

Analysis and Countermeasure of a Power Grid Accident Caused by Lightning Stroke

Hu Qihao¹, Xu Jiachen², Qiao Fuxi³

¹Beijing Jiaotong University, Beijing, China

²Datang Shandong Electric Power Overhaul Operation Co., Ltd., Qingdao, 266500, China

³Datang Group Science and Technology Research Institute Limited North China Electric Power Test Research Institute, Beijing, 100000, China

Keywords: High Voltage Overhead Lines; Power Grid Accidents; Defect Analysis

Abstract: With the development of the power industry, the scale of the power grid is also expanding. Lightning strikes on high-voltage overhead lines also occur frequently, because it is more and more important to improve the lightning protection of high-voltage overhead lines in North China. In this paper, an overseas power grid accident caused by lightning strike is analyzed in detail, and the defects of lightning protection for overhead high voltage lines in China are analyzed statistically. Based on this, the improvement measures of lightning protection for overhead high voltage lines are put forward.

1. Introduction

When overhead lines are struck by direct lightning or lightning falls near the lines, over-voltage, i.e. atmospheric over-voltage (external over-voltage), will occur on-line due to electromagnetic induction. This voltage is often two times or more of the phase voltage of the high line, which causes the damage of the line insulation and causes accidents. When lightning strikes the line, the huge lightning current generates a high potential difference in the line-to-ground impedance, and the insulator bursts, resulting in line insulation flashover. Lightning strikes not only endanger the safety of the line itself, but also lightning will be transmitted to the substation along the wire. If the lightning protection measures in the station are poor, it will cause serious damage to the equipment inside the station.

In a foreign power transmission and transformation project, the PP-KM-PS-BM transmission line adopts two 230kV parallel-connected double-circuit lines, and has KM substation, PS and BM substation. PS substation is also connected to OS substation through two 230 kV parallel double-circuit lines on the same pole. The two transmission lines are responsible for transmitting the power load of the hydropower plant with the installed capacity of 700 MW to the power grid. In addition to satisfying the power consumption in the surrounding area of the substation, the other power loads are transmitted to the load center of the national power grid - PP substation through the PP - KM transmission line.

One day, a 230 kV transmission line in KM-PS was struck by lightning, and its trip was caused by relay protection. The tripping of two 230 kV transmission lines in the north of KM-PP resulted in the loss of voltage in three 230 kV substations (KM substation, PP substation and BM substation) under the jurisdiction of the project. Careful analysis of the causes of the loss of the whole station of the three substations, drawing lessons and formulating corresponding effective measures will be of great benefit to improving the safe operation of the power grid.

2. Accident passing

2.1 Brief introduction of operation mode

Before the accident, 230 kV equipments in three substations were in normal operation.

230 kV PS station operates in parallel with two buses: 273 switch of PK II line, 277 switch of

PO II line, 279 switch of PB II line, connected to I bus. The PB I line 272 switch, the POI line 276 switch, the PB I line 278 switch are connected to the II mother, and the female joint 212 switch is operated in a closed loop.

The 230kV KM station is running in parallel: KPS II line 273 switch, KPP II line 275 switch is connected to I mother. The KPS I line 272 switch and the KPP I line 274 switch are connected to the II mother and the female joint 212 switch is operated in a loop.

The 230kV BM station has two mothers running side by side: the BP II line 279 switch is connected to the I mother; the BP I line 278 switch is connected to the II mother, and the female joint 212 switch is connected to the ring.

Load condition before accident occurs:

PS substation: 230 kV PO I 276 line - 312.1 MW, 230 kV PO II 277 line - 311.8 MW, 230 kV PB I 278 line 74.2 MW, 230 kV PB II line 279 line 74.2 MW, 230 kV PK I line 272 line 231 MW, 230 kV PSKM II line 273 line 229.6 MW.

KM Substation: 230 kV KPS I 272 line - 231 MW, 230 kV KPS II line 273 line - 229.6 MW, 230 kV KPP I line 274 line 229.26 MW, 230 kV KMPP II line 275 line 229.82 MW.

230 kV bus voltage 238 kV.

It can be seen that the transmission load from KM substation to PP is 459.08MW.

The regional wiring of PS station, KM station and its adjacent 230 kV substation is shown in Fig.

1.

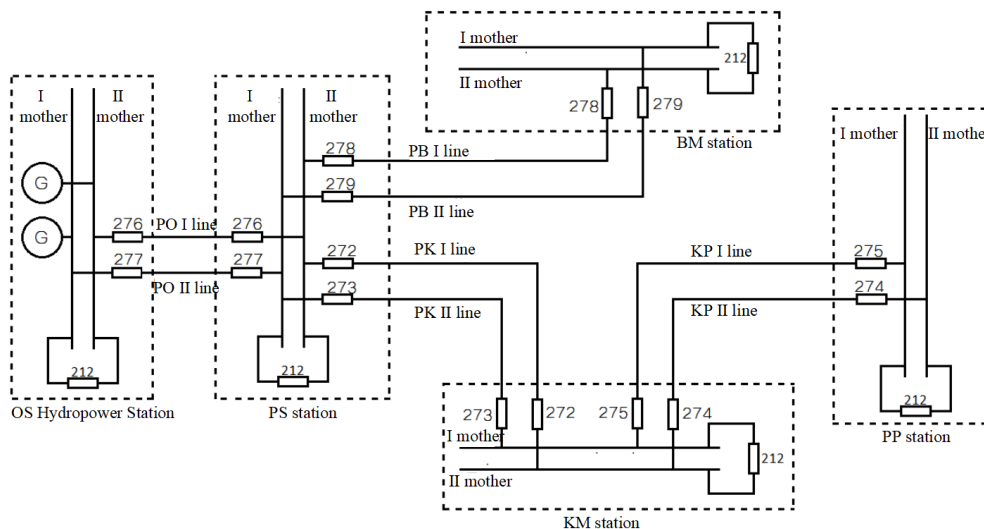


Fig.1. Connection Diagram of a Regional Power Grid

2.2 Accident process

The whole accident process is divided into four stages, as follows:

The first stage: on a certain day in 2018, at 0459:18 seconds 542 milliseconds, the transmission line between KM substation and PS substation: 230 kV KPS I line was struck by lightning and A-phase grounding fault occurred. 230kV KPS I line 272 switch A channel differential action A phase, distance fast segment action A phase, distance I segment action A phase, protection action exit, 272 switch three hops, fault ranging 3.56km. At the same time, the PS substation KPS I line 272 switch trips. The phase A ground fault point is completely removed.

The line inspection found that the 230kV KPS I line 272 line No. 9 tower A phase 14 pieces, the No. 10 tower A phase 14 pieces of insulator burst. The 12-phase insulator of the C-phase of the No. 10 tower of the 230kV KPS II line 273 line bursts. According to the discharge traces of insulator strings on site, it is judged that a large number of explosions of insulators caused by lightning strike lead to phase A grounding tripping of KPS I line 272, as shown in Figure 2.



Fig.2. Insulators Bursting on Line Towers

The second stage: KPP Line II 275 trips at 04:59:18 seconds and 560 milliseconds at PP North Substation; KPP Line 274 trips at 04:59:18 seconds and 569 milliseconds at KPP I. The tripping of the two transmission lines completely removed the KM station, the PS station and the BM station from the PP North Substation of the National Power Grid Load Center, causing the three substations to leave the national grid and operate on isolated networks.

The third stage: after the KPP I, II line 274, 275 trip, the 230kV system voltage rises. KM substation KPP I line 274 overvoltage protection action, PS substation KPS I line 272 overvoltage protection action. From this, the PO I line 276 overvoltage protection action is inferred.

The fourth stage: the loss of electricity in the 230kV system of KM substation, PS substation and KM substation.

At this point, the 230kV KM substation, PS substation, and BM substation 230kV system lost power, and the three substations were disconnected from the country's load center PP North Substation.

3. Accident analysis

3.1 Cause of the accident

After analysis, there are two main reasons for the accident:

First, the switch-off of KPP I line 274 and KPP II line 275 in 230kV substation is the direct reason for the complete separation of 230 kV KM substation, PS substation and BM substation from the state grid.

Secondly, because of the disconnection from the state grid, the load of OS substation which transmits power to PS substation can not be transported out. The hydroelectric power station that causes the OS substation has unstable frequency and large reactive power, which causes the 230kV voltage to rise, which causes the transmission line with overvoltage protection to trip, which reduces the stability of the power system.

Third, the OS substation had no power outage, which caused the three stations of the 230kV substation to lose pressure at all stations. This is a very serious cause.

Fourth, due to the lightning strike on the KPSI line, the KPSI line A is grounded, which is the cause of the loss of power in the unstable substation of the power system.

3.2 Protection behavior analysis

In the 230kV loss of power accident of the three substations, the 230kV KPS line is the communication line between the KM station and the PS station. The line protection of the 230kV KPS line of the KM station is WXH-803A/P of Xuji Electric Co., Ltd. And WXH-802A/P protection device. PP substation protection device is unknown, but this KMPP north line trip is a single-phase grounding fault, resulting in KM substation and the main power grid disconnection, OS substation without 230 kV voltage output causes voltage loss accident to expand the scope.

3.3 Action Behavior Analysis of 230 kV KMPS I Line Protection

According to the configuration and characteristics of 230 kV KPS I line protection, its action behavior is analyzed as follows:

The setting values of WXH-803A/P and WXH-802A/P protection devices for 230 kV KPS I line of KM station are as follows:

Zero Sequence Differential Fixed Value: 0.4A (Quadratic Value)

Positive Sequence Impedance Angle: 85 degrees.

Zero Sequence Compensation Coefficient: 0.62

Grounding Distance I Section Fixed Value: 8.65 Euros (Quadratic Value)

The grounding current of KPS I line is 4.0 A (secondary value). The optical fiber current differential protection of WXH-803 main protection device and 272 switches on both sides of the line are operated to remove the grounding fault. The fault occurrence time is 4:59:18.542, the fault removal time is 4:59:18.602, and the fault duration is 60 ms.

3.4 Analysis of Action Behavior of 230kV KMPP North I II Line Protection

According to the KPPI, II line 274, 275 switch fault recording data provided by the PP station, the 275 switch protection start-up time is 4:59:18.560, the 274 switch protection start-up time is 4:59:18.569, and the fault category is A-phase grounding. It is the zero sequence grounding protection I section action. Zero sequence I grounding distance protection ranges from 70% to 80% of the total length of the protective device from the installation site to the line. The location of this grounding fault is the fault of adjacent lines, so it can be seen that it belongs to protection malfunction.

Fault time	26/Oct/2018 04:59:18.569
Fault phase	A-N
Trip mode	Z1
Trip phase	TP-A1,TP-B1,TP-C1
FL result	47.8km(98%)

[During fault]								
Item	Magnitude	Angle	Item	Magnitude	Angle	Item	Magnitude	Angle
Va	35.1V	-9.34deg	Ia	1.23A	-101.0deg	V1	51.8V	0.0deg
Vb	61.6V	-112.6deg	Ib	0.60A	75.9deg	V2	11.3V	-162.8deg
Vc	58.9V	117.1deg	Ic	0.45A	-38.1deg	V0	5.4V	-129.0deg
Vab	79.0V	37.7deg	Iab	1.83A	-102.1deg	I1	0.62A	-131.5deg
Vbc	109.2V	-88.4deg	Ibc	0.89A	105.5deg	I2	0.44A	-76.8deg
Vca	83.9V	139.0deg	Ica	1.03A	54.7deg	I0	0.34A	-71.6deg
Ra	5.22ohm		Xa	14.89ohm		I0m	0.00A	---
Rb	-655.36ohm		Xb	655.36ohm		Vs1	0.0V	---
Rc	-136.58ohm		Xc	16.45ohm				
Rab	-30.66ohm		Xab	27.21ohm				
Rbc	-124.85ohm		Xbc	19.66ohm				
Rca	35.38ohm		Xca	72.79ohm				
THM	48.1%							

Fig.3. Fault Recording Data of PP Station 274

Fault time	26/Oct/2018 04:59:18.560
Fault phase	A-N
Trip mode	Z1
Trip phase	TP-A1,TP-B1,TP-C1
FL result	44.4km(91%)

[During fault]								
Item	Magnitude	Angle	Item	Magnitude	Angle	Item	Magnitude	Angle
Va	30.2V	-4.1deg	Ia	1.31A	-86.8deg	V1	50.4V	0.0deg
Vb	61.9V	-114.5deg	Ib	0.56A	74.6deg	V2	13.1V	-177.4deg
Vc	60.1V	115.5deg	Ic	0.37A	-50.1deg	V0	7.3V	-167.6deg
Vab	77.6V	44.2deg	Iab	1.85A	-92.3deg	I1	0.58A	-118.9deg
Vbc	110.5V	-90.0deg	Ibc	0.83A	96.0deg	I2	0.49A	-66.1deg
Vca	79.6V	134.9deg	Ica	1.04A	81.1deg	I0	0.38A	-66.3deg
Ra	1.75ohm		Xa	13.27ohm		I0m	0.00A	---
Rb	1.01ohm		Xb	-111.27ohm		Vs1	0.0V	---
Rc	-16.06ohm		Xc	-0.83ohm				
Rab	-30.75ohm		Xab	28.56ohm				

Fig.4. Fault Recording Data of PP Station 275

3.5 Overvoltage Protection of 230 kV Transmission Line

The three substations of the project are based on PS substations. According to the requirements of the national grid, an overvoltage protection device is provided for the KPS I line 272 switch, the KPP I line 274 switch, and the PO II line 276 switch, and the overvoltage setting is 265 kV. The KPS I line 272 switch protection device is installed at the PS station, the KPP I line 274 switch protection device is installed at the KM station, and the PO II line 276 switch protection device is installed at the OS station.

4. Analysis of power system stability

4.1 Accident summary

The 230 kV system is the highest voltage level power grid in the country. The transmission lines of the project are all two-circuit transmission lines with a total length of 294 km. Located in the remote northwest of the country, there is only one power point OS substation in this area, all of which are hydroelectric power generation. The total installed capacity of power generation is 704 MW. OS substation transmits power load through two transmission lines to PS substation. Then, the PS substation is sent to the BM substation and the KM substation. The KM substation sends the power load to the PP North, and the PP is connected to other national power points. The BM substation is a radiative power transmission. The three substations have less load around them, and a large number of power generation loads are sent to PP for consumption.

It can be seen that the OS substation as a power point has only two transmission lines and is not directly connected to the load center PP. At the same time, the three substations are only connected to the system through the KM substation, and the connection with the system is extremely weak for the power plant. This KPS I line grounding fault, and line protection will be removed within 60 ms of failure, such a disturbance, resulting in KPP I, II line protection malfunction, OS substation and the main grid completely separated. As a result, the regional power grid is overvoltage, the frequency rises to 51 Hz, and finally stops. Serious loss of electrical load.

4.2 Line pole grounding device is regularly maintained

Because the line runs in the wilderness for many years, the grounding net will be damaged by different degrees of rust and external force due to the influence of climate, soil and environment. At regular intervals, it must be tested and modified according to the test results to ensure the integrity and qualification of the ground network. The grounding resistance of tower and the integrity of grounding device are checked regularly. The grounding resistance of key lightning strikes lines is surveyed and measured. The grounding device of tower with frequent lightning strikes is maintained in key lightning strikes areas according to the general survey. Maintain the grounding resistance of substation terminals and 5 continuous base towers which are not up to standard, and reduce the grounding resistance.

Table 1 Measurement Period and Requirements of Power Frequency Grounding Resistance of Towers

Project	Cycle	Requirement		Explain
Grounding Resistance of Tower with Overhead Ground Wire	Towers within 1-2 km of power plant or substation access lines for 2 years; poles and towers for other lines for 5 years	When the height of the tower is below 40, the following Table requirements; if the tower height is $\geq 40\text{m}$, take 50% of the following values, but when the soil resistivity is greater than $2000\Omega\cdot\text{m}$, the grounding resistance is difficult to reach 15Ω and can be relaxed to 20Ω		For tower height $\leq 40\text{m}$, if the grounding resistance is difficult to drop to 30Ω , 6 to 8 radial grounding bodies or continuous elongated grounding bodies with a total length of not more than 500m can be used. The grounding resistance can be unrestricted, but for towers with a height of $\geq 40\text{m}$, the grounding resistance should not exceed 20Ω .
		Soil resistivity $\Omega\cdot\text{m}$	Grounding resistance Ω	
		≤ 100	10	
		100~500	15	
		500~1000	20	
		1000~2000	25	
		≥ 2000	30	

4.3 Necessity of arrester

With the continuous improvement of lightning protection technology for transmission lines, line zinc oxide surge arresters have been widely recognized and applied as a new line lightning protection technology. Many years of operation experience shows that installing line-type zinc oxide lightning protection in areas with frequent lightning activities, high soil resistivity and complex topography is very effective in preventing lightning from shielding conductors, lightning striking tower top or ground wire.

The lightning arrester is usually connected between the live wire and the ground, in parallel with the protected equipment. When the overvoltage reaches the specified operating voltage, the arrester acts immediately, flows through the charge, limits the overvoltage amplitude, and protects the insulation of the equipment. After the voltage value is normal, the arrester quickly returns to its original state to ensure normal power supply.

The role of the arrester is to protect various electrical equipment in the power system from damage caused by lightning overvoltage, operating overvoltage, and power frequency transient overvoltage. Its function is to guide thunder and lightning through the protected object, and to release the ground safely, to prevent thunder and lightning direct strikes, and to reduce the probability of direct lightning strikes on electrical equipment (overhead transmission lines and electrified equipment) and buildings within its protection area.

The determination of protection range of lightning rod is an important factor. Its protection range is related to its height. There is a safety zone under a certain height of lightning rod. Its protection radius is 1.5 times of the height of lightning rod, that is:

$$R=1.5H$$

R is the protection radius of the lightning rod on the ground, H is the height of the lightning rod, M.

When a single lightning rod fails to protect a large area, double or multi-needle protection should be adopted.

4.4 Installation of automatic reclosure

Automatic reclosure is widely used in overhead transmission lines and overhead power supply lines as an effective anti-accident measure. When the line fails and the circuit breaker is tripped by relay protection, the automatic reclosure device makes the circuit breaker reclosed after a short time interval. In most cases, line faults (such as lightning strikes, wind damage, etc.) are temporary. After the circuit breaker trips, the insulation performance (insulator and air gap) of the circuit can be restored, and the coincidence can be successful again, which improves the power supply of the power system. Reliability. A few cases are permanent faults. After the automatic reclosing device acts, it will jump after the relay protection action, find out the cause, and then remove the power.

Under normal circumstances, the faster the reclosing of the line fault after tripping, the better the effect. The minimum interval allowed for reclosing is 0.15 to 0.5 seconds. The higher the rated voltage of the line, the longer the deionization time of the insulation. The success rate of automatic reclosing depends on the line structure, voltage level, weather conditions, main fault types and other changes. According to the statistics of China's electric power sector, the success rate of automatic reclosure can reach 60%-90% in general. This shows that automatic reclosure can effectively eliminate lightning fault and avoid power failure caused by lightning stroke. Therefore, the regulation requires that "three-phase or single-phase automatic reclosure should be installed as far as possible in all levels of voltage lines".

5. Prevention and rectification measures

In view of the accident, the following preventive measures are formulated after analysis:

- 1) To carry out comprehensive lightning protection for transmission lines, some lightning protection measures, such as strengthening local insulation, erecting coupling ground wires and reducing tower protection angle, should be taken.

- 2) Attaching great importance to the installation of line arrester, line arrester can effectively avoid the longitudinal breakdown of switch fracture caused by secondary lightning strike.
- 3) Strengthen relay protection setting ability and improve reliability and accuracy of transmission line protection setting.
- 4) Strengthen the maintenance of relay protection devices to ensure that the relay protection devices are always in good operating condition.
- 5) Install line reclosing protection function to reduce lightning strikes.
- 6) Improve the construction of power network, overcome the radiative network with the 230kV main power network, and gradually establish a ring network to improve the stability of the power grid.
- 7) The OS substation is a power point with a large installed capacity in the country. It is recommended to strengthen contact with the national load center.

References

- [1] Benato R, Sessa S D, Poli M, et al. An On-Line Travelling Wave Fault Location Method for Unearthed-Operated High Voltage Overhead Line Grids [J]. IEEE Transactions on Power Delivery, 2018, PP (99):1-1.
- [2] Gang L, Yu X I, Jun T, et al. Influence of Triggered Lightning of High Voltage Overhead Transmission Lines on 10 kV Overhead Distribution Line's Lightning Trip Characteristics [J]. High Voltage Engineering, 2014, 40(3):690-697.
- [3] Tong Z, Dong Z, Ashton T. Analysis of electric field influence on buildings under high-voltage transmission lines [J]. IET Science, Measurement & Technology, 2016, 10(4):253-258.