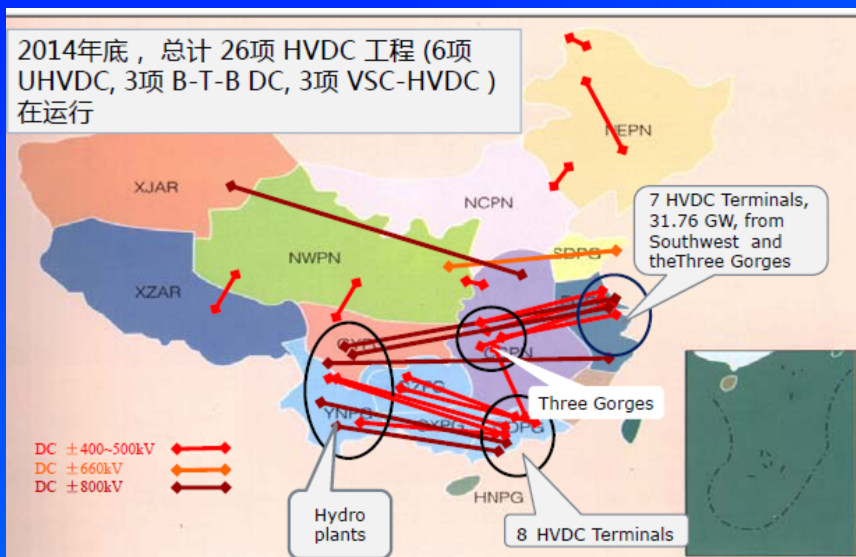


A-Wind Power, B-Solar Energy, C-Hydropower, D-Load center

Future electric power transmission from the western to the eastern area in China (Zhou Xiaoxin,et al.)

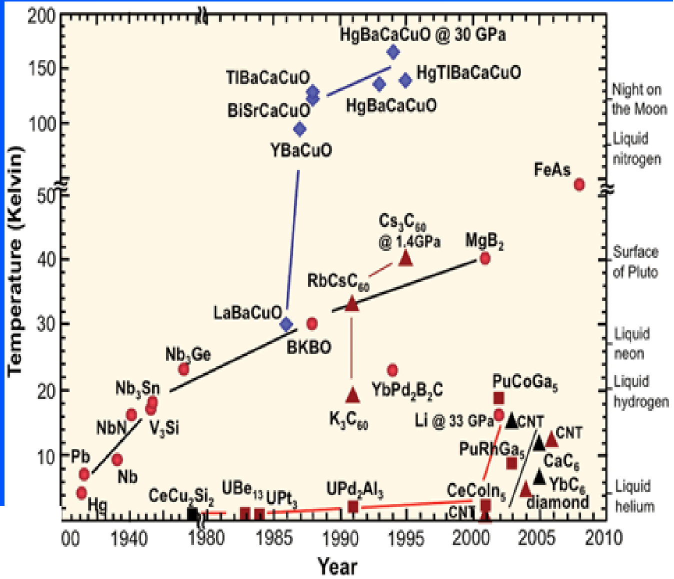
Scene	Project	West and North			Middle East		
		Installed	To the estern	Local Req	Installed	From the wetsern	Local Req
2050 (Case 1)	Power Capacity/100GW	11.8	5.90	5.90	13.83	5.90	19.73
	percentage to the total installed capacity (%)	46.0	23.0	23.0	54.0	23.0	77.0
2050 (Case 2)	Power Capacity/100GW	12.58	6.29	6.29	15.62	6.29	21.91
	Percentage to the total installed capacity (%)	49.1	24.5	24.5	60.9	24.5	85.5
2050 (Case 3)	Power Capacity/100GW	13.36	6.68	6.68	17.40	6.68	24.08
	Percentage to the total installed capacity (%)	52.1	26.1	26.1	67.9	26.1	94.0

The energy (Gas and Electricity) transmission routes from the western to the eastern area in China



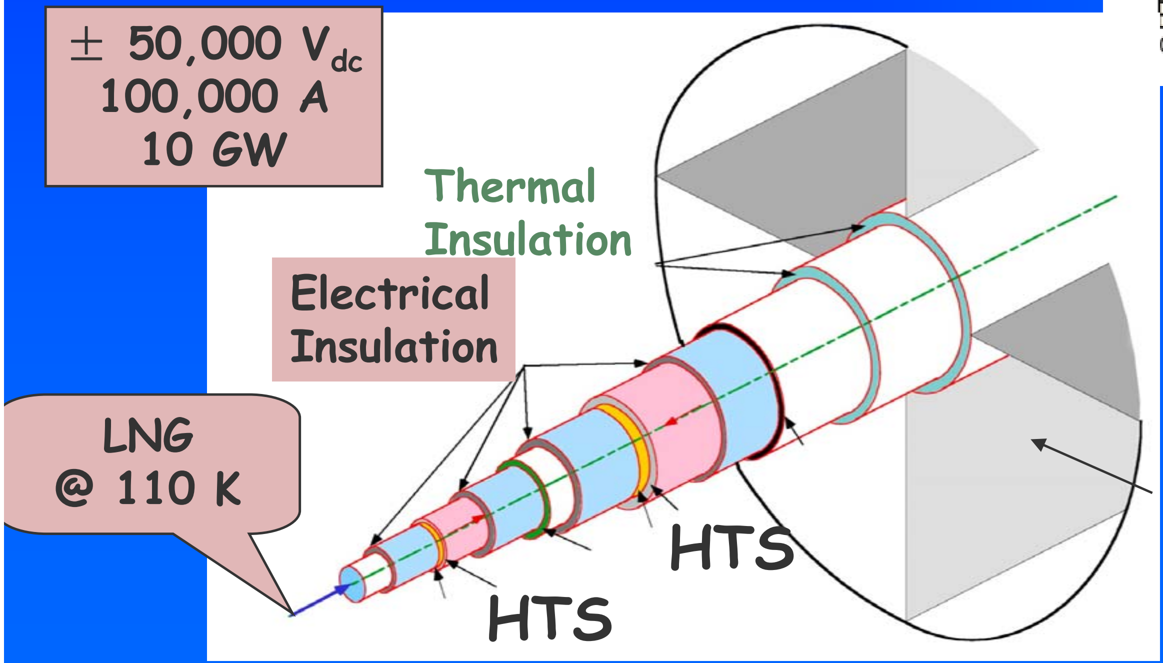
If the LNG and electricity can transferred by one superconducting energy pipeline, it would be a wonderful solution for China's future energy transmission system.

HTS energy pipeline @ LNG temperature



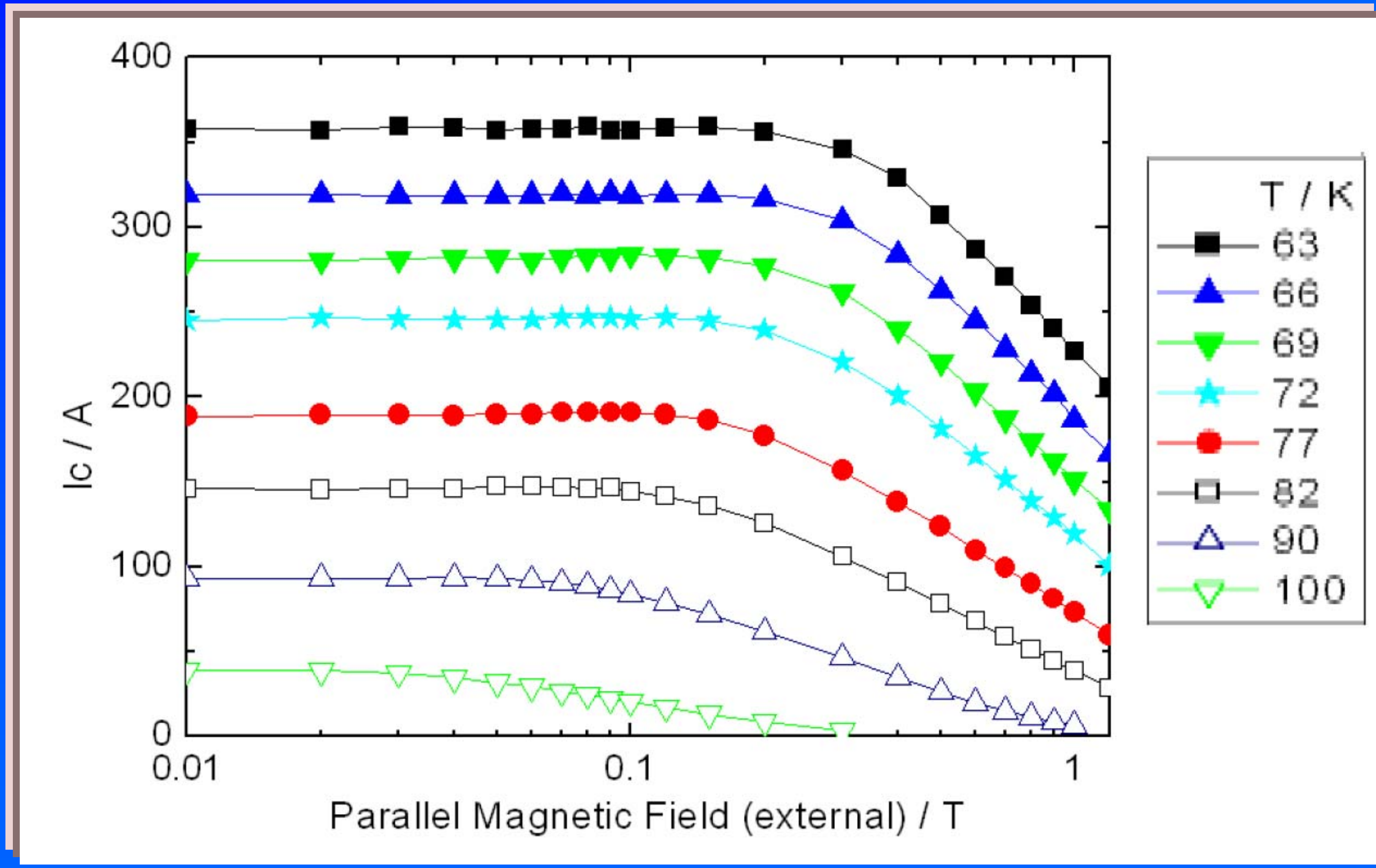
Tc vs year

The HTS Energy Pipeline



Vacuum

Ic-T Properties of Bi2223 Wires (DI-BSCCO)



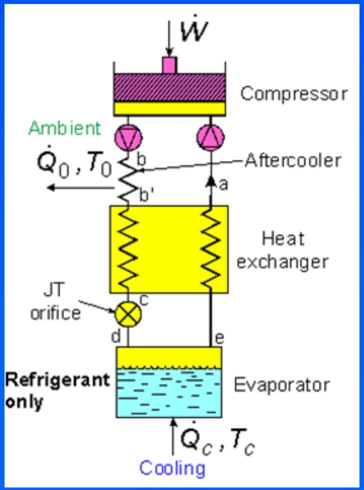
This Picture is supplied by Dr. K. Sato from SEI

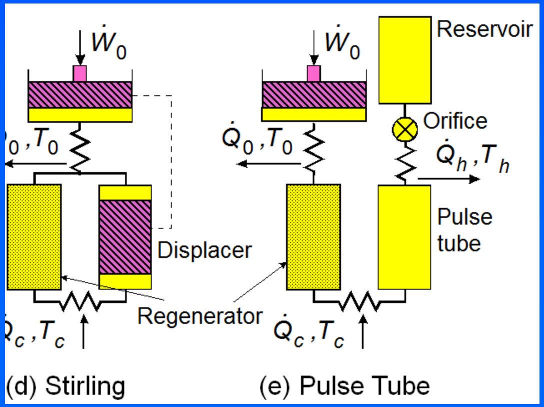
LNG-based hybrid coolant for BSSCO Energy Pipeline@85-90K

With high carbon enriched fractions of liquefied natural gas (LNG) as coolant, the energy pipeline can be operated at 85-90K:

By using conventional LNG as the main component, the C2+ component are used to realize the cooling liquid of 85-90 K.

- **Composition**: LGN plus C2+ (C2+) components such as ethane etc.
- **Pressure**: 0.1~1.0 MPa
- **Temperature**: 85~90 K





Development of the compensating refrigerator for hybrid coolant energy pipeline.

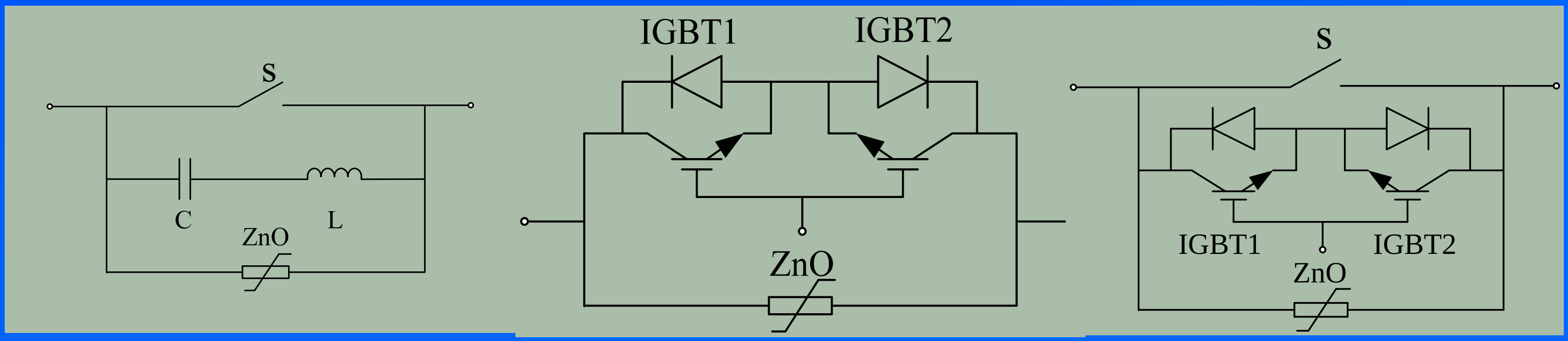
What can be used for HTS in Future DC Power Grid?

- Superconducting DC transmission cable/energy pipeline
- Superconducting DC fault current limiter
- Superconducting DC power electronic transformer

Superconducting DC fault current limiter

Development of high voltage and large capacity DC circuit breaker has been a worldwide problem, because:

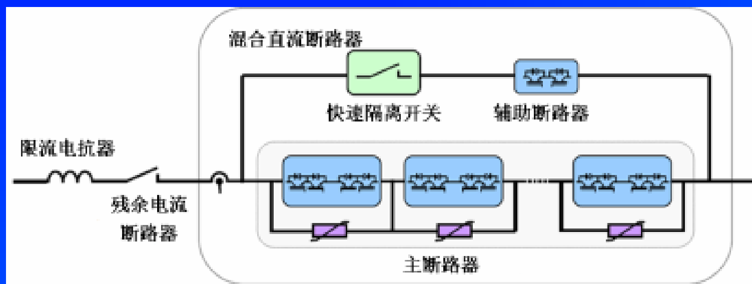
- There is no zero crossing in DC;
- How to absorb the energy storage (MJ) of transmission line in the open?
- Breaking speed should be quick (ms order) enough to prevent a sharp rise in fault current.



Mechanical Solid-State Hybrid

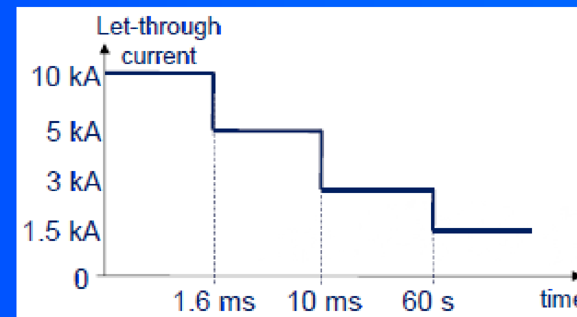
Superconducting DC fault current limiter

ABB



Rated Voltage	320kV
Rated Current	2.6kA
Fault current	16kA
Time to open	2ms

GRID ALSTOM



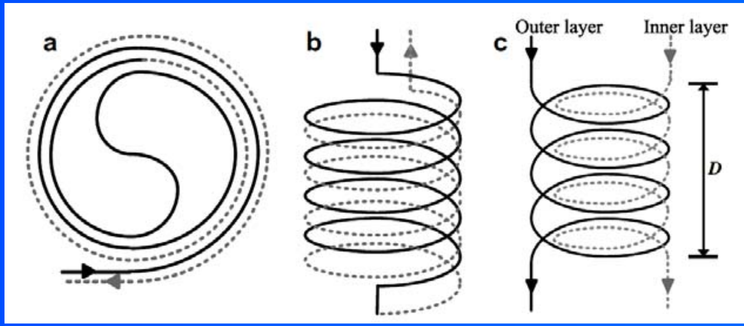
Rated Voltage	120kV
Rated Current	1.5kA
Fault current	7.5kA
Time to open	<1.6ms

DC Breaker developed by ABB and Alstom.

Superconducting DC fault current limiter (resistive type)

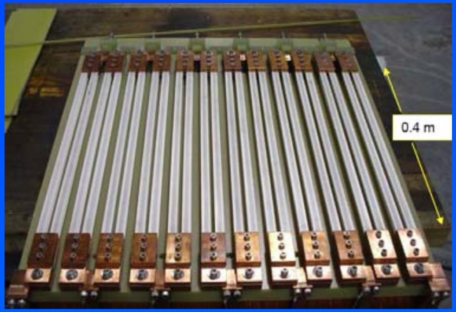
Non-inductive coils:

- Bifilar pancake
- Series solenoid
- Parallel solenoid



(a) Bifilar pancake (b)Series solenoid (c) Parallel solenoid

Siemens & AMSC



SJTU, China

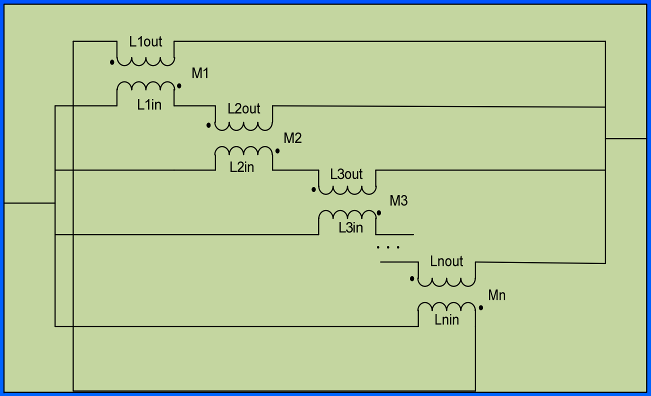
Hyundai, Korea

H. W. Neumueller, W. Schmidt, H. P. Kraemer, et al. Development of resistive fault current limiters based on YBCO coated conductors, IEEE Transactions on Applied Superconductivity, vol.19, pp.1950-1955, 2009

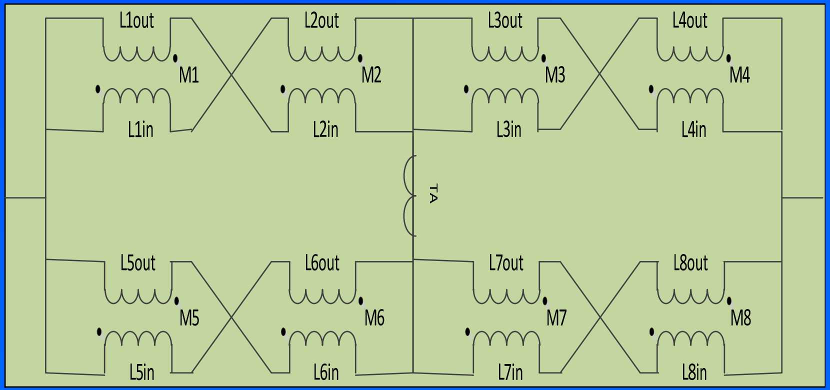
H. Kang, C.Lee, K.Nam, et al. Development of a 13.2 kV/630 A (8.3 MVA) high temperature superconducting fault current limiter, IEEE Transactions on Applied Superconductivity, vol.18, pp.1950-1955, 2008

Superconducting DC fault current limiter (IEE,CAS)

- **Circuit Topology of flux-coupling SFCL**
  - Two novel SFCL with multiple parallel branches are suggested, and the current-distribution problem could be solved effectively.
  - The SFCL could generate larger inductance and smaller resistance at the beginning, but show smaller inductance and very large resistance finally.



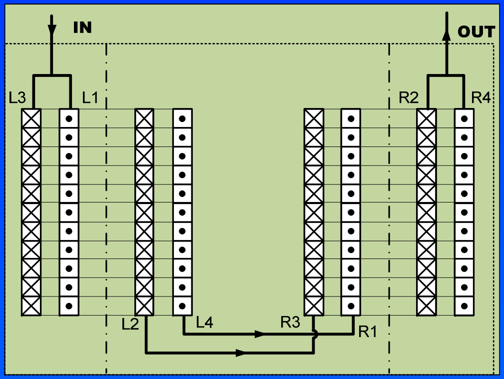
"Hand-in-hand type" circuit topology of SFCL

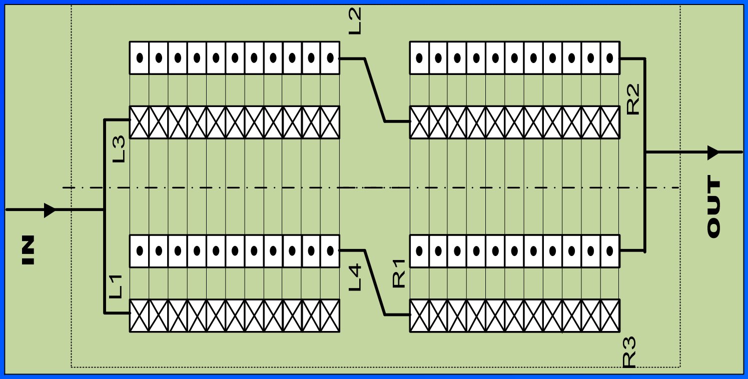


"H-bridge type" circuit topology of SFCL

Superconducting DC fault current limiter (IEE, CAS)

- For the SFCL with two solenoid groups, the coil inlet and outlet could be made at one side or both sides





(a) one side

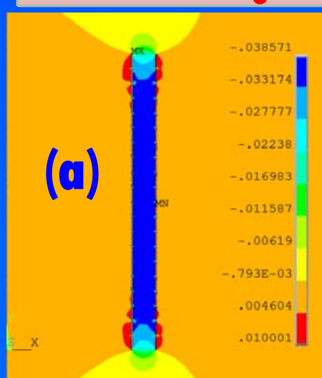
(b) both sides

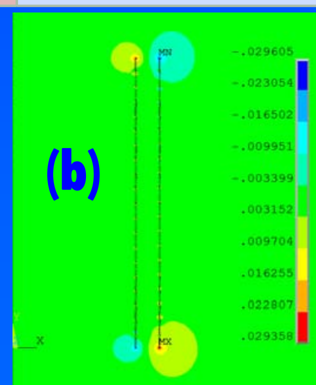
Coil inlet and outlet styles and connections

Superconducting fault current limiter (IEE, CAS)

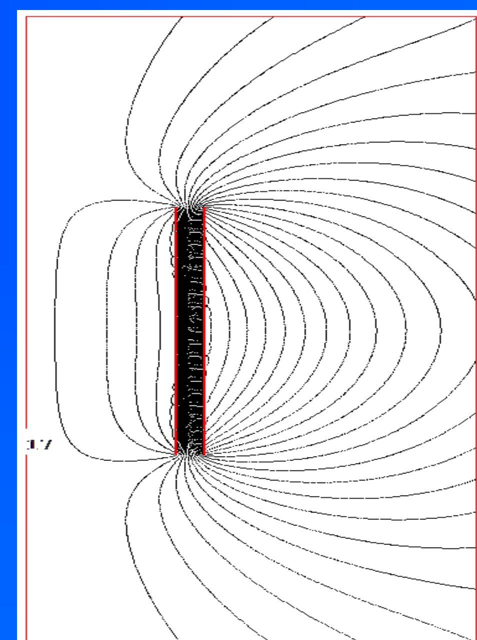
- One solenoid coil group is wound with two layers with cooling channels in longitudinal. The solenoid coil group could be wound with one or two parallel tapes in order to prevent unbalanced current distribution.

Parameters	Designed value
Winding type	solenoid
Number of coil	2
Number of turns	20
Mean diameter	240 mm
Height	380 mm





The axial component (a) and radial component (b) of magnetic flux density.



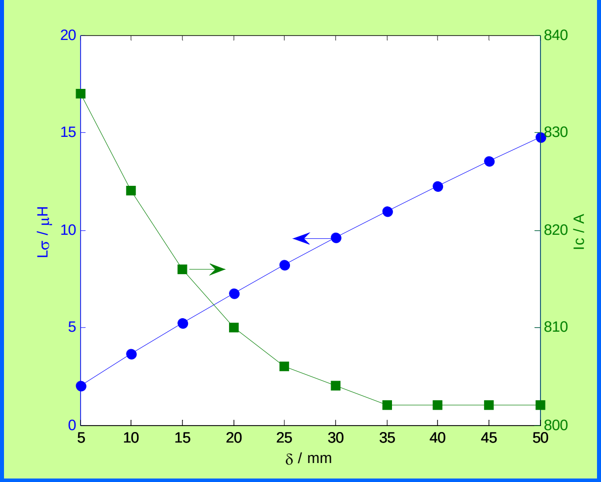
The distribution of magnetic field lines.

Superconducting fault current limiter (IEE-CAS)

- With the increasing of gap between two coils, the leakage inductance of the group increases linearly, then the critical current of the group will be decreased.

Influence of gap on the parameters of solenoid coil group

δ /mm	$B_{\perp}$ /G	B /G	I_c/A	L_σ/ μH	L_{in} L_{out} / μH
5	188.7	197.3	417*2	2	58.8, 64.1
10	228.7	188.4	412*2	3.7	56.7, 66.3
15	253.8	183.1	408*2	5.3	54.6, 68.5
20	275.9	177.4	405*2	5.8	52.5, 70.8
25	288.8	172.8	403*2	8.2	50.5, 73.1
30	298.3	168	402*2	9.6	48.5, 75.4
35	311.3	164	401*2	11	46.5, 77.8
40	291.8	157.1	401*2	12.3	44.5, 80.1
45	298.6	153.3	401*2	13.6	42.6, 82.5
50	305.1	149.6	401*2	14.8	40.7, 84.9



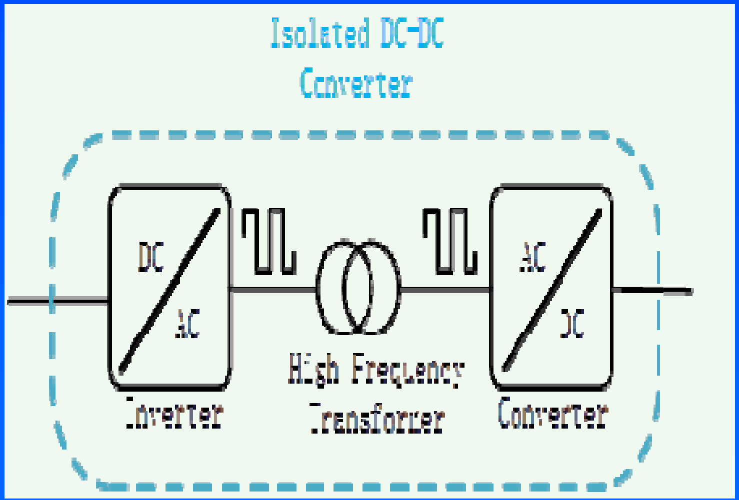
Influence of gap between inner and outer coil on the inductance and critical current

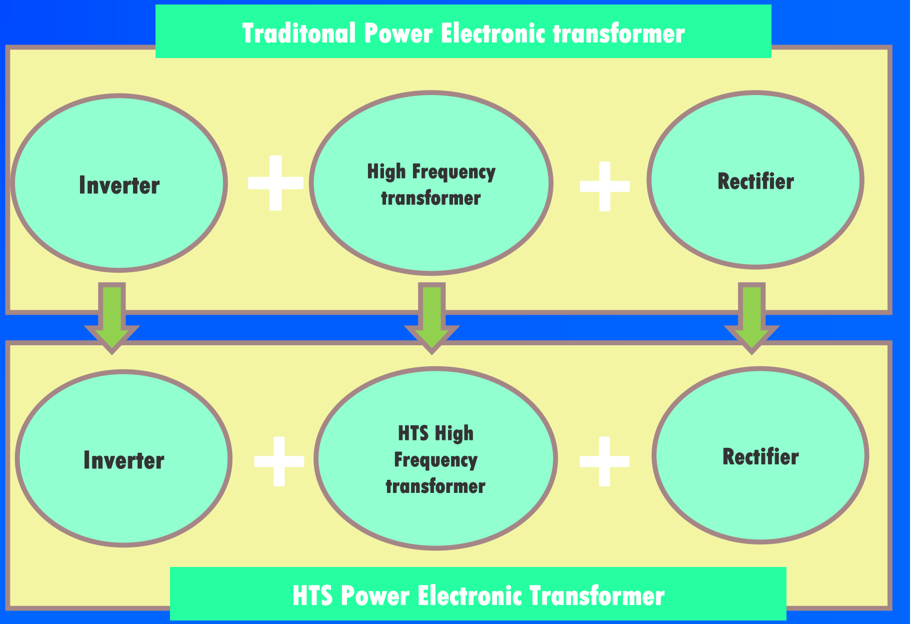
What can be used for HTS in Future DC Power Grid?

- Superconducting DC transmission cable/energy pipeline
- Superconducting DC fault current limiter
- Superconducting DC power electronic transformer

HTS DC power electronic transformer

With the development of DC transmission, distribution and micro grid, the DC power electronic transformer will become an key equipment to achieve energy conversion and network connnection.





High Frequency Transformer

Option I   Iron-core high-frequency transformer

Amorphous iron core

Amorphous soft magnetic alloy with high saturation flux density, high permeability, high Curie point, low high-frequency loss, good thermal stability, can be used for high frequency transformer.

166 kW/20 kHz transformers by copper Litz wire

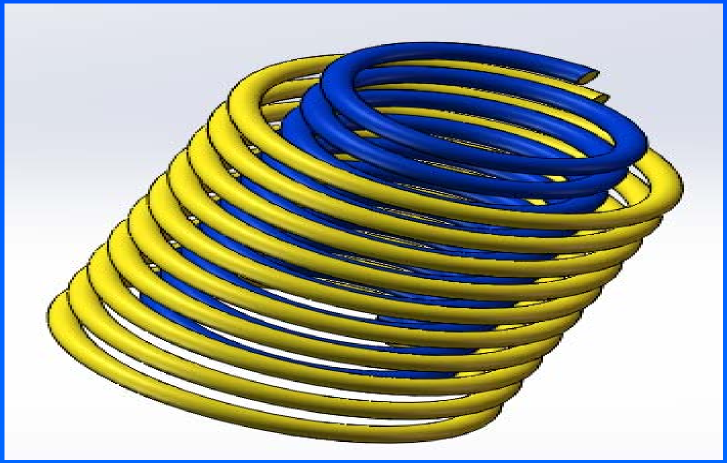
Using of superconductor as primary & second windings can reduce the window area of iron core and the volume of iron core. Therefore, HTS high frequency power transfermer will be smaller in both volume and weight.

High Frequency Transformer-HTS air-core

Option II Air-core high-frequency transformer

- The selections of operating frequency of air-core transformer is more flexible
- HTS superconducting coil can carry larger current
- Resonant coupling can improve the magnetizing current of air-core transformer

→ HTS high frequency air-core transformer with large capacity, small size, light weight, etc.



The efficiency of air-core transformer depends on the coupling strength between windings. Using solenoid coils as primary winding and secondary winding of transformer, the coupling coefficient between windings will be higher than that of pancake coils.

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HTS High Frequency Transformer

Design of high-frequency transformer (Resonant coupling)

TABLE I: Electrical Parameters For Transformer

Items	Value
Rated Power(MVA)	1
Operating Frequency(kHz)	10
Primary Voltage (kV)	1.2
Secondary Voltage(kV)	12
Isolation(kVDC)	>100
Volume of Windings(cm)	32*32*8

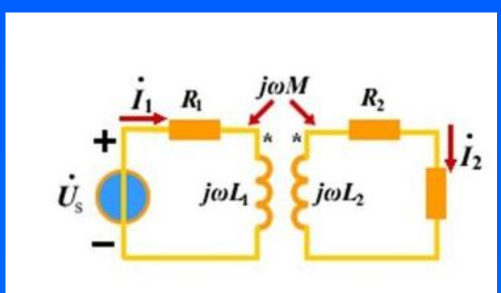

TABLE II: Structure Parameters For Transformer

Items	Primary Coil	Secondary Coil
Self Inductance/ μ H	26.92	2196
Turns	8	68
ID(mm)	300	312
OD(mm)	302	316
Height(mm)	80	68
Length of Tape(m)	75.9	66.8
Coupling Coefficient	0.9	
Interturn Gap Between Coils (mm)	5	
Ic of Tape(A)	220	
Width of Tape(mm)	4	4
Thickness of Insulated Tape(mm)	0.5	0.5

Thank you for your attention!