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Study on Lightning Intruding Overvoltage in Yantan Extension Substation

Hongtao Zeng*, Linlin Lin, Zhixin Wang, Wengang Tian, Cong Feng, Zhihuai Xiao
School of Power and Mechanical Engineering, Wuhan University,
School of Power and Mechanical Engineering, Wuhan University, Wuhan, China
*Corresponding author, e-mail: htzeng@whu.edu.cn

Abstract
500kV substation is especially important to the grid of our country, once it encounters lightning damage, the safety and reliability of the whole power system will be directly affected. As lightning intruding waves will cause overvoltage on electric equipments by intruding from the transmission line or straightly stroking the substation, which seriously influences the insulation level of equipments, so it is essential to calculate overvoltage on electric equipments when substation struck by lightning to ensure their safe operation under the protection of arrester. As for the new connection mode of extension project of Yantan 500kV substation, numerical model of hydropower equipments is established and electromagnetic transient simulation calculation software of ATP/EMTP is used for calculation of overvoltage on electric equipments. According to the result, conclusions about strong insulating of incoming line towers, importance of lightning shielding failure intruding waves and influence of power frequency voltage on lightning intruding overvoltage in 500 kV substation can be drawn. This is the first-time study on overvoltage in 500kV substation extension project and has certain practical guidance.

Keywords: *500kV substation, electric equipment, overvoltage, simulation calculation*

1. Introduction

With the development of China's electric power system, the 500kV power transmission and transformation project are increasing and 500kV grid has become the main transmission network [1]. As the hub of power system, 500kV substation is extremely important, and once encounters lightning damage, the safety and reliability of the power system will be affected, so its reliable lightning performance is strongly required [2]. In the power system, substations and transmission lines are easily struck by lightning stroke, lightning intruding waves will cause overvoltage on electric equipments by straightly stroking the substation or intruding from the transmission line and seriously affect the equipments' insulating. It is then essential to recheck the parameters and configuration of the arrester to make sure that substation electrical equipments are within the protection of arrester andovervoltage on equipments is lower than their withstand voltage when lightening invades.

Design total installed capacity of Yantan hydropower station is 1810MW, with 1210MW built and 600MW in extension project. With extension project implemented, there will be more electric equipments and system operation modes. Once encounters lightening damage, the fault condition will be more complex, andovervoltage on local equipments may be over the insulation level. As for the new connection mode of extension project of Yantan 500kV substation, in this paper,the numerical model of equipments in substation is established, electromagnetic transient simulation calculation software of ATP/EMTP is used for calculation of the overvoltage on electric equipments, overvoltage on equipments and factors affect it are analyzed.

2. Calculation Condition and Model

2.1. Calculation Condition

As the attenuation of lightning and slowing down of wave front in the process of long distance transmission [3, 4], towers within 2km of the incoming line section are considered as lightning points for study. According to experience,the overvoltage is generally higher when lightning strikes # 2 or # 3 tower, so we calculate the condition that lightning strikes # 1 to # 6

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towers with both near zone and far zone lightning taken into account, and select 2.6/50.0μs double exponential waveform as the lightning current source for simulation. In calculation of back striking overvoltage, take 300Ω for lightning channel surge impedance and 260kA for lightning current into strict consideration; in lightning shielding failure calculation, the lightning channel surge impedance is 800Ω and the lightning current amplitude is equal to maximum detour lightning current I_m obtained by electrical geometric model. Yantan 500kV substation uses MOA with 420kV rated voltage and 20kA nominal discharge current in both bus side and line side, and its lightning protection level is 1046kV.

2.2. Calculation Model

In this paper, LCC transmission line model is used in analysis of lightning intruding overvoltage. Based on the LCC model, overhead line model with J. Marti frequency characteristics is used, which is known as the three conductors and two ground wire model [5]. The Multi-wave impedance model is used for tower model.Insulator flashover criterion uses the criterion of predetermination method [6].

As the front time of lightning intruding wave is only as short as several microseconds, the frequency is up to megahertz during the transient process of refraction and reflection caused by lightning strike. For inductive equipments like power transformer and high voltage shunt reactor, they are equivalent to open circuit and their entrance capacitance C_T plays a major role. The capacity of each transformer in Yantan hydropower station is 360MW, according to the calculation formula of C_T and taking additional capacitance caused by corona of connecting line into consideration, we take 5000pF as the entrance capacitance of transformer.

In the simulation calculation, lossless uniform transmission line is selected to simulate the relation between equipments. Take 100Ω for surge impedance of GIS as strict consideration and 300Ω or surge impedance of bus and connecting lines of equipments according to traditional empiric value.The section area of the 500kV power cable is 800mm^2, with the surge impedance of 48.8Ω and the wave velocity of 300m/μs.

Forhigh frequency and short wave front of the lightning strike, maximum overvoltage amplitude can be obtained in only about 10μs, as a result, substation equipments like circuit breaker, disconnecting switch, transformer, etc. are equivalent to their entrance capacitance under the effect of lightning intruding wave. The equivalent capacitance of equipments is shown in Table 1 below:

Table 1. Equivalent Entrance Capacitance of Equipments [pF]

	equipment name	symbol	current transformer
GIS	circuit breaker	CB	300
	disconnecting switch	DS	300(on)/150(off)
	outgoing line bushing	BG	1000
	current transformer	CT	1000
	capacitor voltage transformer	CVT	5000
	bus grounding	M	150
	voltage transformer	TV	1000
	cable termination	TL	500

3. Calculation and Analysis

There are mainly two types of lightning intruding wave in substation: (1) back striking intruding wave caused by insulator flashover when lightning strikes tower top or lightning shield line; (2) intruding wave caused by lightning shielding failure.

Yantan hydropower station uses 3/2 connection mode, including 4 GIS strings and 2 outgoing lines to Pinguo and Shatang. Electric main wiring diagram of Yantan hydropower station is shown as below.

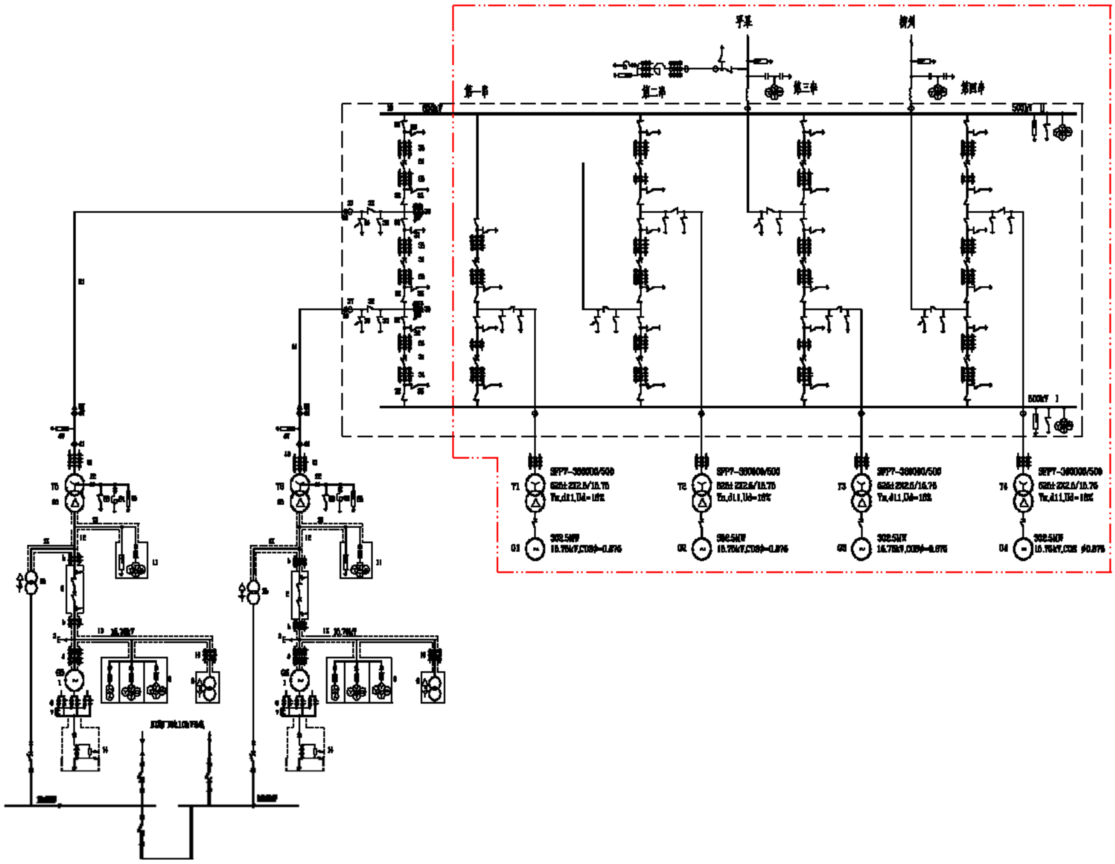


Figure1. Electric Main Wiring Diagram of Yantan Hydropower Station

For common substation, the more the operating outgoing line and transformers are, the more the operating circuit breaker and disconnecting switch are and the lower lightening overvoltage is, thus operation mode with one outgoing line and one transformer is comparatively more dangerous than other modes according to overvoltage theory. This paper selects four modes to calculate, in which overvoltage is relatively serious: (1) transformer T4 operates with bus M1 and bus M2 outage; (2) transformer T4 operates with bus M2 and bus M1 outage; (3) transformer T3 and T4 operates with bus M1 and M2, and bus M2 unloaded; (4) transformer T5 operates with bus M2 and bus M1 outage.

In the calculation, the back striking overvoltage and the shielding failure overvoltage caused by lightning strike on #1 to #6 towers are considered for Yantan-Pinguo line, while for Yantan-Shatang line, #1 to #4 towers are considered.Thearc sag of typical 500kV towerare selected for that of conductor and ground wire, which are 12m and 9.5m.

According to the design of lightning protection in Yantan hydropower station, each line entrance is installed with a set of arrester (L_MOA), and bus M1 and M2 are separately installed with a set of arrester (M_MOA). In the extension project, there will be two more 300MW generators and main transformers T5 and T6 installed with arrester (T_MOA) in each output. This paper focuses on reliability of lightning protection scheme in Yantan extension project based on the existing project.

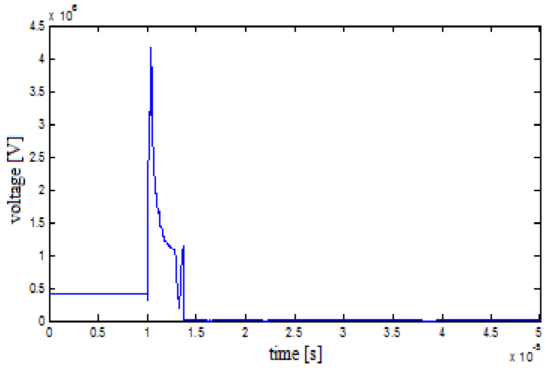
3.1. Analysis of Back Striking Intruding Overvoltage

There are different operation modes in Yantan hydropower station, consequently equivalent network structure of system power varies, resulting in certain influence of different modes on intruding overvoltage level. By respectively calculating overvoltage of four critical modes mentioned before, we get overvoltage on main electrical equipments and maximum current in arresters which are show in Table 2.

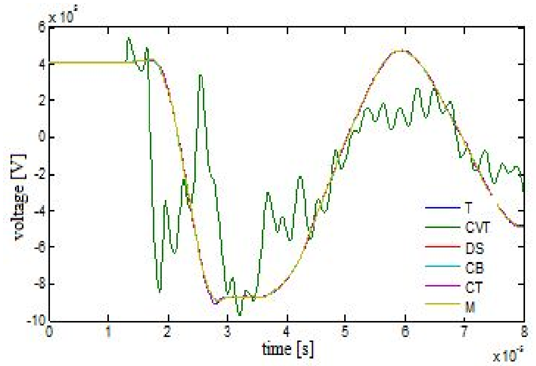
Table 2. Back-strike Intruding Overvoltage and Maximum MOA Current

Operation mode	Tower	Overvoltage on equipments(kV)						MOA current(kA)		
		T	CVT	DS	CB	CT	M	L_MOA	M_MOA	T_MOA
Mode 1	#1	Insulator strings not flashover								
	#2	908	970	892	890	906	893	3.45	1.45	0
	#3~#4	Insulator strings not flashover								
Mode 2	#1~#6	Insulator strings not flashover								
Mode 3	#1	Insulator strings not flashover								
	#2	827	789	819	823	827	824	0.03	0.12	0
	#3~#4	Insulator strings not flashover								
Mode 4	#1~#6	Insulator strings not flashover								
Maximum value		908	970	892	890	906	893	3.45	1.45	0

The simulation results show that the long insulator strings on incoming line towers and their strong insulating make it hard for lightning strike on tower top to cause back striking. Simulation analysis also shows that it is easy to appear back-strike flashover on #2 tower of Yantan-Shatang incoming line, and overvoltage on equipments is higher when substation operates at Mode 1 with least equipments and shortest wiring, related voltage waveform is shown in Figure 2 below.



(a) Voltage waveform of insulator string in flashover phase



(b) Overvoltage waveform of converter station equipments

Figure 2. Electric Main Wiring Diagram of Yantan Hydropower Station

Obviously, there is little difference between each overvoltage on equipments in GIS switching yard. This is mainly because equipments are closed to each other and wave propagation attenuation is not that obvious, so overvoltage tends to be the same.

Take the typical condition that lightning striking on tower #2 in Mode 1 for example, and consider the influence of different power frequency voltage on overvoltage.Suppose power frequency voltage on transmission line is $U_p = 408\sin\varphi$ when lightning strikes on towers, calculation result is shown below.

The result shows that power frequency voltage has significant effect on lightning intruding overvoltage. When power frequency voltage is positive, the tower suffers positive polarity lightning, voltage on insulator string is the sum of voltage on each terminal, and voltage difference between the two terminals cause flashover of insulator strings. When power frequency voltage is negative, the tower suffers negative polarity lightning, voltage on insulator string is the difference between voltage on each terminal and it is relatively small, which is lower than flashover voltage, in this situation insulator strings are not flashover and there is mainly induced overvoltage on equipments with low amplitude. Intruding overvoltage caused by flashover of insulator strings is much higher than induced overvoltage when insulator strings are not flashover.

Variation law of station equipments overvoltage with different phase angle is shown in Figure 3 below, it is obvious that when power frequency voltage is the maximum (phase angle φ is 90°), overvoltage caused by insulator strings flashover when lightning strikes on towers is the most serious.

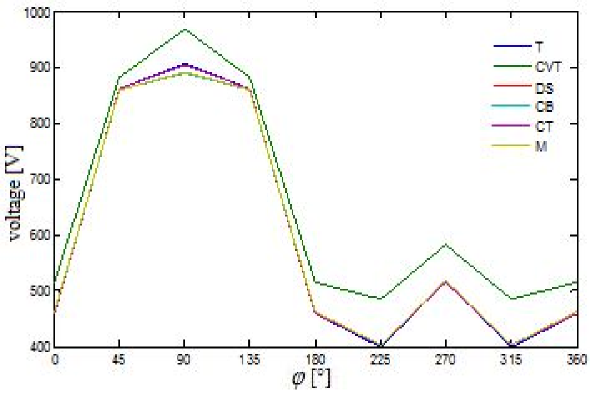


Figure 3. Variation Law of Station Equipments Overvoltage with Different Phase Angle

3.2. Analysis of Shielding Failure Intruding Overvoltage

According to the electrical geometric model, maximum detour lightning current I_m is related to ground tilt angle θ. In this paper we select 10° for ground tilt angle and study overvoltage on various station equipments when lightning shielding failure happen using $I_m$obtained by the model. The result is shown as below.

Calculation result shows that shielding failure intruding overvoltage on equipment is the highest when substation operates at Mode 2 and lightning strikes on tower #1. This is because in Mode 2, tower #1 of Yantan-Pinguo line is an angel tower which is close to the power station, and detour lightning current is large, so shielding failure intruding overvoltage is high. Related simulation voltage waveform is shown in Figure 4 below.

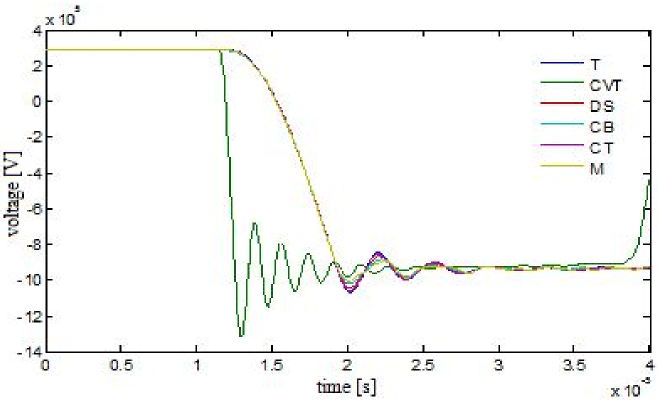


Figure 4. Waveform of Shielding Failure Overvoltage on Equipments

Take the typical condition that lightning striking on tower #1 in Mode 2 for example and calculating lightning overvoltage under power frequency voltage of different phase angle, the result is shown below.

Table 4. Shielding Failure Intruding Overvoltage on Equipments

Operation Mode	Tower	Overvoltage on equipments (kV)						MOA current (kA)		
		T	CVT	DS	CB	CT	M	L_MOA	M_MOA	T_MOA
Mode 1	#1	1002	1262	973	968	995	978	12.59	6.78	0
	#2	1001	1218	974	967	993	975	11.26	6.70	0
	#3	990	1006	964	957	983	961	4.05	5.90	0
	#4	961	863	943	938	956	934	0.53	4.32	0
Mode 2	#1	1089	1318	1060	1034	1081	1019	14.46	8.58	0
	#2	1068	1296	1043	1019	1061	1005	14.25	7.77	0
	#3	1042	1016	1020	998	1037	988	4.29	6.54	0
	#4	1000	900	980	965	992	957	1.08	4.64	0
	#5	1000	870	981	965	993	957	0.64	4.67	0
	#6	1000	866	981	965	993	957	0.58	4.68	0
Mode 3	#1	1011	1262	994	979	1006	987	12.57	5.09	0
	#2	1009	1219	992	977	1005	983	11.27	5.01	0
Mode 3	#3	959	1006	948	938	956	937	4.04	2.95	0
	#4	909	861	904	900	907	900	0.50	1.53	0
Mode 4	#1	938	1318	1028	1024	1025	1021	14.83	5.10	5.47
	#2	938	1296	1027	1023	1025	1020	14.28	5.09	5.43
	#3	921	1016	953	950	951	948	4.30	2.28	3.54
	#4	900	900	907	906	906	905	1.09	1.20	1.94
	#5	900	871	907	906	906	905	0.66	1.12	1.93
	#6	900	867	903	902	902	900	0.59	0.89	1.91
Maximum value		1089	1320	1060	1034	1081	1019	14.46	8.58	5.47

Table 5. Overvoltage on Equipments Under Different Power Frequency Voltage

Phase angle φ (°)	Overvoltage on equipments (kV)						MOA current		
	T	CVT	DS	CB	CT	M	L_MOA	M_MOA	T_MOA
0	1021	1310	1003	986	1016	975	15.45	6.03	0
45	1069	1318	1043	1020	1062	1006	14.79	7.83	0
90	1089	1316	1060	1034	1081	1019	14.46	8.58	0
135	1069	1318	1043	1020	1062	1006	14.79	7.83	0
180	1021	1310	1003	986	1016	975	15.45	6.03	0
225	971	1273	960	950	968	943	15.56	4.17	0
270	950	1244	942	935	948	930	15.37	3.38	0
315	971	1273	960	950	968	943	15.56	4.17	0
360	1021	1310	1003	986	1016	975	15.45	6.03	0

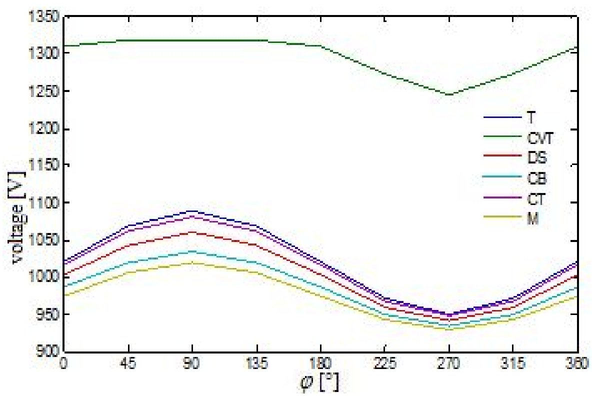


Figure 5. Variation Law of Station Equipments Overvoltage with Different Phase Angle

The result shows thatpower frequency voltage has significant effect on intruding overvoltage. As shown in Figure 5, it is obvious that when power frequency voltage is the maximum (phase angle φ is 90°), overvoltage caused by lightning shielding failure on towers is the most serious.

4. Conclusion

(1) Yantan 500kV substation has long insulator strings with strong insulating on towers of incoming lines, and grounding resistance of towers is small, so it is hard to occur back-strike flashover when lightning strikes on tower top, and there is mainly induced overvoltage on equipments with low amplitude.

(2) As towers in 500kV transmission lines are high and detour lightning current is large, shielding failure intruding wave is the key object to study. Shielding failure intruding overvoltage is related to detour lightning current of towers and distance between towers and switching yard, and the intruding overvoltage is higher with larger detour lightning current or shorter distance.

(3) Power frequency voltage has significant effect on lightning intruding overvoltage of 500kV hydropower station so that power frequency voltage must be considered in overvoltage analysis. Power frequency voltage reaches positive peak value when phase angle is 90°, and meanwhile intruding overvoltage in switching yard is the highest when lightning strikes on towers.

(4) Arresters set in front of transformers T5 and T6 can effectively inhibit lightning intruding overvoltage on them. Though transformers T1 to T4 are not set with arresters, bus arresters also can effectively protect them as they are close to GIS bus.

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References

[1] He Yangzan. *Power System Analysis*. HUST Publication. China. 2006.
[2] Song Jicheng. *Design of Electric Connection in 220~500kV Substation*. Chinese Electric Power Publication. China. 2004,
[3] MS Savic, Z Stojkovic. An Expert System for High-voltage Substations Lightning Performance Estimation. *IEEE T Power Deliver.* 1992; 7(3): 1223-1231.
[4] Z Stojkovic. An Improved Method for HV Substation Lightning Performance Estimation. *IEEE T Power Deliver.* 1999; 14(3): 917-922.
[5] JR Marti. Accurate Modeling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations. *IEEE Trans on Power Apparatus and Systems.* 1982; 101(1): 147-157.
[6] A Pigini, G Rizzi, E Garbagnati, A Porrino, G Baldo, G Pesavento. Performance of Large Air Gaps under Lightning Overvoltages: Experimental Study and Analysis of Accuracy Predetermination Methods. *IEEE T Power Deliver*. 1989; 4(2): 1379-1392.
[7] Takami, Jun, Okabe, Shigemitsu Zaima, Eiichi. Lightning surge overvoltages at substations due to backflashover with assumed lightning current waveforms based on observations. 2010; 25(4): 2958-2969.
[8] Yuan Zhaoxiang, Li Hu, Xiang Ling. *Influence of different tower models on the lightning back-strike intruding wave overvoltage for UHV substation.* High Voltage Engineering. 2008; 34(50): 867-872.
[9] Tatár, Dénes. *Risk evaluation in lightning and overvoltage protection.* Periodica Polytechnica, Electrical Engineering. 2000; 44(2): 201-212.
[10] Nian Liu, Buxiang Zhou, Bo Lin, Luofang Zhu, Ming Liu. An Adequacy Evaluation Model for Power System. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(12): 7793-7800.
[11] An Chang-Ping, Sima, Wen-Xia, Liao, Rui-Jin, Li, Shi-Wei. *Research on 35 kV circuitry vacuum circuit breaker interrupting no load transformer overvoltage.* Proceedings of the Chinese Society of Electrical Engineering, 2002; 22(8): 99-103.
[12] Wu Chenjian, Li Zhiqun, Yao Nan, Zhang Meng, Chen Liang, Cao Jia. 0.18μm CMOS Low Voltage Power Amplifier For WSN Application. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(8): 4470-4476.