Evaluation of cable moisture-proof measures based on AHP

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Abstract. With the widespread use of cross-linked polyethylene (XLPE) cables in the power system, the problem of aging due to moisture ingress of XLPE cables is becoming increasingly prominent. Under the humid laying environment, the XLPE cable sheath is easy to damage. The storage seal is improper or the water fill in the cable channel causes the XLPE cable to be immersed for a long time, which will seriously affect the insulation and service life of the cable. Therefore, it is important to establish a systematic evaluation system for moisture-proof measures of XLPE cables. This paper analyzes the reasons for the moisture of XLPE cables and the common moisture-proof measures. Based on the AHP method, comprehensively considers the impact of economy, technicality, applicability and feasibility, and establishes an evaluation system of cable moisture-proof measures. In the evaluation system, the criteria layer is subdivided into seven secondary indicators. For the plan layer, comprehensively consider the XLPE cable structure, cable materials, cable accessories and laying environment and other factors to select the XLPE cable moisture-proof measures for comparison. This paper uses AHP to figure out the comprehensive weight of each moisture-proof measure to the target layer, and the consistency test was conducted to prove the validity. The results have shown that the XLPE cable using water treeing resistant material in the plan layer has the best comprehensive effect. This paper provides a systematic and comprehensive evaluation system for future researches on cable moisture-proof measures, and the research results provide reference value for cable design and selection in the hot and humid areas.

1. Introduction
At present, power cable is widely used in urban power grid and is the key equipment to undertake power transmission and distribution in power distribution network. Due to the most power cable materials are cross-linked polyethylene, the research object of this paper is XLPE cable.

Getting damp is a crucial reason of aging damage of XLPE cable. Water molecules passing through a damaged sheath or joint will cause water treeing under the action of electric fields. High field intensity is formed at the tip of water treeing and the irregularity of conductor, which increases the dielectric loss and reduces the breakdown voltage. Under the condition of high temperature and high pressure in operation, the water treeing may be transformed after a period of time, which may further cause the electrical treeing, and finally penetrate the whole cable insulation, and break the cable seriously, causing the power system collapse [2, 3].

Many scholars have put forward damp proof measures of XLPE cable from various aspects. In terms of cable production and laying, literature [1] puts forward that due to production impurities,
transportation or external damage caused by laying and other factors, the XLPE cable will be affected by moisture, so it is necessary to control raw material impurities and take protective measures during laying. In terms of the design of the sheath and the moisture-proof layer, literature [5] proposes a laminated metal foil moisture-proof layer structure, combined with the hot melt adhesive sealing technology of the laminated pressure plate, which can effectively prevent the soil. The penetration of water ions into the insulator can solve the aging problem of XLPE cable caused by water treeing. In terms of the moisture-proof protection of cable joints, literature [8] discussed the moisture-proof protection of low-voltage XLPE cable joints in detail, and proposed to improve the construction technology of cable joints, such as sealing cold and hot shrinkable appendage at both ends, cutting the insulation end into a cone and coating the filling glue.

Although many documents have proposed different protection methods for the moisture of XLPE cables, there is no systematic summary and evaluation of the moisture-proof measures of XLPE cables. AHP as a method of hierarchical weight decision-making in fuzzy mathematics, can effectively combine qualitative and quantitative analysis methods, which is convenient to realize the optimal decision-making of multi-scheme selection. This study will establish an evaluation system for moisture-proof measures of XLPE cables through AHP, which can be used to screen the best moisture-proof measures for XLPE cables.

2. Analysis of Moisture-proof Measures of XLPE Cable

The moisture in the air and soil entering the XLPE cable will cause serious damage to the insulation of the body. Moisture of XLPE cable is mainly classified into external and internal factors. The external factors include the laying environment and mechanical damage. The internal factors include the selected materials and defects caused by the manufacturing process.

For the above reasons, there are the following cable moisture-proof measures.

1) Structural water blocking measures for cables. XLPE cable is usually composed of conductor, insulation layer, shielding layer and protective layer. Radial water blocking technology usually refers to the improvement of the structure or material of the sheath. Longitudinal water-blocking technology is more complicated, including improving the compression coefficient of the conductor, filling the water-blocking powder in the conductor, wrapping the water-blocking tape, filling the water-blocking paste and other water-blocking materials [15].

2) Select high-quality cable materials. Choosing high-quality cable materials is the fundamental condition to ensure cable quality. In order to ensure the quality of raw materials, water treeing resistant cross-linked polyethylene can be selected as the insulating layer material. In addition to maintaining the good mechanical and electrical properties of the original cross-linked polyethylene material, this method can also effectively inhibit the growth of water treeing [17].

3) Improvement of waterproof performance of cable joint. When the cable is in a submerged state for a long period of time, moisture is likely to enter the joint gap. In order to ensure the tightness of the cable joints, many waterproof joints are come into service, or a waterproof box is added at the middle joint to avoid the situation where the joint is immersed in the channel water for a long time.

4) Improve the cable laying environment. The XLPE cable generally adopts the direct burial method. Although the construction is simple and the cost is low, the cable directly contacts the soil and the water in this way will easily make the cable get damp. In addition to direct laying, cable trenches, overhead or tunnel laying methods are now used in more and more projects.

In summary, the entire process from cable production to use and the different structure of the cable can be protected by corresponding cable moisture-proof measures, as shown in Table 1.
Table 1. Moisture-proof measures of cables.

| Process       | Part         | Measures                                      |
|---------------|--------------|-----------------------------------------------|
| Production    | Outer sheath | Comprehensive sheath                           |
|               |              | metal sheath                                   |
|               | Cable core   | Water blocking tape                            |
|               |              | water blocking filling paste                   |
|               | Insulation   | Water treeing resistant material               |
|               | Cable accessories | Cable waterproof connector                     |
|               | Cable laying method | Cable trench/tunnel laying                  |

3. Evaluation of moisture-proof measures of cables

3.1. Evaluation steps of AHP

The AHP revolves around the ideas of "system-element-level-matrix-weight", splits the research questions first and then synthesizes them, and finally examines the results. The specific steps and contents are: (1) Establish AHP indicators. (2) Construct the judgment matrix. (3) Hierarchical ranking and consistency check. (4) Hierarchical total ranking and consistency check.

When constructing the judgment matrix, this article adopts 1-9 standard quantification method. In addition, the definition of the consistency index $R$ relative to the matrix dimension $n$ is shown in Table 2:

Table 2. Consistency index corresponding to matrix in different dimensions [10].

| $n$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|-----|----|----|----|----|----|----|----|----|----|
| $R$ | 0  | 0  | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

3.2. Calculation of Index weight

3.2.1. Criterion-level index establishment and weight calculation. This article refines the criteria layer into two-level indicators for evaluation. The first-level indicators include economy $B_1$, technology $B_2$, applicability $B_3$ and feasibility $B_4$.

1) Economic efficiency $B_1$ is the cost of a project from the early stage of procurement, construction, maintenance to the later stage, which is a factor that must be considered in the project plan. In this article, economic efficiency is measured by the second-level indicator engineering cost $B_{11}$, including the early production cost and later maintenance cost of the project.

$$B_{11} = c_1 + c_2 + c_3$$

Among them, the material cost is $c_1$, the labor cost is $c_2$, and the maintenance cost is $c_3$. For the cable production plan, the material cost including raw materials and equipment accounts for approximately 60-90% of the total cost. [19] Therefore, the engineering cost is taken as the engineering cost for reference, $B_{11} \approx c_1$.

2) The technical indicators $B_2$ are mainly evaluated by the three second-level indicators of moisture proof effect $B_{21}$, safety $B_{22}$ and stability $B_{23}$ of the cable. Moisture-proof effect can refer to the comparison of the growth rate of water treeing. Testing cables with different moisture-proof measures in the same environment at the same time. For cables with slower water treeing growth, the moisture-proof effect is better. Safety can be evaluated by the failure rate during operation within one year. The stability can be compared by the maximum temperature and maximum voltage allowed during normal operation of the XLPE cable.

3) Applicability $B_3$ is mainly divided into application cope $B_{31}$ and application time $B_{32}$. The wider the scope of application, the better the applicability, and the applicable time actually reflects the service life of the measure. The longer the service life, the stronger the applicability.
4) Feasibility $B_4$ is used to judge whether the plan is easy to implement, mainly includes the difficulty of implementation $B_{41}$. Factors that need to be considered are: the requirements of the process and equipment, the limitations of the production and construction environment, and whether the skill requirements of the staff are too high.

In summary, the frame structure of the target layer and the criterion layer is shown in Figure 1. From top to bottom are the target layer, the first-level indicators of the criterion layer and the second-level indicators of the criterion layer.

According to the evaluation model, then calculate the weights of the defined criteria layer indicators. First, compare the economics $B_1$, technicality $B_2$, applicability $B_3$ and feasibility $B_4$ of the first-level indicators, then compare the second-level indicators among the first-level indicators separately, and finally calculate the weight of the second-level indicators based on the ratio of the two-level indicators.

For the first-level indicators, the most important factor is the technical indicator $B_2$, followed by the economic indicator $B_1$, and finally the program feasibility indicator $B_4$ and applicability index $B_3$. We have the importance rank as: $B_2>B_1>B_3>B_4$.

Comparing the second-level indicators of technical indicators $B_2$, since safety is a prerequisite for production and operation, safety indicator $B_{22}$ should be considered first. Then should consider the moisture-proof effect $B_{21}$. Thus we have the importance rank as: $B_{22}>B_{21}>B_{23}$.

Comparing the second-level indicators under the applicability indicators $B_3$, the applicability time $B_{32}$ relative to the applicability range not only represents a longer period of use of the scheme, but also is closely related to economics and technicality, and is more reference for the choice of the scheme. Thus we have the importance rank as: $B_{32}>B_{31}$.

According to the above rules, construct the index evaluation matrix at each level of the criterion layer, calculate the indicator weights at all levels, and then perform the consistency check calculation. The weight of the seven second-level indicators of the criterion layer to the target layer can be finally calculated, as shown in Table 3. We have the importance rank as: $B_{32}>B_{31}>B_{22}>B_{21}>B_{33}>B_{41}>B_{34}$.

**Table 3.** Comprehensive weight of criteria-level indicators.

| $A$ | $B_1(0.245)$ | $B_2(0.507)$ | $B_3(0.155)$ | $B_4(0.093)$ | $\text{Weight (w)}$ |
|-----|-------------|-------------|-------------|-------------|------------------|
| $B_{11}$ | 0.245      | -           | -           | -           | 0.245            |
| $B_{21}$ | -          | 0.330       | -           | -           | 0.167            |
| $B_{22}$ | -          | 0.570       | -           | -           | 0.289            |
| $B_{23}$ | -          | 0.100       | -           | -           | 0.051            |
| $B_{31}$ | -          | -           | 0.333       | -           | 0.052            |
| $B_{32}$ | -          | -           | 0.667       | -           | 0.103            |
| $B_{41}$ | -          | -           | -           | 0.093       | 0.093            |
3.2.2. Determination of the anti-moisture measures at the project level and calculation of weights. Summarize the current commonly used cable moisture-proof measures as the program layer indicators, as shown in Table 4

| Measures | advantages                                                                 | disadvantages                                                                 |
|----------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Water-blocking tape $C_1$ | Good water absorption, high expansion rate, good moisture resistance; simple process | Increase the outer diameter of the cable, make it difficult to dissipate heat, accelerate thermal aging, and limit the transmission capacity |
| Water blocking filling paste $C_2$ | Low cost and wide range of applications | Heavy weight, poor conductivity, difficult to clean and construct joints |
| Comprehensive sheath $C_3$ | Good water tightness and good moisture resistance | High production cost, poor welding reliability, unable to detect the degree of polyethylene film welding and damage; more capital and equipment investment |
| Metal sheath $C_4$ | Good waterproof effect, good water-blocking durability, no effect on heat dissipation | High production cost and heavy weight |
| Water treeing resistance Material $C_5$ | Retain water tree, high breakdown strength, low failure rate, long service life | Low popularity, unstable production process, limited by price |
| Waterproof joint $C_6$ | Good sealing, good moisture-proof effect, wide application | High production environment and process requirements, greatly affected by vibration |
| Cable tunnel laying $C_7$ | Laying environment is safe, easy to overhaul | High investment cost and difficult construction |

Based on the indicators of the criterion layer, compare the indicators of the plan layer, then construct the judgment matrix, calculate the weight of the plan layer to the criterion layer. After the consistency test, calculate the weight of the plan layer to the target layer.

For the project cost $B_{11}$ of the second-level indicator in the criterion layer, the lowest cost is the water blocking tape $C_1$ and the water blocking filling paste $C_2$, especially the water blocking filling paste, which is widely used for its low cost. Relatively speaking, sheaths made mainly of metal materials $C_4$ are more expensive. A certain amount of capital and equipment need to be invested in the production of aluminum-plastic composite tape in the comprehensive sheath $C_3$ to ensure the reliability of the welding process. The price of water treeing resistant material $C_5$ is higher than that of ordinary XLPE cable. The investment cost of tunnel laying is much higher than traditional direct buried laying. After comparison, we have the importance ranking as: $C_5 > C_1 > C_6 > C_3 > C_4 > C_7$.

For the indicator of moisture resistance $B_{21}$, according to the accelerated water treeing aging test, the growth rate of the water treeing resistant cross-linked polyethylene material $C_5$ is twice as slow as the common cross-linked polyethylene material $C_2$. Among the water-blocking materials, the active water-blocking materials such as the water-blocking tape $C_1$ have better waterproof effect; if the water blocking filling paste $C_2$ is not fully filled during the production of the ointment, a gap will be left, and the moisture-proof effect is limited. From the perspective of water permeability, the function of the metal sheath $C_4$ and the comprehensive sheath $C_3$ is better, especially the water tightness of the aluminum-plastic composite tape is thousands of times higher than ordinary materials. After comparison, we have the importance ranking as: $C_5 > C_7 > C_3 > C_2 > C_4 > C_6 > C_1 > C_2$.

For the safety indicator $B_{22}$, it is mainly measured by the failure rate of the cable. Water-blocking tape $C_1$ is difficult to dissipate heat and it is easy to accelerate the thermal aging of the cable. After filling with waterproof grease $C_2$, the conductivity is reduced. If the cable is not filled completely, a gap will occur if the cable is bent, which affects the safety of cable. The water treeing resistant material $C_5$ has high safety, high breakdown strength, and the breakdown rate is only 20% of ordinary XLPE cables, the
failure rate is also in a low degree. The safety of the metal sheath $C_4$ is also good, which can not only ensure the moisture-proof effect, but also play a role in the thermal stability of the zero-sequence current. After comparison, we have the importance ranking as: $C_5 > C_7 > C_4 > C_3 > C_6 > C_1 > C_2$.

For stable performance index $B_{23}$, Water blocking tape $C_4$ and water blocking filling paste $C_2$ are not resistant to high temperature. The water treeing resistant material $C_5$ has good stability and can still maintain good performance at high temperatures. The cable tunnel $C_7$ provides a safe and stable operating environment for the cable, making the cable less susceptible to interference from the external environment. After comparison, we have the importance ranking as: $C_7 > C_5 > C_6 > C_3 > C_4 > C_1 > C_2$.

For scope indicators $B_{31}$, Water blocking tape $C_1$, water treeing resistant material $C_5$, waterproof joints $C_6$ have a wide range of applications. The metal sheath $C_4$ is usually used for high-voltage cables in engineering, and the comprehensive sheath $C_3$ is usually used for medium and low-voltage cables. Cable tunnels $C_7$ will be constrained by the number of cables, geographical environmental conditions, so the scope of application is small. After comparison, we have the importance ranking as: $C_6 > C_5 > C_7 > C_2 > C_3 > C_4$.

For applicable time indicators $B_{32}$, In the moist environment, the service life of the cable is only about 30 years using water-proof materials such as water blocking tape $C_1$, the life span of the water tree resistant material $C_6$ is 35-40 years, and the life span of the metal sheath $C_4$ is about 60 years. After comparison, we have the importance ranking as: $C_4 > C_3 > C_5 > C_7 > C_6 > C_1 > C_2$.

For the difficulty of implementation indicators $B_{41}$, Water-repellent filling paste $C_2$ and metal sheath $C_4$ are heavy, which will cause inconvenience during construction. The comprehensive protective layer $C_3$ requires that the aluminum-plastic composite tape and the outer sheath be welded as reliably as possible in the production process, which has high requirements for production equipment and workers' technical operations. Cable joints $C_6$ not only have technical requirements, but also prevent joint damage during construction. The construction amount of cable tunnel $C_7$ is larger, and the construction requirements are higher. After comparison, we have the importance ranking as: $C_1 > C_2 > C_4 > C_3 > C_5 > C_7 > C_6$.

According to the above judgment, combining with the weight of the criterion layer, the weight of the scheme layer to the target layer is calculated, the results are shown in Table 5.

Table 5. The weight of the scheme layer to the target layer.

|   | $B_{11}$  | $B_{21}$  | $B_{22}$  | $B_{23}$  | $B_{31}$  | $B_{32}$  | $B_{41}$  | $w$  |
|---|----------|----------|----------|----------|----------|----------|----------|-----|
| $C_1$ | 0.266   | 0.045   | 0.042   | 0.035   | 0.160   | 0.049   | 0.316   | 0.129 |
| $C_2$ | 0.376   | 0.032   | 0.030   | 0.026   | 0.104   | 0.034   | 0.232   | 0.138 |
| $C_3$ | 0.054   | 0.150   | 0.113   | 0.098   | 0.072   | 0.244   | 0.050   | 0.110 |
| $C_4$ | 0.040   | 0.098   | 0.185   | 0.070   | 0.051   | 0.317   | 0.076   | 0.126 |
| $C_5$ | 0.096   | 0.341   | 0.367   | 0.272   | 0.234   | 0.165   | 0.121   | 0.241 |
| $C_6$ | 0.145   | 0.068   | 0.065   | 0.138   | 0.342   | 0.077   | 0.170   | 0.114 |
| $C_7$ | 0.023   | 0.266   | 0.198   | 0.361   | 0.037   | 0.114   | 0.034   | 0.142 |

According to the table, it can be concluded that the comprehensive ranking is: $C_6 > C_7 > C_2 > C_4 > C_3$. The results show that the comprehensive sheath $C_5$ and metal sheath $C_4$ have better safety and longer application time the water blocking tape $C_1$ and the water blocking filling paste $C_2$ are more economical; the cable tunnel laying method $C_7$ is safe and stable; The waterproof joint $C_6$ has a wide application range and is easy to implement. The water treeing resistant material $C_5$ with the highest comprehensive weight is the best moisture-proof measure and has excellent performance in all aspects.

4. Conclusion

This article establishes an evaluation system for cable moisture-proof measures based on AHP. Comprehensively considering the four factors of economy, technicality, applicability and feasibility, the criterion layer is subdivided into seven secondary indicators for a comprehensive evaluation, which
provides a theoretical framework for the selection of cross-linked polyethylene cable moisture-proof measures. Under the comprehensive consideration of multiple indicators, this article evaluates seven moisture-proof measures and analysis the advantages of each measure and screens out the comprehensive best moisture-proof measures.

In the future research, the judgment matrix can be modified according to the actual needs of the project to meet the application of different scenarios.

Acknowledgments
This work was financially supported by

References

[1] Wang Yongwei, Discussion on water-proof and moisture-proof technology of XLPE power cable [J]. Henan Science and Technology, 2013 (20): 59.

[2] Zhou Kai et al, Growth characteristics of water treeing in XLPE cable insulation [J]. High voltage technology, 2019, 45 (10): 3207-3213.

[3] W. Tao et al., "Study on the electric-field characteristics of water tree region on the dry or wet condition in XLPE cables," 2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), Chengdu, 2016, pp. 1-4.

[4] Sun Botao et al, Waterproof and moisture treatment of XLPE cable [J]. Metallurgical Power, 2001 (05): 32-34.

[5] Bow, K. E. New developments in medium and high voltage cable with laminate sheaths as moisture barriers [J]. IEEE Electrical Insulation Magazine, 1993, 9 (5): 17-28.

[6] Bayer, M.G., Bow, K.E., Snow, J.H., Voltz, D.A. Chemical-moisture barrier cable concept and practice [P]. Petroleum and Chemical Industry Conference, 1994. Record of Conference Papers. Institute of Electrical and Electronics Engineers Incorporated Industry Applications Society 41st Annual, 1994.

[7] Dong Zhaolin et al, The necessity and measures of XLPE cable waterproof [J]. Optical fiber and cable and its application technology, 2017 (01): 43-44.

[8] Tang Zhengsen et al, Construction process analysis and improvement measures of 10kV XLPE cable joint [J]. Insulation Materials, 2009, 42 (02): 71-74.

[9] Liu Jie et al, Review of waterproof and moisture proof technology of cross-linked polyethylene cables [J]. Communication Power Technology, 2019, 36 (07): 209-210.

[10] Xie Jijian et al, Fuzzy mathematics method and application [M]. Huazhong University of Science and Technology Press, 2005.

[11] Li Rui et al, Evaluation of typical power supply models of important power users based on AHP and expert experience [J]. Power System Technology, 2014, 38 (09): 2336-2341.

[12] Luo Junhua, Qiu Yuchang, Yang Liming, Statistical analysis of operation faults of 10kV and above power cables [J]. High Voltage Technology, 2003 (06): 14-16.

[13] Yuan Ye, Chen Jian, etc, Research on the damping insulation characteristics of 10kV XLPE cable [J]. Power System Technology, 2014, 38 (10): 2875-2880.

[14] Tang Zhengsen, Li Jinglu, Li Zhijuan. Analysis of construction technology and improvement measures of 10kV XLPE cable joints [J]. Insulation Materials, 2009, 42 (02): 71-74.

[15] Yang Yuzhi, Tian Hongye. Main structure and key process of water-blocking power cable [J]. Wire and Cable, 2003 (01): 14-16+19.

[16] Wang Jinfeng, Zheng Xiaoquan, Kong Zhida, Huang Jianfeng. Structural analysis of waterproof XLPE cable [J]. Wire and Cable, 2009 (06): 4-8+44.

[17] Pan Aimei, Wang Yong, Qiao Yan, Xiang Rongqing, Feng Mingxing. Review of water-resistant tree cross-linked polyethylene cables [J]. Electric World, 2012, 53 (07): 11-13.

[18] Xu Kehua, You Yuan. Analysis and countermeasures of the reduction of insulation of cross-linked cables due to moisture [J]. Sichuan Electric Power Technology, 2007 (06): 48-50.

[19] Sun Kaixin, He Hua, Li Tankang, Liang Jiarong. Research on production cost control of wire and
cable industry——Taking Shenzhen Dawei Cable Company as an example [J]. Chinese and Foreign Entrepreneurs, 2018 (24): 61-65.

[20] Liu Zhaojian, Chang Jun, Fang Peng. Water blocking technology of power cable [J]. Wire and Cable, 2013 (01): 12-14+20.

[21] Huo Yi. Application and analysis of XLPE insulated cable waterproof joints [J]. Journal Papers, 2012, 33 (6).

[22] Li Jiucheng. Selection of cable laying method and determination of cable channel size [J]. Yunnan Electric Power Technology, 2008, 036 (006): 55-56.

[23] Caronia P J, Brigandi P J, Person T J, et al. A next generation advanced water tree-retardant crosslinked polyethylene insulation for long life power cables [C] // 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D). IEEE, 2016.