Experimental and Simulation Analysis of Electrical Breakdown for 220kV Silicone Rubber Pre-Molded Cable Joints

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HV Cable System in CSG

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Overall Scale

Voltage Level	Circuit No.	Yearly Growth	Total Length (km)	Yearly Growth
110kV & above	2285	16.30%	5042	14.40%
110kV	2122	16.02%	4057	2.30%
220kV	162	20.90%	504	22.90%
500kV	1	0.00%	31	0.00%

Note: data collected by the end of 2016, including pure and hybrid lines.

Pure Cable Lines

Voltage Level	Circuit No.	Total Length (km)	Yearly Growth
110kV & above	550	2006	39.79%
110kV	491	1685	41.53%
220kV	59	321	63.69%
500kV	0	0	0.00%

HV Cable System in CSG

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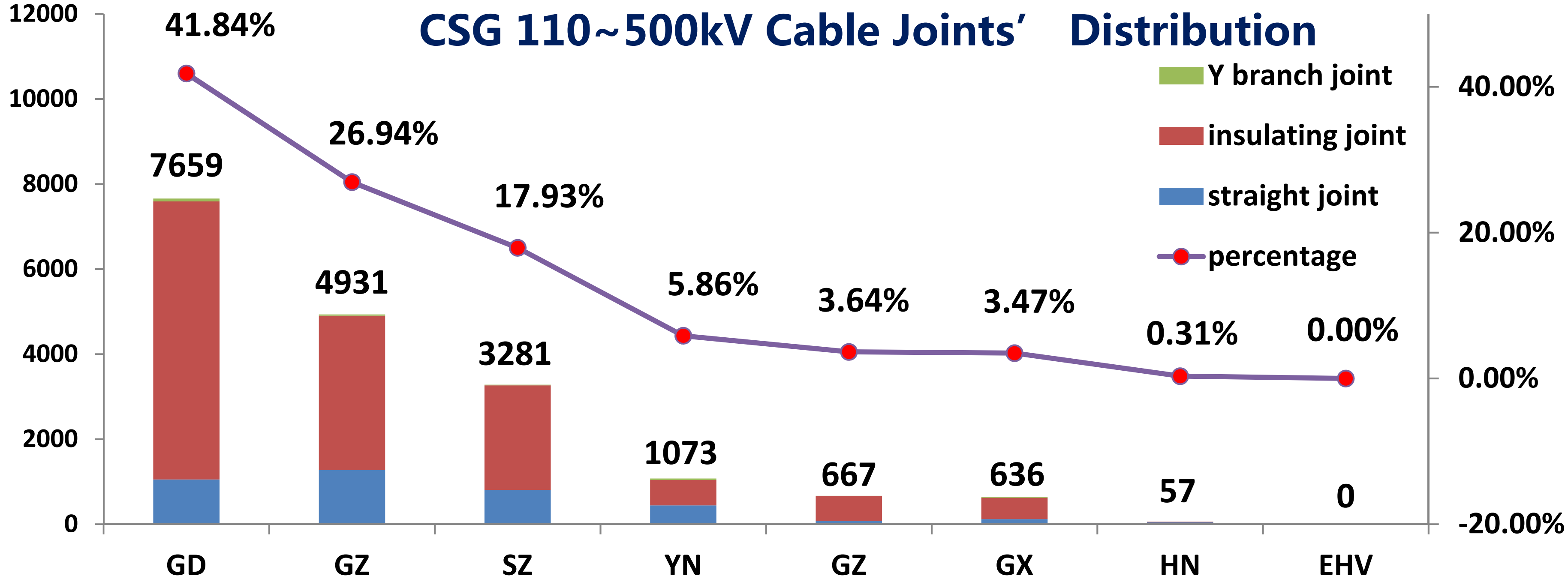
Cable Joints



- By the end of 2016, 18304 110kV~500kV high-voltage cable joints are in operation in South China Power Grid.
- As the most commonly used and maintenance free HV cable joints, PMJ dominates the application of HV power cable systems for 110kV and above in China.

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Background of PMJ Breakdowns

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Cable Failures 2016 China

Fire in cable trench of 330kV substation, 18 June, Xi’an

Fire in 220kV cable tunnel, 22 August, Chongqing

Blast of 220kV cable terminal,

19 August, Hebei

Background of PMJ Breakdowns

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Cable Joint Breakdowns in CSG

No.	Operation time	PMJ No.	Failure No.	Failure time	Action	Operation time
1	2008.02	4	1	2013.02	Switch-on	5y
2	2010.12	16	3	2013.11	Switch-on	3y
3	2012.07	30	3	2015.11	Switch-on	3y
4	2012.07	31	2	2013.07	Switch-on	1y
5	2013.12	30	3	2016.01~02	Switch-on	2y
6	2013.12	6	1	2015.12	In operation	2y
7	2013.12	57	2	2014.10/2016.02	Switch-on	1~2y
total			**15**			

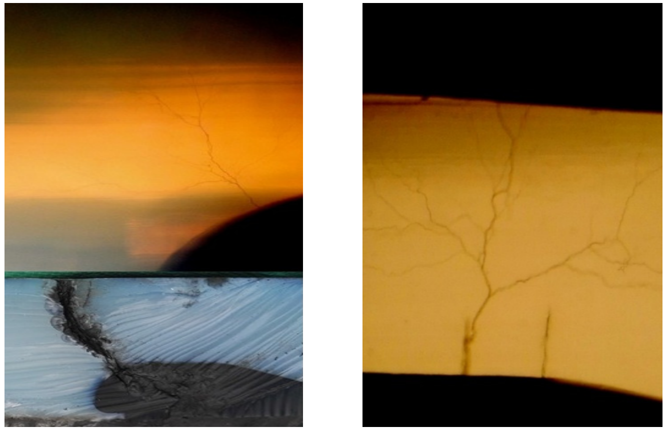
Cable Joint Breakdowns in other areas of China

No.	Operation time	Failure No.	Failure time	Action	Operation time
1	2011.06	1	2012.01	Switch-on	0.5y
2	2011.06	1	2012.11	In operation	1.5y
3	2011.06	8	2013.05	OWT	2y
4	2005.01	1	2014.06	Switch-on	9y
5	2011.07	4	2014.07	Switch-on	3y
total		**15**			

Background of PMJ Breakdowns

- In recent 10 years, CSG had 15 220kV silicone rubber pre-molded cable joint (PMJ) breakdowns, which seriously threaten the personal safety and stable operation of power system. HV cable PMJ breakdowns were largely reported in China.
- The dissections of the cable PMJs mostly showed an apparent breakdown paths and electrical trees. Impurities, protrusions and voids by careless production have been assumed to be the main cause.

220kV Cable PMJ Breakdowns



Typical Breakdown Paths

But is this assumption true?

Background of PMJ Breakdowns

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- After several PMJ breakdowns in January 2016, this study was required by CSG to start on products of two main manufactures (A & B), which also have the biggest market occupancy in CSG.
- PMJs in service for about 3 years were substituted and collected for the analysis, as well as the breakdown PMJs. The study included:
  - **electrical test** – endurance, PD, load cycle (temperature cycle)
  - **microscopic observation** – stress cone sliced, looking for impurities/voids/protrusions and electrical trees
  - **mechanical analysis** – elongation at break, tensile strength, elastic modulus, simulation on the interfaces
  - **overvoltage simulation** – EMTP circuit modelling, on site oscillograph

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Experimental & Simulation Study

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Electrical Test

❈ Test Samples:

- non-fault PMJs in the same cable circuits
- replaced from the service
- in operation for three years of time

❈ Experimental Setup:

- 220kV cable test circuit (2500mm^2)
- High voltage resonance test system
- High voltage divider
- Digital PD detector
- Impulse voltage generator

Experimental Setup for Electrical and Partial Discharge Measurement on 220kV PMJs

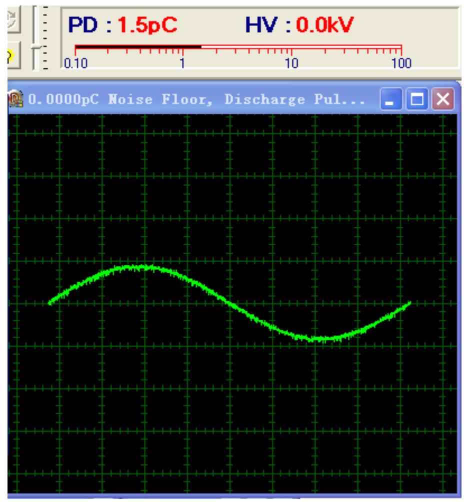
Electrical Test

Step	Test	requirements
1	Voltage endurance and PD test at room temperature	Increase voltage to 1.7U_0 (216kV) step by step with partial discharge monitoring, stay 1h and decrease voltage to 0 step by step
2	Warm up test	The same as step 1 at 70℃
3	Cool down test	The same as step 1 after cooling back to room temperature
4	Impulse test	Crest: 1050kV Range 3% Wavefront time T1:1~5us Wave tail time T2 is 40~60us
5	Test after impulse	The same as step 1 after 10 positive and 10 negative impulse voltages

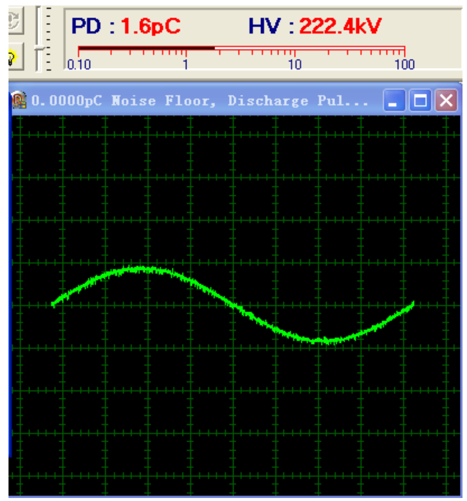
Experimental & Simulation Study

Electrical Test

- All tests were carried out on serviced PMJs of manufacture A (MA) and manufacture B (MB), according to China National Standard (GB/T 18890, 2015).
- The 220kV PMJs of two manufactures all passed above voltage withstand tests, and no partial discharges were detected above background 2pC.
- The outcomes of electrical test didn't show the evidence that the load cycling and circuit breaker switching have brought any direct impact on these PMJ failures or tree growth.



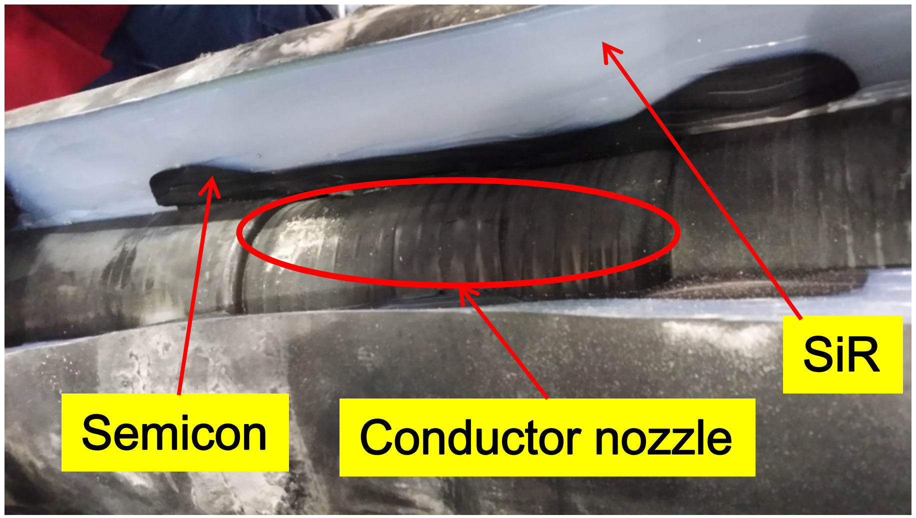
Background noise



1.7U_0 endurance

Microscopic Observation

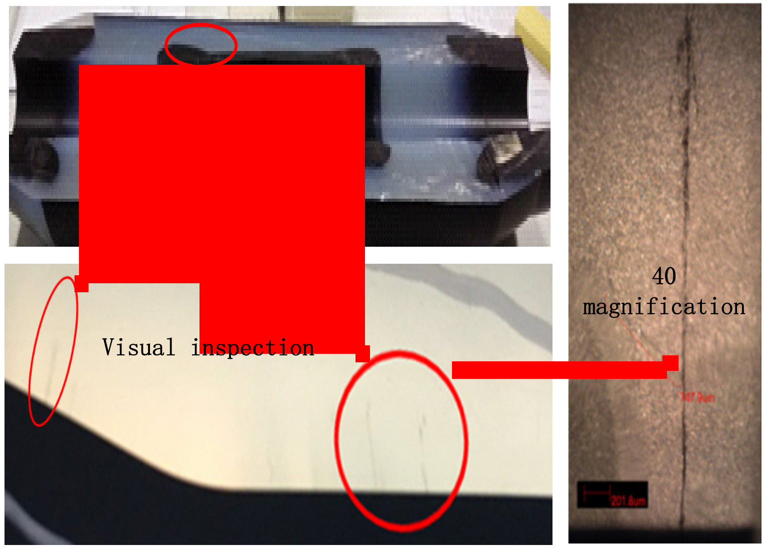
- PMJs stress cones were investigated by microscopic observation. Silicone rubber insulation, semi-conductive material and their interfaces were checked.
- MA and MB PMJs were dissected and sliced with microscopic observation at National Key Lab in Xi’an Jiaotong University.



Experimental & Simulation Study

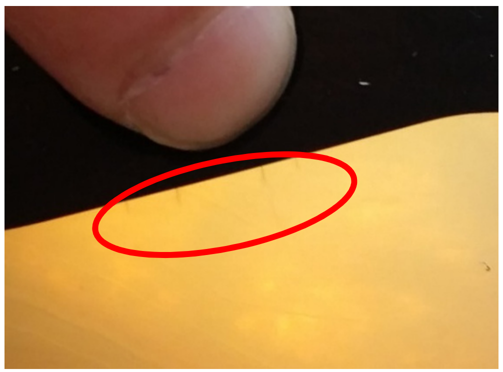
Microscopic Observation

- MA PMJs:
  - The average protrusion size of is 16μm (all smaller than 50μm).
  - Electrical trees were found at the interfaces in all 3 breakdown PMJs and 2 serviced PMJs, mostly at their preliminary stage with short and straight sprout.
  - Some of these small trees even did not begin from the region with the highest electrical field.



Electrical Trees at the Interface of 220kV PMJ Stress Cone

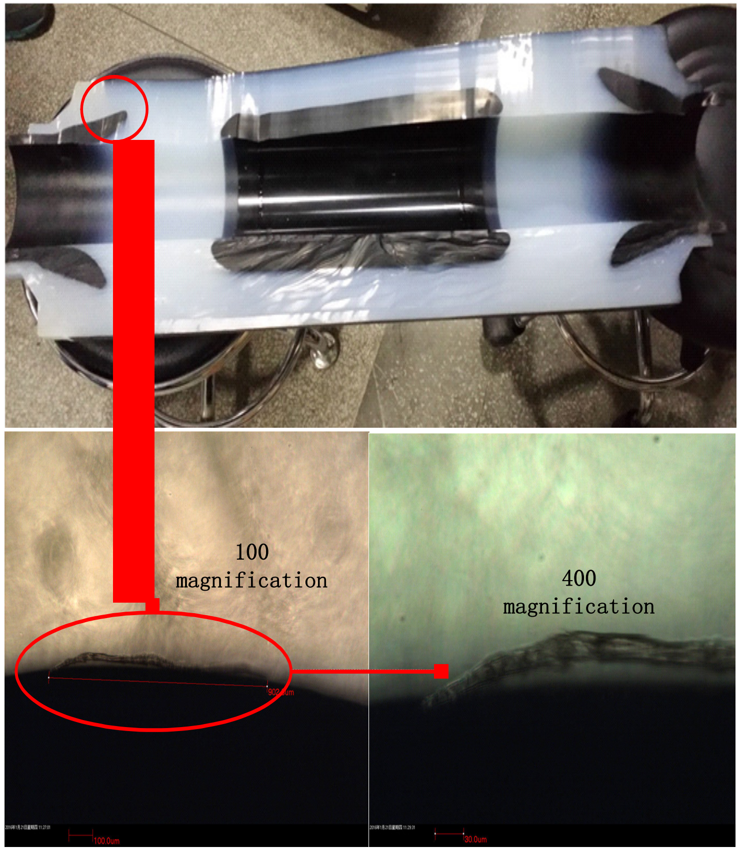
Where are these tree from?



Microscopic Observation

❋ MB PMJs:

- Large size air voids and protrusions from 50μm to 900μm were found at the semicon-SiR interfaces.
- PD and electrical trees will initiate with such big voids and protrusions under long-term and complex operating conditions, though these "defects" could hide from routine tests before service.
- Quantitative requirement of 50μm was suggested to CSG technical standard for the impurity sizes.

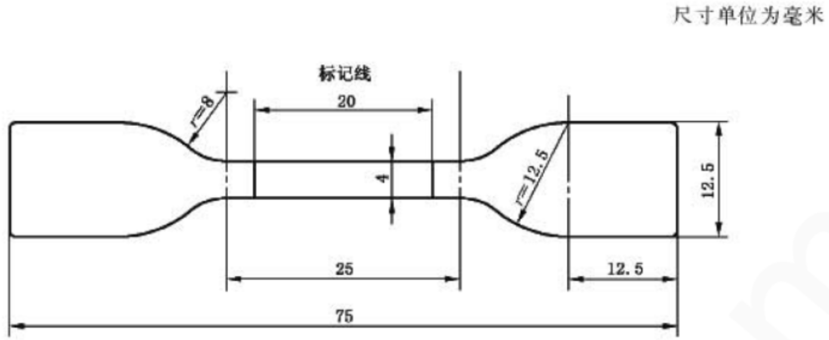


Microscopic Defects of 220kV PMJ Stress Cone (Manufacture B)

Mechanical Study – Experiment

- Five dumbbell samples cut from each PMJ were tested at room temperature (23±5℃) at the stretching rate of 200mm/min, according to GB/T 528-2009.
  - MA: (1) elongation percentage at break measurement results of 2 samples were 416% and 446%, which failed to meet China National Standard requirement of 450%; (2) tensile strength test results of 2 samples were 4.6MPa and 4.9MPa, which failed to meet China National Standard requirement of a minimum value of 5.5MPa.
  - MB: all meet the standard.

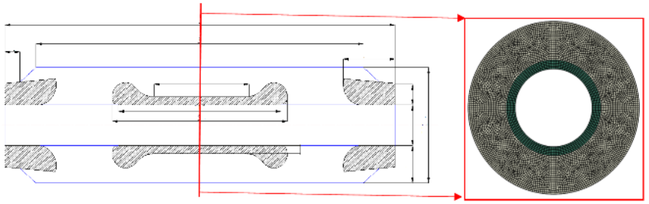
Conclusion: MA PMJ samples exhibited an unqualified mechanical performance.



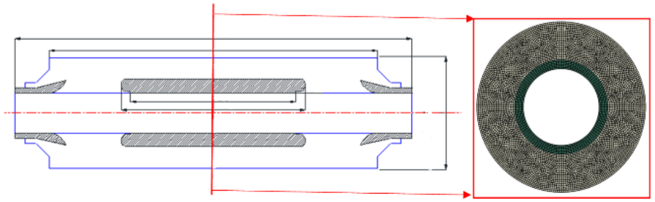
Experimental & Simulation Study

Mechanical Study – Simulation

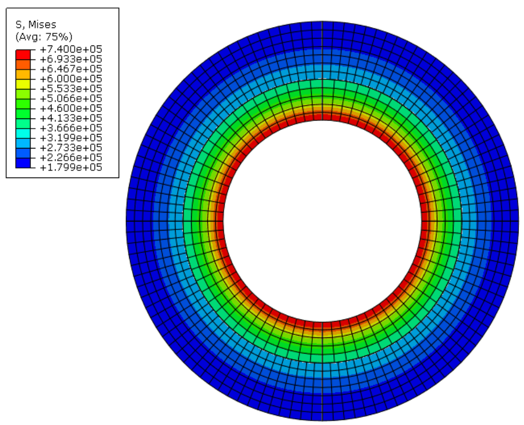
- The software ABAQUS was used for this job at the unique cross section at the very middle of PMJ's stress cone on MA and MB designs.



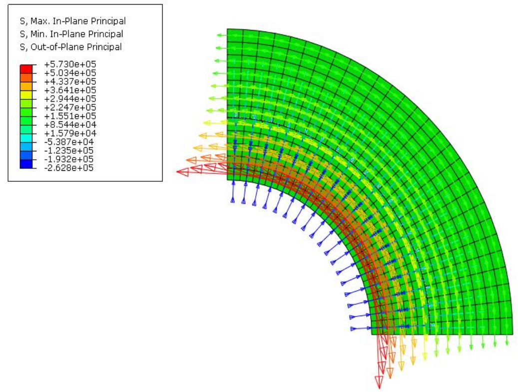
stress cone of manufacture A



stress cone of manufacture B



stress field distribution



stress vector of 1/4

Experimental & Simulation Study

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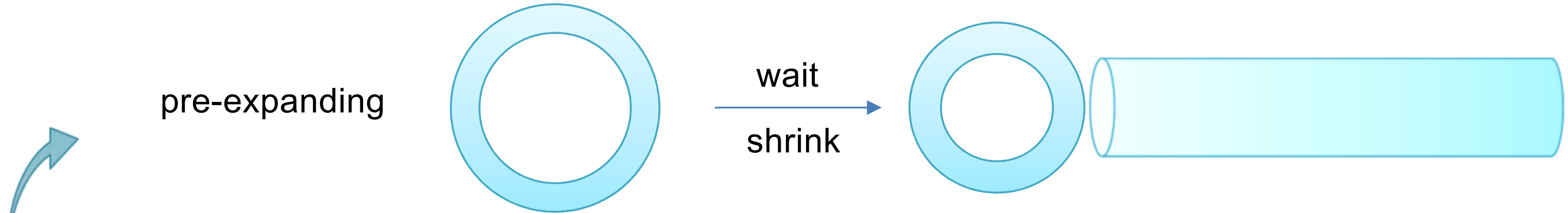
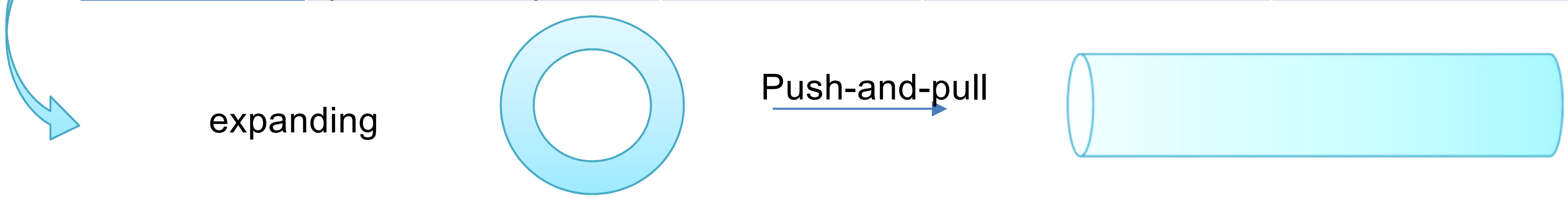
Mechanical Study – Simulation

- Material selection, structure design and installation technique are important for the interface stress. For example, MB PMJ has bigger SiR stress with higher elastic modulus and smaller expansion rate of 26%, compared with MA.

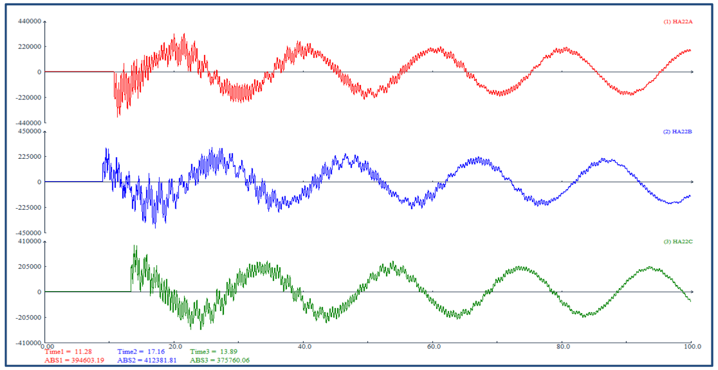


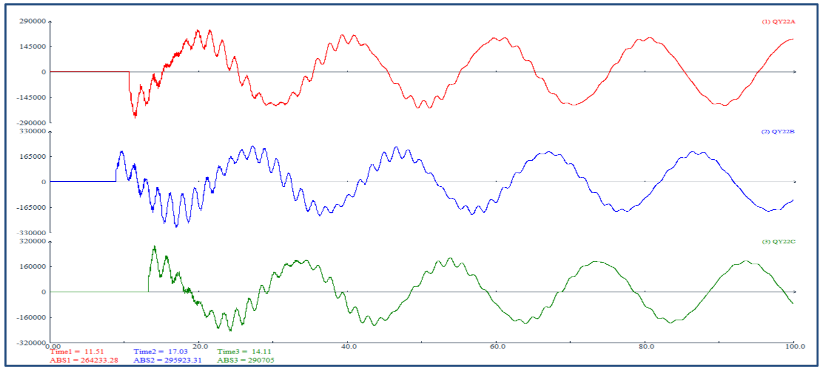
Provider	Installation technique	Exp. rate	Max. semicon stress	Max. SiR stress
M A	Pre-expanding	129%	2.43MPa	1.13MPa
	Operation	57%	0.87MPa	0.36MPa
M B	Push-and-pull (operation)	26%	0.74MPa	0.37MPa



Experimental & Simulation Study

Overvoltage Simulation





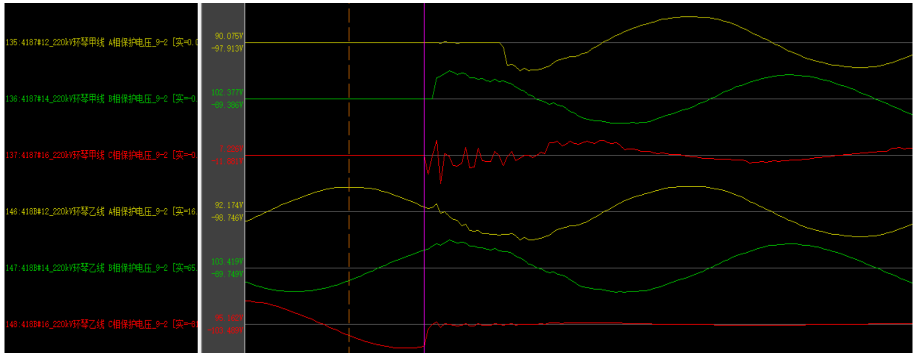
- Transient overvoltage was calculated by using EMTPE to check if the PMJ failures were caused by switching overvoltage as most of them occurred during switcher’s closing.
- The cables’ equivalent circuit models, including power supply, substations and arresters were built, same 220kV double circuit cable lines.

Experimental & Simulation Study

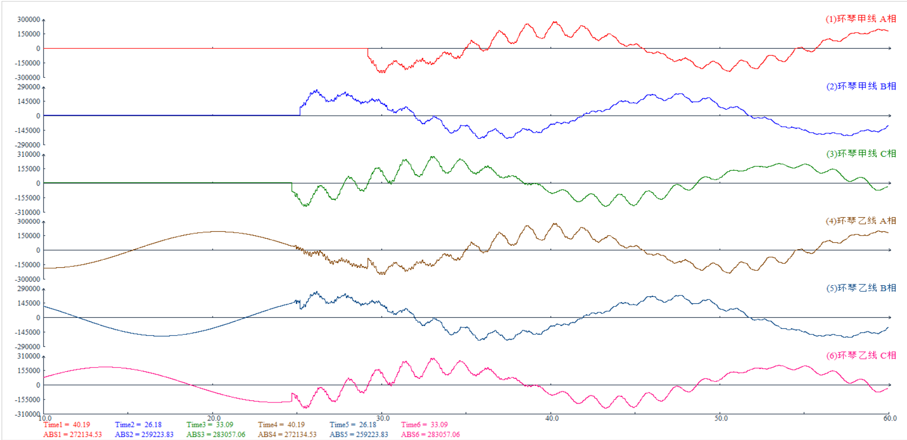
Overvoltage Simulation

position	SA	1km	2km	3km	4km	5km	6km	7km	8km	9km	SB
overvoltage kV	305.0	321.0	337.7	351.5	365.1	376.2	387.0	399.4	407.1	411.2	412.4

- The highest overvoltage along the line was 412.4kV_{peak}, with the worst situation (random switching phase, no synchronization).



- Recorded fault oscillograph shows that the maximum transient voltage are 283kV_{peak} (1.37p.u.) and 223.1kV_{peak} (1.08p.u.) on the failure cable lines.



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Discussion & Conclusion

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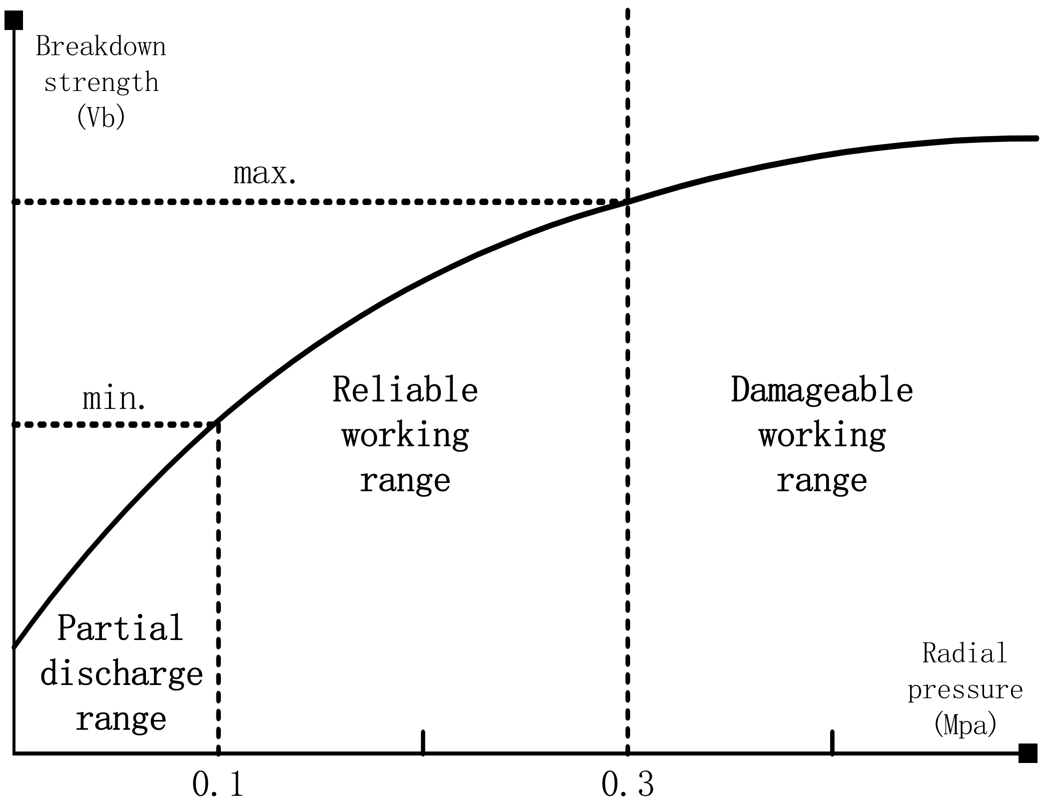
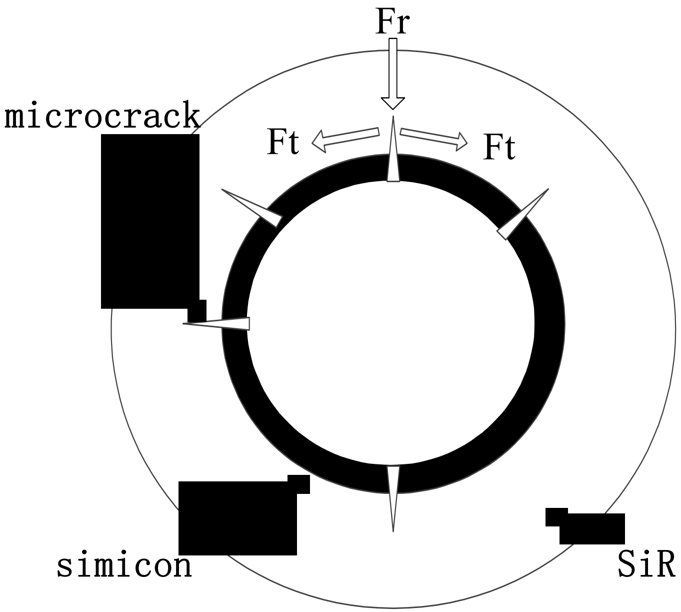
- Cable PMJ failures are attracting attentions with its imperfect technology. The mechanical properties of insulating and semiconducting materials and the mechanical stresses they experienced with a typical design are rarely investigated when dealing with their breakdowns.
- Based on previous study, 0.1MPa was advised to maintain a seamless contact that can prevent surface discharge along the interface.
- The higher of the radial pressure, the better of the dielectric strength. But what about the operation reliability?



Discussion & Conclusion

- However, there are two reasons for setting an upper limit (hypothetically 0.3MPa):
  - the elastic material, silicone rubber or EPR, may have micro-cracks that trigger electrical tree growth with partial discharge;
  - the increment of interface breakdown strength slows down with the further increasing of interfacial pressure.



switch on = last straw?

Discussion & Conclusion

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(1) Mechanical performance of HV cable PMJs play a key roles in assuring the dielectric strength and reliability. Electrical trees can be developed from micro-cracks probably at the molecular dimension if the expansion ratio is too high. Pre-expanding installation is more risky than push-and-pull installation, since the material would have more chance of getting micro-cracks.

(2) Impurities and protrusions can initiate partial discharge in long-term service. PMJs with good quality control are suggested to have impurity size less than 50μm.

(3) Transient voltage by switching operation may work as the trigger for well developed trees to bring about a breakdown.

A more systemic research project is ongoing on the failure mechanism of HV cable PMJs. Rubber material's deterioration properties, electrical tree initiation and propagation under different mechanical stress and voltage types are being studied.

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Thank You!

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