International Journal of Smart Home
Vol. 9, No. 7 (2015), pp. 49-60
http://dx.doi.org/10.14257/ijsh.2015.9.7.06

Review on Operation Fault of High-voltage Power Transmission Lines and Effective Prevention Countermeasures

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Abstract

In the power system, transmission line as a guarantee for effective power supply, takes charge of the transmission from output power of substation to the consumers. The present study mainly focuses on the fault of transmission line resulted from external uncertainties, such as lightning, wind age yaw, ice coating and bird damage, as well as internal factors of high-voltage transmission line, including the grounding and short circuit. Accordingly, fault diagnosis and protecting measures on the high-voltage transmission line are proposed with advices on the improvement of operation and maintenance management of the line to reduce the fault frequency of the transmission line in the process of operation at a greater extent and to ensure the power supply stability of the whole power grid system to the user.

Keywords: *high-voltage power transmission lines, operation, power supply, fault*

1. Introduction

With the growth of national economy and promotion in life quality, the scale and scope of grid construction is increasingly expanded, and daily power supply has become a basic requirement of people's work and life. In the power grid system, the electric energy is transferred to thousands of households through constructing transmission line. Therefore, as an electricity transmission hub, the stability of transmission line determines the stability of the grid electricity. Once fault occurs, power interruption might be induced in some section even the whole line and consequently, private electricity or industrial electric power would be disturbed, causing economic losses to a certain degree.

However, with the increase in the transmission voltage grade of the power grid and the power conveying distance, problems encountered in the operation of the transmission line have become more complicated and risks in the occurring of line fault are elevated, severely threatening the stability of power supply system. In addition, due to the limitation in the landform of our country and the current power construction technology, the power transmission line is mainly outdoor operation, and during the operation, it will be inevitably influenced by various uncertainties, such as climate, ambient temperature, humidity, etc. As a consequence, problems, including line fault, power interruption might be induced, causing a series inconvenience to power supply for production and daily life. Thus it is of great necessity to conduct effective control and checking on the line fault, as well as the effective protective measures through analysis on the cause of fault, to ensure the safe protection of transmission line and meet the need of power demand in different area.

2. High-Voltage Power Transmission Lines

Not only the nearby industries and living power but also the remote areas require the electric power transmitted by power supply enterprise. The power transmission process is achieved by artificially transmitting the electric power according to the

ISSN: 1975-4094 IJSH

track of transmission line. However, general electric wire could not meet the need of power transmission. Instead, high voltage transmission line is selected as the carrier of the transmission. In general, the transmission line with voltage in the range of 220 kV to 38 kV is named high voltage transmission, while in the range of 330 kV to 765 kV, it belongs to extra-high voltage power transmission. Grade of voltage relies on the maximum transmission power, that is, the greater the maximum transmission, the higher the voltage grade.

2.1. The Form of High-Voltage Transmission Line

In view of the impact of terrain and the transmission distance, two forms are included in the high voltage transmission line: overhead transmission line and cable transmission lines. Taking advantage of the transmission tower to hang the wire and ground wire in the high altitude and keep safe distance among wires, wire and ground wire, wire and the tower, wire and plants and buildings, overhead transmission line makes certain of security in the power supply and becomes main form of current power transmission. In contrast, the cable transmission line which is mainly applied to the city and line across river, utilizes the cable underground, not occupying any space. The relative merits of the two forms of power transmission line are listed in Table 1.

Table 1. The Comparison of Different High Voltage Transmission Forms

Form of power transmission / Characteristic analysis	Overhead transmission line	Cable transmission line
Construction environment	Exposed in the air	Buried underground
Construction cycle	Short term	Long term
Capital investment	Little	Much
Maintenance and repair	Convenient	Complex

2.2. The Construction of High-Voltage Power Transmission Lines

The study mainly focuses on the overhead transmission line which is as a current predominate transmission method. Since the transmission method is carried out in outdoor environment, factors such as changes of climate and landform should be taken into consideration in the course of construction. The construction mainly includes path selection, pole and tower and fundamental design. As an important part in the construction of high voltage power transmission line, path selection directly determines the safety performance and construction cost. In the process of path planning, the following principles shall be complied with: first, choose the cross-over point of high-speed road, highway, railway, power and class II telecommunication lines and avoid factories and enterprises, town planning area, as well as the area with frequent geological activities; second, the path chosen in the scheme shall be as short as possible with relatively convenient transportation and construction [1].

The tower and its foundational construction acts as important support in power transmission line, thus the design and construction should be carried out in strict accordance with the relevant national standards. Under different terrain environment, the requirement as to the ground level of tower is various. The selection of tower materials, such as wood pole, iron pole and reinforced concrete, is based on the different types of transmission conductor and the hydrologic condition, as well as the practical situation in the course of construction. In addition, auxiliary component in the tower, such as insulator, metal product and lightning rod should be arranged reasonably in accord with the tower type and external environment to ensure the safety and reliability of transmission line.

3. The Fault in High-Voltage Power Transmission Line

3.1. Summary of the Fault

With the development of the processing technology of transmission line conductor and construction level, the safety precautions applied to high-voltage power transmission line in the process of operation have achieved certain progress, providing a strong support for the safe and reliable operation of transmission line. However, in view of the outdoor working environment, years of external influence and problems in equipment itself, the faults inevitably occurs in the transmission line, especially the unpredictable external effects, such as extreme and bad weather. Therefore, in response to the fault in the transmission line, especially the uncontrollable external damage, the only way is to conduct careful checking on problems in high voltage power transmission line to find out failure cause and secure the smooth power transmission with effective diagnosis and solution.

3.2. Fault Analysis of External Force on High-Voltage Power Transmission Line

As is mentioned above, weather emergencies, including rainstorm and lightening, might give rise to the fault in transmission line which is exposed in the air. Common faults in the power transmission line induced by external forces are summarized below.

3.2.1. Lightning Stroke Fault: Since all the overhead transmission lines are field operation, when encountered with thunderstorm weather, insulating layer of the device in transmission line might be damaged or accidents such as flashover and line break, might occurred in the insulator chain, then give rise to line fault. In the high-voltage transmission line, the lightning stroke is acted in the form of direct lightning, mainly influencing the tower body, lightning wire and the conductor, as is shown in Figure 1. The back flashover and shielding failure are two main modes in the lightning. The lightning back flashover refers to the produce of extreme high voltage and flashover in both ends of the insulator chain occurred in the lightning rod, wire, or tower body, due to the inflow of lightning current to the ground [2]. The shielding failure refers to the arcing fault caused by the direct effect of lightning on the conductor rather than the lightning wire.

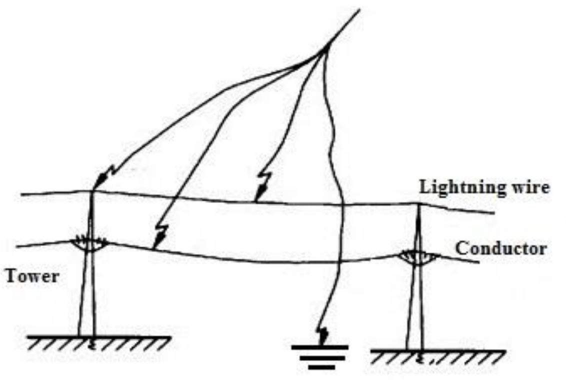

Figure 1. The Lightning Schematic Diagram

The hazard of lightning fault on the line is expressed as the following aspects. The first one is short circuit of line to the ground. Although the over-voltage time of lightning is short, power frequency voltage of the line would select the flashover channel as discharging line, if the short circuit of line to the ground or the flashover of lightning wire and tower emerge. Consequently, the power frequency arc grounding is formed and then induces the action in relay protection device. Finally, the breaker tripping breaks off normal power supply of the line. The second one is the damage on the inductance components and elements in substation when the lightning intrudes the substation in the form of lightning wave along the transmission line. The extreme high over-voltage would breakdown the insulating layer of the device and compels the tripping operation of circuit breaker.

In the area that is active in lightning, such as Eastern China and Central China, the line tripping induced by the lightning adds up to hundreds of times annually.

3.2.2. The Fault of Wind Age Yaw Discharging: High-voltage transmission line is also subject to the impact of wind power in the area with strong breeze, such as typhoon and tornadoes, leading to discharging accident. The strong convection effect of strong breeze is formed, when the cool air at high altitude with slow movement speed flows together with hot air at low altitude in a small local scope. In consequence, the action of the strong breeze is merely in the range of a few square kilometers to dozen with short time of duration. However, the instant wind speed could be as high as 30 m/s, accompanied with thunderstorm, hailstone, *etc.*

The wind age yaw of the conductor could be induced under such strong wind effect, leading to narrow air gap between conductors or the distance between conductor and the tower. While the electric strength of the gap couldn’t bear the maximum voltage in the line during power supply, disruptive discharge is formed. In particular, when encountered with wind of squall line, the insulator chain is compelled to the direction of tower under strong wind. As a consequence, the flashover problem is apt to happen, due to the marked shortening of the air gap between conductor and tower. The taller the tower, the larger the distance between conductor and the ground, and the stronger the wind. Then the possibility of occurring discharge will be enlarged.

3.2.3. Line Icing and Oscillation Fault: In recent years, the increasing transmission line tripping accidents and line fault induced by line icing has become a potential threat to safety operation of power grid. The damage of icing to transmission line is embodied in the problems, such as overload of tower, oscillation, ice flashover of insulator, resulting in the risks of tower falling, line oscillation and flashover of insulator. The falling of tower is an accident in electrical and mechanical connection of transmission line, caused by the failure of line bearing when the thickness of ice exceeds certain degree, taking into account the loading from horizontal, vertical and length wise direction. For the non-uniform ice cover on each part of the conductor, line oscillation is induced by the asymmetry of fracture surface in the line when wind blows. In accord with the intensity of wind force, the frequency of wind is in the range of 0.1 to 3 Hz and amplitude of oscillation exceeds 10 m, probably causing faults such as strand breakage and interphase short circuit. In addition, the icing coating is formed on the surface of insulator accompanied with large amount of suspended impurity in the air, and changes into ice-melting membrane with extreme high conductivity (In some cases, it exceeds 300 μs/ cm) when the weather is warming. Meanwhile, the insulating performance of the insulator chain will be destructed by the ice water melt from the tower. During the melting of ice layer, local air gap will lead to the uneven distribution of the voltage in insulator chain, resulting in local arcing and flashover problems.

Different climate condition results in various degree of icing in the line. As is indicated in Table 2, the hazard rating on circuit is related to its ice covering type. The practical effect of icing could be estimated according to the following equation.

$$B_0 = \frac{1}{2}\left(\sqrt{d^2 + \frac{\rho}{0.9}\left(a \times b - d^2\right)} - d\right) \quad (1)$$

Where B_0 denotes the thickness of standard ice (the density of ice is 0.9 g/cm^3), ρ represents the observed density of ice on the line, a is the major axis of the line with ice covering, b is the minor axis of the line with ice covering, d is the diameter of the line.

The standard thickness of ice on the line is estimated prior to conducting the comparison to the value designed during the construction. If the ratio is below 0.4, it could be concluded that the effect of the ice on the line is in the safe range. While the ratio is in the range of 0.4 to 0.7, the monitoring will be necessary. When it comes to the ratio above 0.7, the line is already in dangerous situation, and requires impairment without delay to avoid severe accident, such as line disconnection and the falling of pole.

Table 2. Type of the Ice on the Line [2]

Type	Property	Formation condition and process
Glaze	Pure, transparent ice with stiff character. It could form into an icicle with density of 0.9 g/cm^3 or higher, possessing strong adhesive power.	It is formed by the landing of overcool rain or fine drizzling rain in lowland to the object with a temperature above freezing temperature. In mountain land, it is formed by ice crystal from cloud or the ground fog containing large water drop under high wind speed.
Mixed-phase ice	Non-transparent or semi-transparent ice interlaced by transparent layer and non-transparent layer. It is stiff with density of 0.6 to 0.9 g/cm^3 and high adhesive power.	In lowland, it is formed by the ice crystal from cloud or ground fog containing raindrop. In mountain land, it is formed by ice crystal from cloud or ground fog containing water drop in medium size under quite high wind speed.
Soft rime	The white lightweight snow in the form of granular. It is a relative solid crystal with density of 0.3-0.6g/cm^3 and rather weak adhesive power.	It is formed by ice crystal from cloud or fog containing water drop under medium wind speed.
Rime	It is snow-like white irregular needle-shaped crystal of lightweight. It is fragile and lightweight with density of 0.05~0.3g/cm^3 and weak adhesive power.	It is formed by direct condensation of water vapor from air in a cold and calm weather.

3.2.4. Bird Damage: With the improvement in the awareness of natural ecological environment protection strengthening, the number of bird has gradually increased and the scope of its activity has also increasingly expanded. On the other hand, the activity of bird does a great harm to transmission lines. As bird damage is coincidental and strong liquidity, security risk is increased with the bird damage area expanding. Three reasons in inducing bird damage are analyzed in detail as follows [3].

(1) Bird nesting: Birds begin nesting, eggs production and hatching on the transmission line tower in spring. The nest built by branches would not cause accident in dry weather, but as for rainy weather, the nest in the line tower will be scattered and fell on the live wires or hanging bottles. The branches contacting wire (or near wire) will lead to short circuit ground accident.

(2) Bird flight: Line fault will be caused by wires and weeds and other things in bird mouth, which fell on the tower cross arm or suspending insulator equalizing ring when birds fly round-trip on the lines. Short circuit caused by food when bird eats food on the tower cross arms, which may lead to grounding line tripping. Large-size birds or birds in fighting fly between the wires may cause phase fault and single-phase ground fault.

(3)Bird excrement flashover: Some birds perch on the tower while they don't build nest on the tower. The defecation will pollute insulator, causing bird excrement flashover accident in the wet and frog weather.

3.3. Fault Analysis of the Power Transmission Line

3.3.1. Single-Phase Grounding of the Power Transmission Line: As a common fault problem in high-voltage power transmission line in the course of operation, the single-phase grounding is caused by long time working of the wire under severe environment, such as overcast and rainy weather, high humidity, etc. In high-voltage system ranging from 35 kV to 330 kV, the single-phase grounding makes zero to electric potential of fault point short to ground, while the phase voltage of line in normal operation is increased to voltage value in the line, inducing increase in voltage drop and forming overvoltage. In this case, long term overvoltage exceeding the withstand voltage of the device will finally breakdown the device. In addition, if the problem of high voltage drop did not solved in a timely manner, the relative high line resistance will give rise to accidents such as short circuit, through rapidly elevating the ambient temperature of the circuit.

3.3.2. Short Circuit of Power Transmission Line: As is mentioned above, lightning stroke or wind age yaw might induce problems such as the shortening of gap between line conductors, the breakdown of insulator, and then gives rise to short circuit in transmission line.

3.3.3. Open Circuit of Power Transmission Line: In terms of long distance power transmission line, the disconnection in line, another common fault in transmission line, may have impact on large scale normal power supply. In high-voltage power transmission line, a gap exists in the open-circuit contact when the disconnection is not fully completed, and it will induce air discharging in the form of voltaic arc. The huge quantity of heat elevates temperature of adjacent area which may result in fire or explosion.

4. The Prevention and Treatment of High-Voltage Power Transmission Line

Since the fault in transmission line in course of operation is mainly due to the effect of the environment and the line itself, the prevention of the fault is based on the two aspects, as is shown below.

4.1. Fault Prevention from External Forces

4.1.1. Improving the Lightning Protection Performance: The fault caused by lightning stroke is major part of fault type, thus the lightning protection performance should be promoted to effectively protect against the lightning. Prior to the construction of high-voltage power transmission line, lightning location system should be utilized to conduct statistical record on annual lightning field distribution and its current strength, and select the area that is a loopholes of the lightning distribution by integrating the landform of the region the line passes through. Furthermore, if necessary, the devices such as the lightning rod and lightning arrester, should be installed in accord with the local conditions, introducing the lightning into ground. In the process of tower installation, grounding resistance value of the tower could be decreased by using natural grounding or external grounding device to improve the overall lightning protection performance and decrease the tripping numbers of the circuit. Also proper increase in the numbers of the bracing wire which acts as electric conductor in shunting current from the lightning, will reduce the hazard from the lightning, enlarge the equivalent radius of tower, and cut down the wave impedance of the tower. In general, the shunting effect of the bracing wire has a direct correlation with the position connecting to the tower and the ground fault protection status of the line. The smaller the distance between bracing wire and tower, the smaller the ground resistance. As a consequence, the larger shunting effect promotes the protection performance on the line.

4.1.2. Reduction in Wind Effect: During the construction of high-voltage power transmission line, design parameter should be optimized and a certain allowance should be maintained to reduce the impact of the wind force on transmission line. Similar to the preparatory work for lightning protection, relevant weather condition upon the region the transmission line passes through, shall be figured out. And the wind speed at different altitude could be estimated by using the following equation. In this way, the height of the line conductor from the ground can be reasonably set.

$$Vi = Vz(Hi / Hz)^{a} \tag{2}$$

Where Hi and Vi represents reduced height (m) from the ground and the corresponding reduction wind speed (m/s) respectively, Hz and Vz refer to the practical observation height (m) from the ground and the corresponding observed wind speed (m/s), a is the value of ground roughness (0.12, 0.16, 0.2).

Apart from this, the wire should be adjusted if the amplitude of swing is relatively large under the wind force. One more tower shall be built between the two towers if the conductor is relatively loose. In the course of running, the insulator string and the wire jumper should be augmented as well as counter weight device, in response to the fault in jumper of tension tower and other external-angle jumpers having jumper-free string with large rotation angle. Thereby, the amplitude of oscillation is reduced, avoiding the fault of short circuit and flashover.

4.1.3. The Control of Ice on the Transmission Line: The countermeasure of controlling the ice on the transmission line mainly includes the following several aspects. First, the scope of ice region along the transmission line should be conducted with correct division in the anti-icing design. And the designed ice thickness should be determined, especially for the area with microclimate ice coating along the line. During the construction of overhead conductor, the area severely afflicted with ice coating shall be avoided, and observation station shall be set up along the line to capture the instant information about the ice coating status and estimate its perniciousness. Second, as to the tension region of the area severely afflicted with ice coating, especially the tension region extended for a long distance, tension tower or reinforced tangent tower should be added to a proper position thereof [3]. In case of the icing flashover of insulator string induced by the ice coating, large diameter insulator and large shed should be applied to cutting off the connection route of the ice layer in response to suspension type insulator, and for the double-string insulator, the distance between hanging points should be increased, otherwise spacer devices can be installed to improve the ice coating condition.

4.1.4. Prevention Measurement of Bird Damage for Transmission Line: Since the bird activity is greatly affected by the seasons, the bird damage is obviously seasonal. The winter and spring are the frequent bird damaging periods, so feasible measures and plans can be made according to the activity patterns of bird. Currently, the prevention measurement of bird damage can be taken as follows [3].

(1) Well defined and classified the characteristic area of bird damage;

(2) Actively carry out supervision inspection, keep abreast of insulators pollution situation, and launch state maintenance;

(3) Clean insulators, especially insulators needed repeated cleaning in the area with bird damage frequent activity;

(4) Install bird stab device to prevent birds stop on the pole arm.

(5) Install bird scare device, windmills or baffles, *etc*.

4.2. Fault Prevention and Treatment of High-Voltage Transmission Line

4.2.1. Improvement of the Fault Diagnosis Level Of High-Voltage Transmission Line: When the transmission line breaks down and an alarm is send out, the fault source should be instantly located and the reason should be analyzed according to the protection device operating status of the central control room and the distance and ranging information showed in the wave recording device and other related equipment. A maintainer should be also arranged to the spot to repair the fault in a timely manner.

4.2.2. Fault Prevention High-Voltage Transmission Line: Aiming at the single-phase grounding fault of lines, a commissioner should be arranged to regularly test running state of lines, and clean up its surrounding environment to avoid obstacles interfering the normal operation of transmission lines. In addition, the cleaning treatment should be strengthened on the surface of insulator and porcelain insulator to insure transmission clean. The election of insulator type should be fully taken into account the properties of the transmission line. During electricity demand at peak hours, infrared thermometers should be periodically used to detect the line wire connector’s temperature, which is to avoid accidents caused by high temperature.

To avoid transmission line arc short-circuit accident, the wire quality should be guaranteed reliable and the use of cross, bent, broken wires should be eliminated during choosing the transmission line. It should also control arc sag error in 5% range within design criteria value at the installing wires.

4.2.3. The Application Of On-Line State Detection Technology In Transmission Line: Since most transmission line failure are centered with the insulators, towers, grounding and other components, line fault can be determined and prevented through real-time monitoring status of these components. With the improvement of infrared detection, UV detection, and other core detection technology, and the development of communication technology, on-line detection technology can be introduced to the transmission line. The heating situation of each component on the line can be obtained through infrared imaging. And the discharge phenomenon and discharge intensity can be determined by ultraviolet light, which can help to facilitate long-distance lines running state supervision and find the fault and fault source.

Besides, status maintenance on the high voltage transmission line can be carried out based on the on-line maintenance. Through automatic comparison of the equipment operation status information with the normalization and standardization information, and output of the diagnostic result to obtain health status, we can determine whether the device needs repairmen or not. The Figure 2 shows below the schematic diagram of the procedure from on-line monitoring technology to status maintenance.

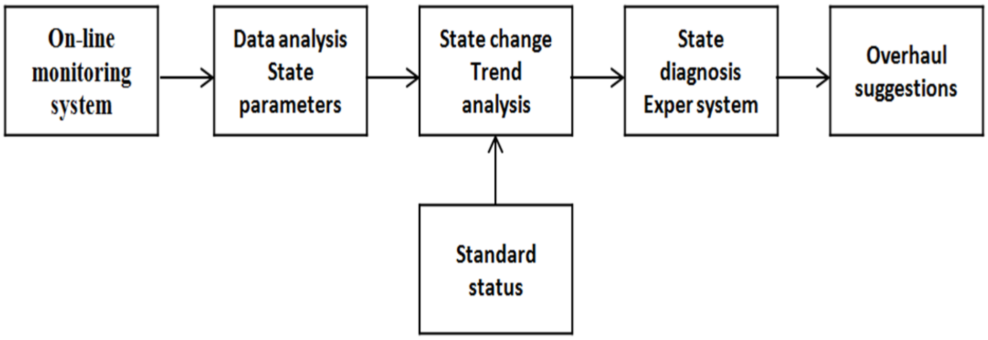

Figure 2. Schematica Diagram of the Procedure from On-Line Monitoring Technology to Status Maintenance

5. Conclusion

In the grid system, high-voltage transmission line plays an important role in the function of power delivery and is one of the key components of the grid system. Since the transmission system is outdoor work, and can be easily influenced by external force, such as climate change, obstacles and other unpredictable factors, it is still apt to induce faults and affect users normal electricity demand, though its structure is simple and reliable. To protect the normal power of grid system and ensure smooth passage of transmission lines, this paper presents the fault preventive measures from the external force (such as lightning, wind, icing, *etc.*) and the line itself and other aspects. In practice, the specific circumstance of transmission line should be fully taken into account to establish reasonable fault prevention strategies. To ensure the reliability of the grid system supply and better meet users' electricity demand, it should be strengthen regular tests of transmission lines, and promptly clean up foreign bodies in the transmission lines to control the occurrence rate of fault to a lesser extent.

Acknowledgements

The authors gratefully acknowledged the financial support from Liaoning Education Department (serial number: L2013494, L2014526), Nature Science & Foundation of Liaoning Province (serial number: 2013020124) and National Natural Science Foundation of China (serial number: 61372195, 61371200).

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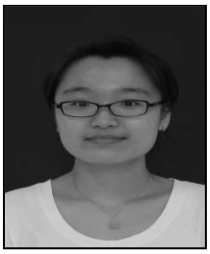

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