TRV Phenomenon in Chinese 1100kV UHV Series Compensated System

Bin Zheng, Zutao Xiang, Liangeng Ban, Jimin Lin, Nihong Gu, Gang Sun, Bin Han

***Abstract*: Based on the planned Ximeng-Beijingdong UHV project in China, this paper mainly focuses on the TRV phenomenon in UHV series compensated system. The results show that, without countermeasure, the peak value of TRV during clearing single phase to ground fault in Ximeng-Beijingdong UHV series compensated lines may exceed 2.7p.u.(1p.u.=1100kV*$\sqrt{2}/\sqrt{3}$) and the TRV during clearing multi-phase fault may exceed 3.0p.u., which are much larger than the amplitude of TRV in present circuit breaker (CB) standards. This phenomenon may result in the failure of clearing system fault and the damage of circuit breaker. Several influencing factors for TRV in UHV series compensated transmission lines are analyzed. In order to limit the TRV, different countermeasures are investigated. The investigation indicates that, for Ximeng-Beijingdong UHV series compensated system, fast bypass series capacitors during system fault can effectively reduce the TRV peak value of line CBs, but the peak value still statistically exceeds related standards. Through the discussion with purchasers, manufacturers and test labs of UHV CBs, a common view of increasing the withstand capability for TRV of UHV CBs used for series compensated system is reached and a new higher test requirement for 1100kV CB is suggested.**

***Keywords*: UHV, Series compensation, Circuit breaker, Transient recovery voltage, Countermeasure, Increasing test requirement**

I. Introduction

On January 6th, 2009, in China, the first 1100kV AC system was successfully put into service[4]. Recently, for advancing the advantage of UHV power transmission technology, meeting the need for long distance and huge capacity power transmission and enhancing the system stability performance, State Grid Corporation of China (SGCC) plans to build more UHV double-circuit transmission projects and take the initiative in the world to adopt series compensation (SC) technique in UHV system. [9], [10, [11]].

Ximeng-Beijingdong 1000kV transmission project, which is 363km long, is the first segment of a huge planned UHV project—Ximeng-Nanjing project(about 2*1400km) in east China. As shown in Fig.1. Ximeng-Beijingdong 1000kV line consists of 163km double circuit lines and 201km single line. The shunt reactors are adopted on both line sides, with 840Mvar for Ximeng side and 720Mvar on Beijingdong side. The compensation degree of SC is 40% and is planned to be installed on Chengde station instead of on one line side for some location selection limitations, being 68km far away from Ximeng UHV station. Based on the system research, 5.3kArms is adopted as the rated current of Ximeng-Beijingdong UHV SC capacitors. In the primary stage of Ximeng-Beijingdong UHV project, the supply side is mainly linked with several power plants, which shows the characteristic of radial power transmission system.

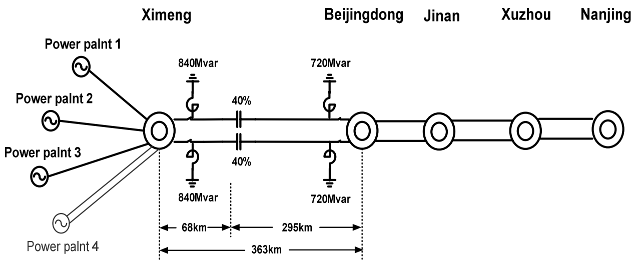

Fig.1 Ximeng-Beijingdong-Nanjing UHV transmission system of State Grid Corporation of China

Many researches on UHV series compensated transmission system have been carried out in China [10], [11]. CB is one of the most difficult and critical equipment of UHV transmission project [1], [6], [13]. And the transient recovery voltage (TRV) issue is crucial to clearing short circuit fault and it takes on one key performance of CBs breaking capability. By EMTP tool, this paper mainly focuses on the TRV phenomenon of CBs in 1100kV series compensated system [5].

II. TRV for UHV Lines with SC and Test Standards for 1100kV Circuit Breakers

When fault occurs on SC lines, according to the overvoltage protective strategy of UHV SC equipment, if the short current passing by is large enough, the capacitor may be bypassed quickly by the triggering of forced triggered gap (GAP). In this condition, TRV level is close to that with no series capacitors. Due to the factors such as long line, light load operation mode and so on, the fault current may be small and the GAP wouldn't be triggered. Because of the residual voltage of series capacitor, as shown in Fig.2, the recovery voltages across the CB increases while breaking [8], [14], which may result in the failure of clearing fault and the damage of CB[1], [6]. There are several influencing factors for TRV in UHV series compensated transmission lines, such

Bin Zheng is with China Electric Power Research Institute (CEPRI), Haidian District, Xiaoying East Road 15, Beijing, China (e-mail: zhengbin@epri.sgcc.com.cn).

Zutao Xiang, Liangeng Ban, Liming Lin, Nihong Gu, Bin Han are all with China Electric Power Research Institute, Haidian District, Xiaoying East Road 15, Beijing, China (e-mail: xzt@epri.sgcc.com.cn)

Gang Sun is with the Department of Ultra-high Voltage Construction, State Grid Corporation of China (SGCC), Changan Street 86, Beijing, China (e-mail: g-sun@epri.sgcc.com.cn).

Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

as SC's compensation degree, rated current, layout position, protective system performance, etc [7].

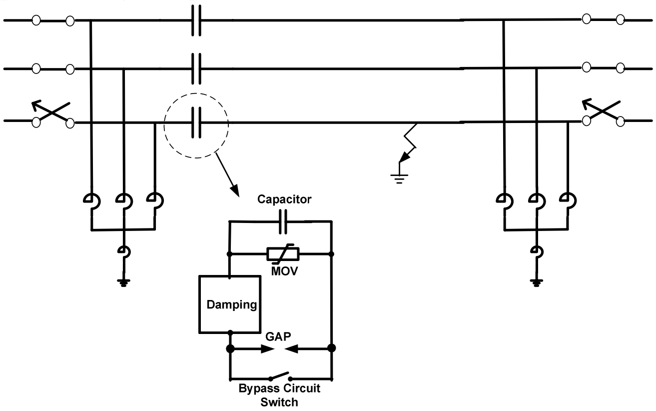

Fig.2. Sketch for Circuit Breakers Clearing Single Phase Fault in UHV Series Compensated Lines

At present, the standard for 1100kV CBs TRV has not been added by IEC [19]. China has put forward it as national test standard in [20], the main parameters are shown in Tab I. T100, T60, T30, T10 present the different test conditions of 100%, 60%, 30% and 10% opening rated short-circuit current separately. OP1-OP2 presents the test condition of out-of-step interruption. The rated breaking current is not less than 50kArms.

TAB I PRESENT 1100KV CB TRV TEST STANDARD IN CHINA

Rated voltage	Test Mode	First-pole-to-clear factor	Amplitude factor	TRV peak value (kV)	RRRV (kV/μs)
1100	T100	1.3	1.40	1635	2.0
	T60	1.3	1.50	1751	3.0
	T30	1.3	1.53	1786	5.0
	T10	1.3	1.53	1786	10.0
	OP1-OP2	2.0	1.25	2245	1.54

Peak value, rise rate of recovery voltage (RRRV) and breaking current are the main parameters about CBs TRV. For the case that the fault occurs at some position being far away from the CB, the peak value tends to be large, while the interrupting current is below 1/4 of rated short circuit breaking current and RRRV is below 1.54kV/μs. Whereas, 2245kV (2.5p.u., 1pu=1100kV* $\sqrt{2}/\sqrt{3}$) for OP1-OP2 can be adopted as the permitted peak value of TRV for this situation [21].

III. TRV OF XIMENG-BEIJINGDONG UHV SC LINES CIRCUIT BREAKERS WITHOUT COUNTERMEASURES

Without any countermeasures, the TRV of Ximeng-Beijingdong UHV lines with SC are analyzed. Different impact factors are considered in the research, such as system operation modes, fault types, fault positions and so on. 1) Operation modes include normal and one line out of service (N-1).2) Fault types include Φ-to-ground fault (1LG), 2Φ-to-ground fault (2LG) and 3Φ-to-ground fault (3LG). 3) 14 fault positions along the UHV line are considered including Ximeng and Beijingdong station. The overvoltage protective level for Ximeng-Beijingdong UHV SC equipment is 2.3p.u. (1p.u. presents SC rated voltage) [11]. Also, the dispersion of fault time, and trip time of CBs on two sides are also taken into consideration. Tab II to Tab IV lists statistical results.

Fig.3 shows the fault positions distribution of Ximeng-Chengde-Beijingdong UHV lines considered in this paper.

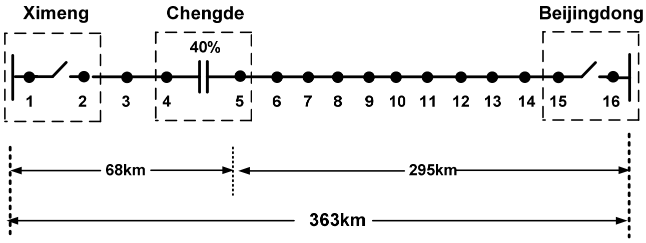

Fig.3. Fault position N.O.of Ximeng-Chengde-Beijingdong UHV lines

TABLE II
TRV OF XIMENG-BEIJINGDONG LINE CBS WHEN OPENING 1LG FAULT

Fault type	Operation mode	Fault position	TRV Peak value of offside CB (kV)/p.u.
1LG	Normal	Ximeng	2206 /2.46
		Beijingdong	2440 /2.72
	Line N-1	Ximeng	2267 /2.52
		Beijingdong	2423 /2.70

TABLE III
TRV OF XIMENG-BEIJINGDONG LINE CBS WHEN OPENING 2LG FAULT

Fault type	Operation mode	Fault position	TRV Peak value of offside CB (kV)/p.u.
2LG	Normal mode	Ximeng	2369 /2.64
		Beijingdong	2605 /2.90
	Line N-1	Ximeng	2336 /2.60
		Beijingdong	2673 /2.98

TABLE IV
TRV OF XIMENG-BEIJINGDONG LINE CBS WHEN OPENING 3LG FAULT

Fault type	Operation mode	Fault position	TRV Peak value of offside CB (kV)/p.u.
3LG	Normal	Ximeng	2588 /2.88
		Beijingdong	2784 /3.10
	Line N-1	Ximeng	2532 /2.82
		Beijingdong	2793 /3.11

Above results show the following two conclusions:

(1) Without any TRV restriction measures, when clearing 1LG fault at one side of SC line, the TRV peak value of CB at the other side of SC line may exceed 2245kV which is required by OP1-OP2 test in standard, with the maximum reaching to 2440kV(2.72p.u.). Corresponding to these cases, the interrupting current of this CB is below 1/4 of rated short circuit breaking current and the RRRV is below 1.54kV/μs.

(2) Without countermeasures for TRV, when clearing 2LG or 3LG fault, the TRV peak value of line CB exceeds the 2245kV required by OP1-OP2 test, with the maximum reaching to 2793kV (3.11p.u.). Corresponding to these cases, the interruption current of the CBs are all below 1/4 of rated drop out current and the RRRV are all below 1.54kV/μs.

IV. STUDY ON COUNTERMEASURES FOR RESTRICTING TRV OF XIMENG-BEIJINGDONG UHV SC LINE CIRCUIT BREAKERS

Several countermeasures for restricting TRV of UHV

CBs are analyzed for Ximeng-Beijingdong 1100kV series compensated lines.

A. *Fast bypass SC measure.*

When relay protection system detect the faults occurring on the line, the signal would be sent out to open CBs and it is suggested to be simultaneously delivered to the SC equipment to bypass the capacitors quickly. After receiving the bypass order, the gap of SC would be triggered to bypass SC if the voltage between the electrodes of GAP is higher enough. If the capacitor is bypassed by the GAP triggering, the TRV caused by the adverse impact of capacitor can be reduced.

However, if the fault position is too far, the fault current through the target CB maybe low and the overvoltage across the GAP may be under the minimum trigger voltage. Thus the GAP can't be triggered and the TRV is consistent to that without fast bypass measure. Fig.4 and Fig.5 show the TRV results while clearing 1LG fault after taking the bypass measure. Normal operation mode and N-1 mode are both provided.

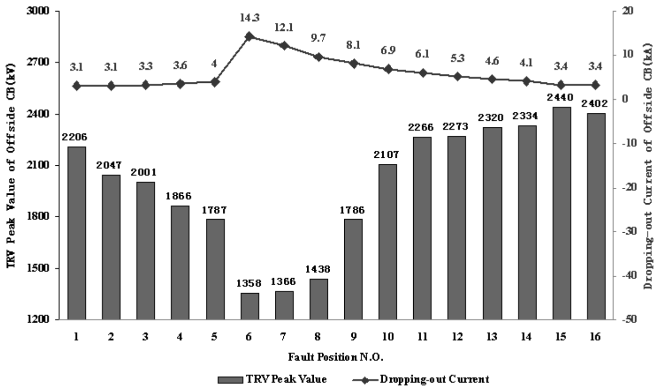

Fig.4. TRV peak value and breaking current of offside CB when Ximeng-Beijingdong UHV lines occurs 1LG fault under normal mode

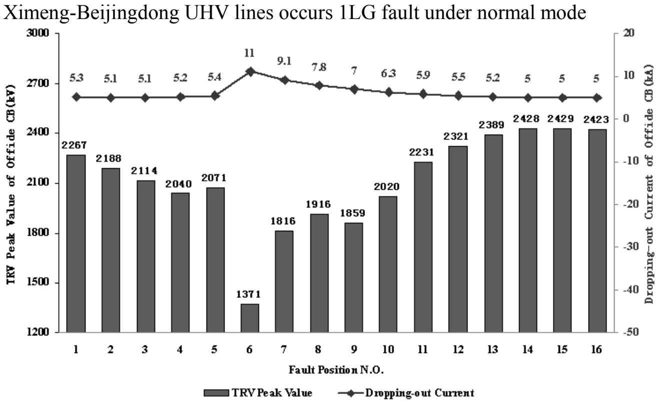

Fig.5. TRV peak value and breaking current of offside CB when clearing 1LG fault on Ximeng-Beijingdong UHV lines under N-1 mode

Fig.4 and Fig.5 show the maximum TRV peak value during clearing 1LG fault along the line is 2440kV(2.72p.u.), as shown in Fig.6, which is about 200kV higher than 2245kV permitted in the standard. It occurs at the Ximeng line CB while clearing 1LG fault at Beijingdong station SC line side. For those TRV peak value exceeding 2245kV, the steady breaking current is below 1/4 of rated breaking current and the RRRV are all below 1.54kV/μs.

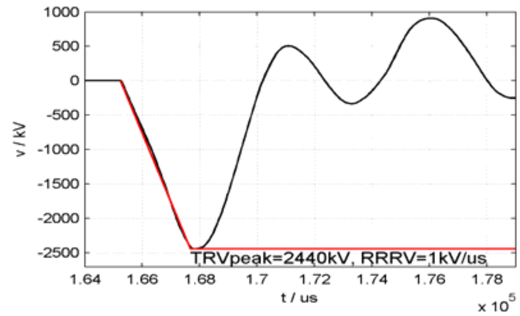

Figure.6 TRV of Ximeng CB when clearing 1LG fault occurring at Beijingdong line side under normal mode

With respect to clearing multi-phase faults like 2LG and 3LG, although the fast bypass measure is adopted, the TRV peak values of CBs are still much higher than 2245kV for many cases. Table V and VI show the results.

TABLE V

TRV OF XIMENG-BEIJINGDONG LINE CBS WHEN OPENING 2LG FAULT

Fault type	Operation mode	Fault position	TRV Peak value of offside CB (kV)/p.u.
2LG	Normal mode	Ximeng	2369 /2.64
		Beijingdong	2605 /2.90
	N-1 mode	Ximeng	2318 /2.58
		Beijingdong	2638 /2.94

TABLE VI

TRV OF XIMENG-BEIJINGDONG LINE CBS WHEN OPENING 3LG FAULT

Fault type	Operation mode	Fault position	TRV Peak value of offside CB (kV)/p.u.
3LG	Normal mode	Ximeng	2588 /2.88
		Beijingdong	2742 /3.05
	N-1 mode	Ximeng	2448 /2.73
		Beijingdong	2793 /3.11

B. *Reducing the compensation degree of SC.*

Results show that reducing the compensation degree of SC could help to restrict the TRV peak value. For clearing 1LG fault occurring at Beijingdong Station, by degrading the SC compensation degree from 40% to 25%, and together with the fast bypass measure, the TRV peak value of Ximeng CB can reduced from 2440kV to 2171kV, as shown in Fig.7. While the breaking current is below 1/4 of the rated CB breaking current of 50kArms and the RRRV is below 1.54kV/μs.

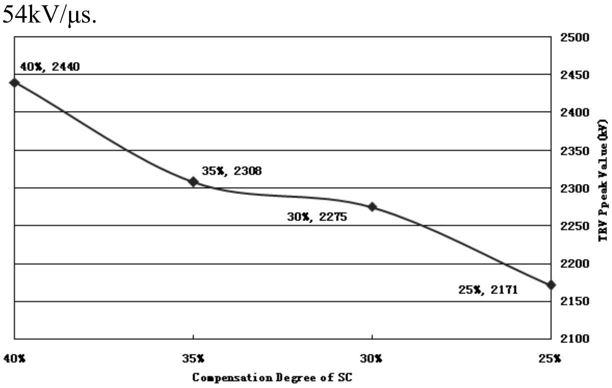

Fig.7 TRV peak value of Ximeng side CB with SC compensation degree varying from 40% to 25% while 1LG fault occurs at Beijingdong station under normal mode

However, considering the demand of advancing the line power transmission capability and the system stability by installing SC, the measure of reducing the compensation degree may bring some limitations for its utility.

C. Laying out SC at two line sides.

As the trapped voltage of SC capacitor enhanced the TRV peak value, taking measures to low the rated voltage of SC capacitor can help to reduce the TRV level. Dividing the SC of Ximeng-Beijingdong lines into two parts and laying them out at the two terminals of the line. Results show that, for the most severe condition that 1LG occurs along the line (not in substation), the maximum TRV peak value of CB turns to be 2127kV and the breaking current is below 1/4 of the rated CB breaking current of 50kArms and the RRRV is below 1.54kV/μs. So, if there are no problems to deal with the land for construction, laying out SC at two line sides is one effective way to reduce TRV level.

D. Adopting opening resistor with CB

Because of damping effect of the resistor, adopting CBs with opening resistor can help to reduce the TRV peak value across CB main contactor. When adopting 600ohm opening resistor with Ximeng-Beijingdong 1100kV line CBs, the TRV peak value between main contacts and auxiliary contacts while clearing 1LG fault are restricted to 1733kV (1.93p.u.) and 1418kV (1.58p.u.). However, research shows that the TRV across the auxiliary contactor may be rather high in certain cases. So, it is necessary to analyze the TRV across CB main contact and auxiliary contact for clearing terminal fault, close-in fault, long line fault and out-of-step fault [3]. The cost and reliability of CB with opening resistor are also important factors that should be estimated in this measure.

E. Paralleling MOV with CB.

This measure was adopted in Turkey 420kV series compensated system [16] since Nov, 1995. Taking this measure, the impact on the TRV while clearing 1LG fault on Ximeng-Beijingdong UHV SC lines are analyzed. The results obtained by 3 MOVs differing in protective level are shown in Fig.8. When 1.85p.u. MOV is paralleled with CB, the TRV peak value is limited to 2201kV.(1p.u.= 1100kV* $\sqrt{2}/\sqrt{3}$).

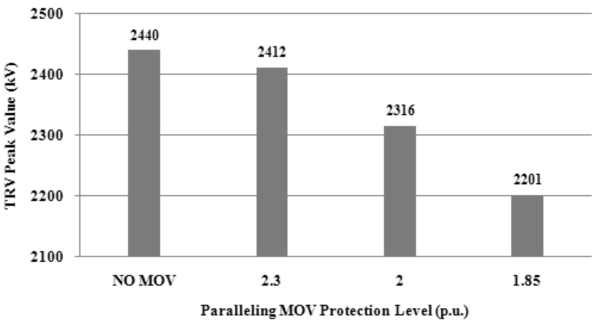

Fig.8 TRV peak value of Ximeng side CB with CB are fixed with paralleling MOV while 1LG fault occurs at Beijingdong station under normal mode

Actually, in some extreme system conditions such as out of phase state, without countermeasures, the energy absorbed by CB paralleling MOV may be rather large. So it is suggested to apply cooperation measures to the disconnectors of CB, which may add the complexity of system operation

F. Increasing the test requirement o f 1100kV CBs TRV amplitude.

In current China and IEC EHV/UHV CB standard, it is required for CBs to bear the TRV peak value of 2.5p.u.and RRRV of 1.54kV/μs when interrupting 25% of rated breaking current. But for SC line CBs, the TRV peak value across CB may exceed 2.5p.u.in some fault conditions. Aiming at these issues, some CB manufactures designed the CB of higher TRV withstand capability and applied it into project. For example, in Turkey, some CBs TRV capacities are enhanced to bear the TRV peak value of 3.2p.u. (1p.u.=420kV* $\sqrt{2}/\sqrt{3}$) and RRRV of 1.54kV/μs for breaking current to be 12.5kArms [15]. While in Canada 735kV SC system, CBs are capable to bear 2.8p.u.(1p.u.=800kV* $\sqrt{2}/\sqrt{3}$) for TRV peak value in order to satisfy the need of system operation, which is higher than IEC standard Also in west Canada 500kV power system, several 500kV SC line CBs can withstand TRV peak value of 3.3p.u.(1p.u.=550kV* $\sqrt{2}/\sqrt{3}$) for breaking current of 6kArms[19].

For Ximeng-Beijingdong UHV SC lines CBs, when clearing 1LG fault, the maximum TRV peak value is 2440kV (2.5p.u.), RRRV is 1.3kV/μs and the steady breaking current is less than 8.5kArms. Referring to above simulation results, the higher TRV test condition for 1100kV CBs is suggested for the CBs used in series compensated transmission lines as shown in Tab VII. 1p.u.= 1100kV* $\sqrt{2}/\sqrt{3}$.

TABLE VII
NEW TRV TEST CONDITION FOR UHV LINE CBs

Rated voltage (kV)	Breaking current	TRV Peak value (kV)	RRRV (kV/μs)
1100	18%	2450 (2.73p.u.)	1.3
Note: (1) If rated breaking current is 50kA, the test current is 9kA. (2) If rated breaking current is 63kA, the test current is 11kA.			

G. Other TRV restricting measures.

Above A to F present the possible countermeasures for restricting TRV and its effectiveness for Ximeng-Beijingdong UHV SC lines. Besides these, there are also some others like degrading the rated current and overvoltage protective level of SC, and degrading the minimum triggering voltage of GAP. Results show that these measures all can help to reduce the TRV peak value to some extent.

V. CONCLUSIONS

This paper focuses on the TRV issues of planned Ximeng-Beijingdong 1100kV UHV AC transmission system with SC in China, the results are shown as follows:

(1) Without countermeasures, in many cases, the TRV peak values of 1100kV SC line CBs when clearing 1LG fault may exceed the present related circuit breaker standard. And it may be much higher during clearing multi-phase faults. Some countermeasures are necessary.

(2) Adopting fast bypass SC measure can help to reduce the TRV amplitude. Because it can be easily reached through improving the relay protection system, so it is suggested to be adopted for SC lines as its low cost and no side-effect features. While in some conditions, such as 1LG fault occurring near Beijingdong station, the TRV peak value of Ximeng CB can reach to 2440kV(2.72p.u.), with the breaking current below 8.5kArms and the RRRV below 1.3kV/μs.

(3) Reducing the compensation degree to 25%, laying out SC at the two line sides can both limit the TRV peak value of clearing 1LG below 2245kV. Adopting CB opening resistor or paralleling 1.85p.u.MOV across CB can also degrade TRV below 2245kV. In addition, degrading rated current and overvoltage protective level of SC, and the minimum triggering voltage of GAP can all help to reduce the TRV peak value to some extent. However these countermeasures all have some limitations, so it is suggested to make rounded estimation before the project application.

(4) Increasing the TRV withstand level of 1100kV CB is another way to deal with TRV over-standard issue. A new test requirement for TRV of 1100kV CBs used in series compensated transmission line is suggested.

(5) The TRV issue of clearing Φ-to-Φ ungrounded fault may be more severe than that of clearing phase-to-ground faults, which are not covered by present CB test standards. Thus further researches should be carried out to deal with this issue.

VI. Acknowledgment

Thanks for the support from SGCC, the manufacturers and test labs of 1100kV CBs. They provide good conditions for the research.

VII. References

Periodicals:

[1] Nakamura Akio, Okamoto Hiroshi, Cao Xianglin, "Introduction to 1000kV transmission technologies conducted by Tokyo electric power company", Power System Technology, vol.29, no.6, pp.1-5, 2005.

[2] Li Ye, Jing Wei, "Operation analysis on Extra-high Voltage Transmission Lines Series Capacitors", Power Capacitor, 2006, vol.4，pp.8-12

[3] Lin Jiming, Gu Mihong, Wang Xiaogang, Ban Liangeng, Wan Chengyu, Xian Zutao, Su Gang, Zheng Bin, "A Study on Transient Recovery Voltage of UHV Circuit Breakers", Power System Technology, vol.31, no.1, pp.1-5, 2007.

[4] Zheng Bin, Ban Liangeng, Zhang Yuanyuan, Wang xiaotong, Wang Xiaogang, Xiang Zutao, Han Bin, Ge Dong, "Contrastive Analysis on Simulation and Measured Overvoltage of 1000kV AC Pilot Project in China",Power System Technology, vol.33, no.16, pp.24-28, 2009

Books:

[5] Dommel H W., "EMTP Theory Book", Canada, 1986

[6] Liu Zhenya, Ultra High Voltage Grid, Beijing, China, 2005

[7] Zhou Xiaoxin, Guo Jianbo, Lin Jiming, Wu Shouyuan,Power System Controllable Series Capacitor Compensation, Beijing, China, 2009, pp.221-230

[8] P.M. Anderson, R.G. Farmer, Series Compensation of Power Systems，PBLSH Inc，USA，1996.

Technical Reports:

[9] Lin Jiming, Ban Liangeng, Wang Xiaotong, Han Bin, "Overvoltage Insulation Cooperation Research on 1000kV UHV AC Double Circuit Transmission Lines", China Electric Power Research Institute, Beijing, China, Aug.2008

[10] Zheng Bin, Ban Liangeng, Xiang Zutao, Qin Xiaohui, "Electromagnetic Analysis on Ximeng-Beijingdong UHV Double Circuit Series Capacitor Compensation Lines", China Electric Power Research Institute, Beijing, China, Mar.2010

[11] Xiang Zutao, Zheng Bin, Ban Liangeng, " Study on Basic Design, Main Equipments Specifications and Overvoltage Protection Strategy of Ximeng UHV Series Compensators", China Electric Power Research Institute, Beijing, China, Mar.2010

[12] "Statistical Analysis on Clearing Fault Time of 220kV and Higher Voltage Power Lines and Equipment Failure Rate between 1999-2004 in China", State Grid Corporation of China, China Electric Power Research Institute, Beijing, China, 2005

Papers Presented at Conferences (Unpublished):

[13] Lin Jiming, Ban Liangeng, Wang Xiaogang, "Discussion About Electromagnetic Issues of China UHV System", UHV AC International Symposium，Beijing, China, 2005.

[14] Q.Bui-van, F.Gallon, "Long-Distance AC Power Transmission and Shunt Series Compensation Overview and Experiences. CIGRE 2006, Paris.

[15] Roberto Campos, Per Lindberg, "Operational Experience of 800kV Series Capacitors", Inaugural IEEE PES 2005 Conference and Exposition in Africa, Durban, South Africa, 11-15th, July.2005

[16] F. M. Gatta, F. Iliceto, S.Lauria, B.Dilli, "TRVs Across Circuit Breakers of Series Compensated Lines.Analysis, Design and Operation Experience in The 420kV Turkish Grid", CIGRE 2002, Paris

[17] H. Khodabahhchian, S. Breault, E.Portales, H.Huynh, Y.Hotte, "TRV and The Non-zero Crossing Phenomenon in Hydro-Quebec's Projected 735kV Series Compensated System", CIGRE 1992, Paris

[18] G. Trudel, J.-P. Gingras and J.-R. Pierre, "Designing a Reliable Power System–The Hydro-Québec's integrated Approach," Proceedings of IEEE, Vol. 93, No. 5, May 2005.

Standards:

[19] High Voltage Alternating-current Circuit Breakers, IEC Standard 62271-100, April,2008

[20] Specification for 1100kV Alternating-current high-voltage circuit-breakers, GB/Z 24838-2009

[21] Overvoltage and Insulation Coordination of 1000kV UHV AC Transmission Project, Standard Guide Technique File of China, GB/Z 24842-2009, Nov.2009