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고장 발생에 따른 HVDC 시스템용 TP 케이블의 절연체 수명 손실 분석+

(Analysis of Insulation Life Loss due to Fault Occurrence of TP Cable for HVDC Systems)

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요 약 HVDC (high-voltage direct current) 시스템에 TP (thermoplastic) 케이블을 안전하게 사용하기 위해서는 다양한 연구와 테스트를 통해 운전 중 발생할 수 있는 시스템 고장으로 인한 케이블의 수명 손실률 분석이 필요하다. 본 논문에서는 HVDC 시스템 운영 중에 발생할 수 있는 고장 유형에 따른 TP 케이블의 절연체 수명 손실률을 분석하였다. TP 케이블 모델에 고장으로 인한 전력을 인가하고, 2D 유한요소법을 통한 분석 결과를 바탕으로 Arrhenius-IPM (Inverse Power Model)을 적용하여 절연체의 수명 손실률을 분석하였다. 분석결과 절연체 수명 손실률은 전기장 세기의 영향이 높았으며, 고장 발생 시 절연체 내부 측에서 손실률이 가장 높았다. 이러한 결과는 TP 케이블 상용화를 위한 초기 설계 단계에서 중요한 특성으로 사용될 수 있다.

핵심주제어: HVDC 케이블, HVDC 케이블 전기장 분포, HVDC 케이블 FEM 시뮬레이션, HVDC 케이블 수명 손실 분석

Abstract In order to safely use thermoplastic (TP) cables in high-voltage direct current (HVDC) systems, it is necessary to analyze the life loss rate of the cable due to system fault that may occur during operation through various research and tests. In this paper, we analyzed the insulation life loss rate of TP cable according to the type of faults that may occur during HVDC system operation. Electric power due to fault was applied to the TP cable model, and the life loss rate of the insulator was analyzed by applying the Arrhenius-Inverse Power Model (IPM) based on the analysis results through the 2D finite element method. As a result of the analysis, the life loss rate of the insulator was highly influenced by the electric field strength, and the loss rate was highest inside the insulator when a fault occurred. These results can be used as important characteristics in the early design stage for commercialization of TP cables.

Keywords: HVDC cable, HVDC cable electric field distribution, HVDC cable FEM simulation, HVDC cable life loss analysis

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1. Introduction

As industry and equipment technology develop, electricity demand is increasing and environmental regulations are strengthening. Accordingly, the demand for high voltage direct current (HVDC) systems to efficiently connect to the construction of power plants using new and renewable energy is increasing. HVDC systems are intended for long-distance and stable power transmission, and cable costs account for a significant portion of installation costs. Cable selection is very important when building an HVDC power system for stable power transmission. Cross-linked polyethylene (XLPE) cables with extruded insulation have been applied in most AC systems since 1972 to replace conventional oil-filled (OF) cables that require insulating oil injection (Murata et al., 2013). Compared to conventional cables, XLPE cables are more stable in terms of operating temperature range and influence of external conditions. However, the design life of the cable is about 30 to 40 years, so the replacement period is approaching. XLPE insulation is made of thermosetting material and cannot be reused, raising environmental concerns. Accordingly, leading groups are using TP cables with improved thermal and electrical properties and eco-friendly materials.

In the past, HVDC system cables were mainly used under the sea, and most of them were mineral insulated (MI) cables with high mechanical strength to minimize external influences. However, in recent years, large-capacity onshore HVDC systems have been installed, and XLPE cables using extruded insulation have been used to solve the limitation of transmission capacity due to the low operating temperature range of MI cables. When applying XLPE cables to HVDC systems, there is a risk of insulation breakdown due to problems such as polarity reversal and space charge accumulation. However, with the technological advancement of the voltage-sourced converter (VSC) method, problems that occurred in the past have been resolved, and XLPE cables can now be applied to HVDC systems.

During the cable manufacturing process, pre-qualification (PQ) tests are performed to assess the stability of the cable in response to potential overvoltages (Conseil, 2012). Despite extensive research on existing XLPE cables, faults frequently occur in systems and equipment, causing serious damage to cables and affecting their service life (Susakova et al., 2017). In HVDC systems, cables can be thermally and electrically damaged in the aftermath of accidents, which can lead to deterioration of insulation performance, loss of transmission power, and interruption of transmission. Therefore, for stable commercialization and operation of TP cables, simulation analysis of various fault scenarios that may occur in HVDC systems is essential. Based on the results of overvoltage analysis due to fault through simulation, the operating state can be analyzed by applying it to a finite element method (FEM) model. In addition, by applying the operating temperature and electric field distribution to the cable insulation life loss rate analysis model based on the FEM analysis results according to the occurrence of a defect, the insulator life loss according to the fault occurrence scenario can be predicted.

In this paper, the results of specific fault scenario analysis were applied to supplement the analysis of life loss rate in simple transient phenomena due to fault occurrences in the existing HVDC system. For this purpose, the insulation life loss rate due to faults occurring in the arm reactor, AC side, and DC transmission line side was analyzed as representative cases among various fault scenarios that may occur during the operation of a VSC-HVDC system for a 250 kV TP cable designed according to extruded cable test conditions.

The analysis of the insulator life loss rate due to fault occurrences was conducted as follows. The results of overvoltage analysis due to faults occurring during operation in the VSC-HVDC system, obtained through PSCAD/EMTDC, were applied to the COMSOL Multiphysics TP cable FEM model, and the operating temperature and electric field distribution were analyzed using the 2D finite element method. Based on the FEM simulation results, the Arrhenius-Inverse power model (Arrhenius-IPM) considering thermal and electrical stress was applied to compare and analyze the insulation life loss rate of the cable according to the fault types.

Compared to the existing cable test procedure and the life loss rate analysis through general transient phenomenon analysis, the influence of the cable according to the fault scenario could be specifically confirmed. The analysis results showed that the life loss rate of the insulator is greatly affected by the intensity of the electric field. In the steady state, the life loss rate of the outer layer of the insulator is high. However, when an overvoltage occurs due to a fault, the electric field distribution is reversed, and the life loss rate inside the insulator increases. Among the representative fault cases that can occur during the operation of the HVDC system, the one with the greatest impact due to a single occurrence was the AC side fault. In addition to the analyzed scenarios, if there is data on the electric field distribution and temperature change through mathematical calculation or simulation, it can be analyzed by applying it to the Arrhenius-IPM model. These analyses are helpful in commercializing TP cables for application to HVDC systems and in analyzing the electric field distribution, temperature, life loss rate, and characteristics of the insulator according to the operating state of power equipment used in the industry.

2. Characteristics of the TP cable applied to HVDC systems

2.1 Electrical and thermal properties of the extruded cables for HVDC systems

The polypropylene (PP) is primarily used as the insulation for TP cables. By eliminating the cross-linking process compared to the existing XLPE insulation, impurities can be reduced. This minimizes problems related to polarity reversal and electrical stress, and increases dielectric breakdown strength and maximum operating temperature, enabling stable power supply. Table 1 shows the electrical and thermal properties of XLPE and PP insulations (Kim et al., 2023).

Table 1 Comparison of the electrical and thermal properties for XLPE and PP cables

Items	XLPE	PP
Resistivity [Ω·m]	2.14E+16	7.45E+16
DC breakdown strength [kV/mm]	181.87	273.22
Maximum operating temperature [℃]	70	90
Melting point [℃]	130	170

In an HVDC system, a high electric field is initially formed on the inner side of the cable due to the applied voltage, like an AC cable, according to Equation (1) (Mazzanti, 2018).

$$E_{AC}(r) = \frac{U_0}{r\ln(r_o/r_i)} \quad (1)$$

where, $E_{AC}(r)$ is the AC electric field strength at radius r, U_0 is the design voltage of the cable, r_i and r_o are the inner and outer layer of cable insulation position.

After the electric field distribution is initially formed by the transmission voltage, the conductivity changes and can be reversed according to changes in the voltage of the cable and the temperature distribution of the insulation, as shown in Equation (2) (Mazzanti et al., 2013). Fig. 1 shows the electrical conductivity of PP insulation and is applied to the FEM analysis model (Green, 2015).

$$\sigma(T,E) = \sigma_0 e^{a(T-T_{ref})+b(E-E_{ref})} \quad (2)$$

where, $\sigma(T,\ E)$ is the electrical conductivity of the insulation, σ_0 is the electrical conductivity at reference temperature, a and b are the temperature coefficient and electric field coefficient, T and E are the operating temperature and electric field, T_{ref} and E_{ref} are the reference temperature and reference electric field, respectively.

Additionally, in the event of overvoltage resulting from a fault, the intensity of the electric field may exceed the dielectric breakdown strength, potentially causing damage to the insulation. In order to the application of TP cables in HVDC systems, the electric field distribution in response to fault occurrence was analyzed.

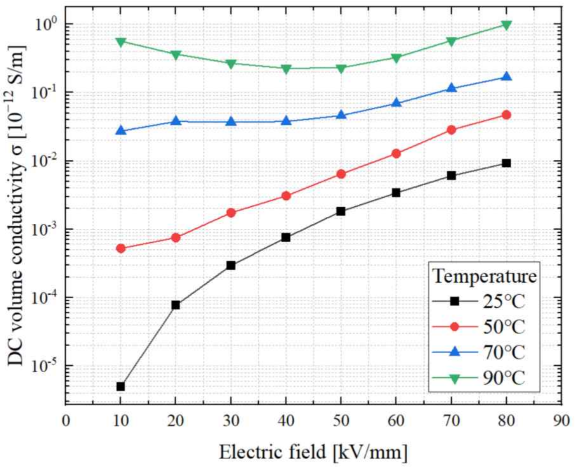


Fig. 1 Electrical conductivity of PP material

2.2 Life loss rate analysis model for TP cable

Three models are presented to estimate the life loss rate of cable insulation. Equation (3) shows the Arrhenius model for thermal loss, while Equation (4) shows the inverse power model (IPM) for determining the life loss coefficient due to the electric field. Equation (5) is an Arrhenius-IPM model that can obtain the life loss coefficient considering both thermal and electrical characteristics (Tomaszewska et al., 2010; Wang et al., 2016; Choudhary et al., 2022).

$$k_{temp} = Ae^{-\frac{E_{a,temp}}{RT}} \quad (3)$$

$$k_{field} = BV^{n} \quad (4)$$

$$k_{total} = k_{temp} + k_{field} \quad (5)$$

where, A is the pre-exponential factor, $E_{a,temp}$ is the activation energy for temperature, R is the gas constant, T is the operating temperature, B is the material constant, and n is the stress exponent.

Equation (6) shows the calculation of cumulative damage over the occurrence time of fault using the life loss coefficient. This allows confirmation of the ratio of insulation life loss to the cable's designed lifespan, as determined by Equation (7) (Zhou et al., 2024).

$$D = \int_{0}^{\Delta t} k_{total}\ dt \quad (6)$$

$$LF = \frac{D}{L_{total}} \quad (7)$$

where, D is the integrate aging rate over time, LF is the life loss rate, L_{total}(years) is the total expected life.

The IPM and Arrhenius models are provided by international standards applicable to HVDC cable insulation (Conseil, 2012; IEC 60216-1, 2013). Since the short-term current change due to a fault has little effect on the cable operating temperature and many deterioration analyses have been conducted on the insulator, the existing XLPE cable was mainly analyzed using the IPM model that considers the electric field strength. To apply the TP cable in the early stages of development and operate it stably, it is necessary to consider the phenomena that occur due to a fault. The Arrhenius-IPM electrothermal life model shows suitable agreement with measured fault time data on insulation materials for various voltage and temperature variations (Mazzanti, 2018). Therefore, to analyze the life loss rate, the FEM analysis results for the occurrence of a fault were applied to the Arrhenius-IPM model, which considers thermal and electrical characteristics. The insulation loss rate was analyzed based on a cable design life of 40 years.

3. Composition of the TP cable for FEM simulation model

Fig. 2 shows the structure of the TP cable for HVDC systems used in the FEM analysis, and Table 2 presents the material and thermal conductivity of each cable element (Lee et al., 2022). The analysis model was applied to a 250 kV TP cable designed in accordance with CIGRE TB 496, which represents an extruded cable test condition (Conseil, 2012).

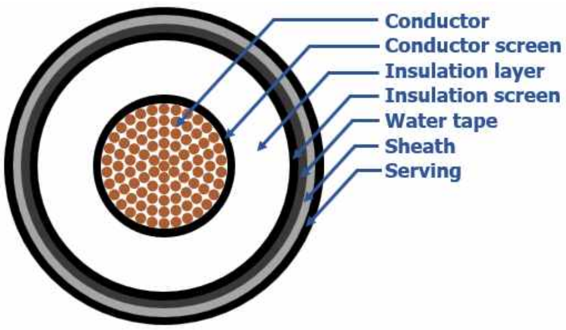


Fig. 2 Structure of TP cable for HVDC systems

4. Comparison of the life loss rate based on FEM analysis results

Conventional cable life analysis is conducted according to the pre-qualification (PQ) test under extruded cable test conditions. During this process, the conductivity of the insulation changes depending on the cable's operating state, causing the movement of space charge, and a high electric field is formed in the outer layer of the insulation, which leads to a high life loss rate in that area. Since the life loss rate is typically analyzed by applying overvoltage for general transient conditions, this method is insufficient for applying TP cables. Therefore, it is necessary to analyze the life loss rate for specific fault scenarios

Table 2 Materials and thermal conductivity of the TP cable by component

Cable components	Materials	Thermal conductivity [W/(m·K)]
Conductor	Copper	402
Conductor screen	Semi-conducting PE	0.286
Insulation	PP (Polypropylene)	0.224
Insulation screen	Semi-conducting PE	0.286
Water tape	PVC (Poly vinyl chloride)	0.15
Sheath	Aluminum	237
Serving	PVC	0.15

that may occur in the VSC-HVDC system and apply this analysis to various fault scenarios.

Fig. 3 shows typical fault cases that can occur in an HVDC system. Each fault location means the following:

① Phase A-ground fault occurred on the AC side of the system connected to HVDC (Chaudhary, 2009)

② A ground fault occurred in the arm reactor of the HVDC converter station (Goertz, 2019)

③ A pole-to-ground fault occurred in the HVDC negative pole cable (Jardini, 2015)

Faults occurring at these locations can cause rapid voltage changes in the cable, potentially leading to damage. To analyze the impact on cable life when a fault occurs, a simulation of transient conditions was performed using PSCAD/EMTDC. Fig. 4 shows the voltage changes measured at the P_{inv} point when a fault occurs ① to ③, respectively.

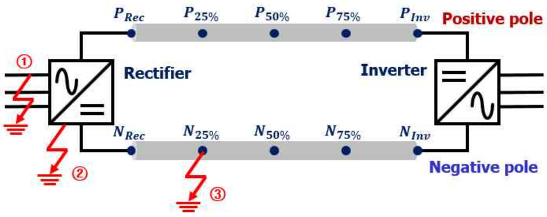
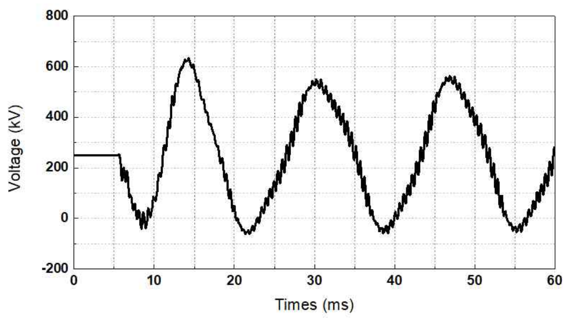
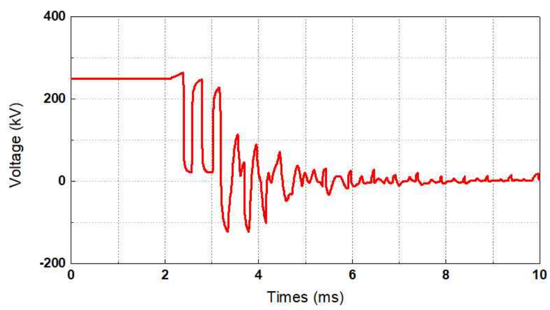


Fig. 3 Scenarios of fault occurrence in a VSC-HVDC system

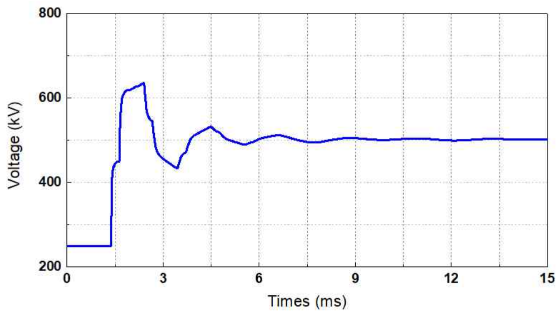
The electric field analysis was performed by applying the voltage formed at the P_{inv} point of the positive pole cable as each fault occurred. Since the electric field can be reversed depending on voltage and temperature changes, the life loss rate of the insulation was analyzed at inner, 25%, 50%, 75%, and outer points in the radial direction of the TP insulation.



(a) Fault occurrence on the AC side



(b) Fault occurrence on the arm reactor



(c) Fault occurrence on the DC cable

Fig. 4 Transmission voltage at P_{Inv} according to fault occurrence

Based on the results of fault voltage analysis using PSCAD/EMTDC simulation, the electric field distribution and life loss rate of the cable were analyzed by applying these results to the COMSOL Multiphysics FEM model as described from section 4.1 to 4.4. The conductivity of the insulation was applied to the 250 kV class TP cable FEM model as shown in Fig. 1. The steady-state electric field distribution through FEM analysis is as shown in Fig. 5.

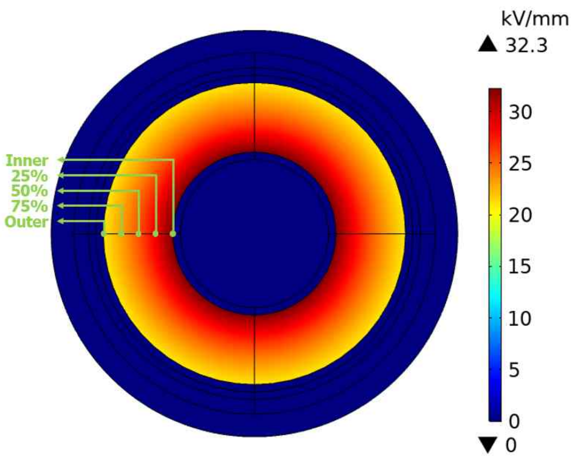


Fig. 5 FEM analysis results of the electric field at steady state

The electric field distribution was confirmed through FEM analysis according to the operating status of the cable, and the life loss rate was analyzed through the equation given in Section 2.2. In Section 4.4, the loss rate for a representative fault in the VSC-HVDC system was confirmed, and the life loss rate for one year from the design life of the cable was analyzed by considering the annual fault occurrence rate.

4.1 Analysis results of a fault occurrence on the AC side

Fig. 6 shows the results of electric field distribution analysis according to the occurrence of AC side fault. The strength of the cable electric field was largely influenced by voltage. It was highest at 53.24 kV/mm inner the insulation, and the range of change in the electric field was 68.09 kV/mm, within the range of the DC breakdown strength of 273.22 kV/mm for the TP insulation shown in Table 1.

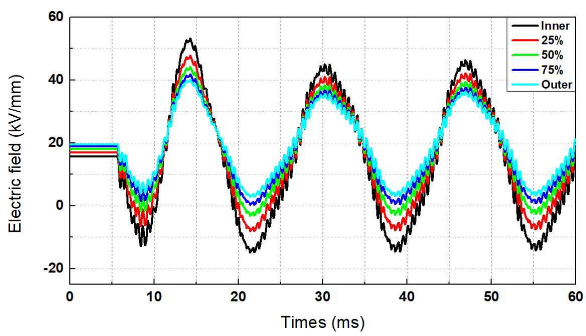


Fig. 6 Electric field analysis results for AC side fault

Fig. 7 shows the life loss rate by insulation location based on FEM analysis results according to the occurrence of AC side fault. The life loss rate was higher from the inner layer to the outer layer of the insulation depending on the electric field highly distribution.

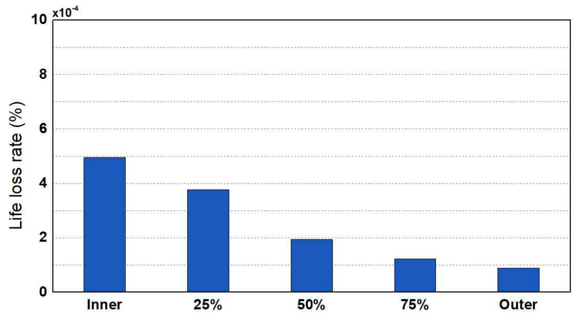


Fig. 7 Life loss rate for AC side fault

4.2 Analysis results of a fault occurrence on the arm reactor side

Fig. 8 shows the results of the electric field distribution analysis according to the fault occurrence on the arm reactor. As a fault occurred, the voltage gradually decreased and was lowest on the N_{inv} side. Since there was not increase in voltage due to a fault, no space charge was generated after the electric field was reversed, so the movement gradually decreased and the electric field strength was decreased.

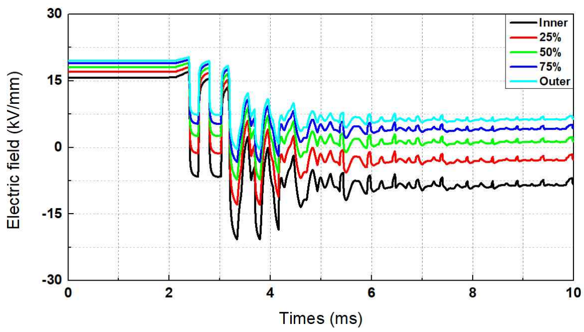


Fig. 8 Electric field analysis results for arm reactor side fault

Fig. 9 shows the life loss rate by insulation location based on FEM analysis results according to the fault occurrence on the arm reactor. The life loss rate was higher from the outer layer to the inner layer of the insulation depending on the electric field strength distribution.

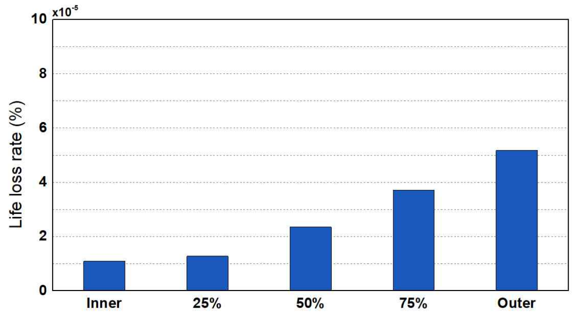


Fig. 9 Life loss rate for arm reactor side fault

4.3 Analysis results of a fault occurrence on the DC cable side

Fig. 10 shows the results of the electric field distribution analysis according to the fault occurrence on the DC cable side. When a fault occurred on the DC cable side, a higher capacity than 250 kV was generated in the cable under normal conditions. As a result, space charges accumulated in the insulation inner, which is close to the conductor, and the electric field became high in the insulation inner. After the electric field was stably formed, it was highest at 53.49 kV/mm in the insulation outer.

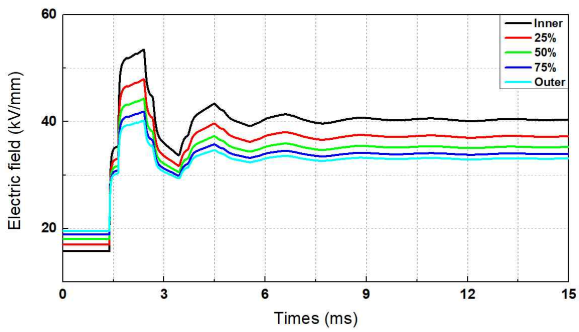


Fig. 10 Electric field analysis results for DC cable side fault

Fig. 11 shows the life loss rate by insulation location based on the FEM analysis results according to the fault occurrence on the DC cable side. The life loss rate was higher from the inner layer to the outer layer of the insulation depending on the electric field strength distribution.

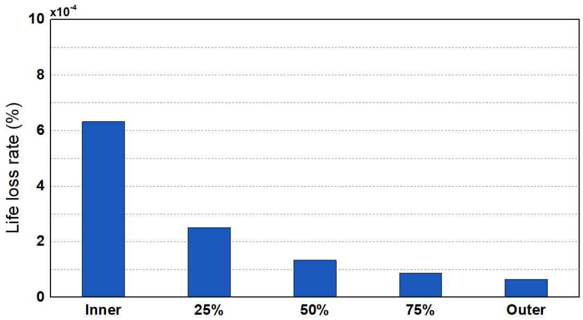


Fig. 11 Life loss rate for DC cable side fault

4.4 Comparison of the life loss rate according to fault scenarios

Table 3 shows the number of life days lost due to fault through FEM analysis. When a fault occurred on the arm reactor side, there was little damage to the lifespan, whereas relatively high damage occurred when a fault occurred on the AC side. The maximum number of days of damage due to a fault was reduced by approximately 4 days for the inner layer of the insulation and approximately 1 day for the outer layer of the insulation.

Table 3 Number of days loss due to faults occurrence

Insulation radial direction	Arm reactor side	AC side	DC cable side
Inner	0.01	4.33	1.39
25%	0.02	3.30	0.55
50%	0.03	1.70	0.29
75%	0.05	1.08	0.19
Outer	0.08	0.78	0.14

Table 4 shows the annual fault rates of HVDC systems (Li et al., 2019). Faults on the arm reactor side occur approximately 6 times per year, faults on the AC side occur approximately once per year, and faults on the DC cable side occur approximately 80 times.

Table 4 Fault rates according to fault scenarios

Fault scenarios	Fault rates [occurrences/day]
Arm reactor side	0.015
AC side	0.0028
DC cable side	0.22

Based on the life loss rate analyzed in Sections 4.1 to 4.3, the life loss days per fault according to the cable design life of 40 years are shown in Table 3. The number of faults per year was determined by relating the number of life loss days per fault to the annual fault rate using Equation (8). With the highest number of faults occurring on the DC cable side, the lifespan within the TP insulation was reduced by approximately 116 days per year. Fig. 12 shows the number of damage days per year for TP cables by applying the results of the analysis of the life loss rate due to fault occurrence to the number of faults per year.

$$L_{damage} = N_{loss} N_{times} \quad (8)$$

where, L_{damage} is the damage per year due to fault occurrence, N_{loss} is the number of days loss due to faults occurrence, N_{times} is the number of fault per year.

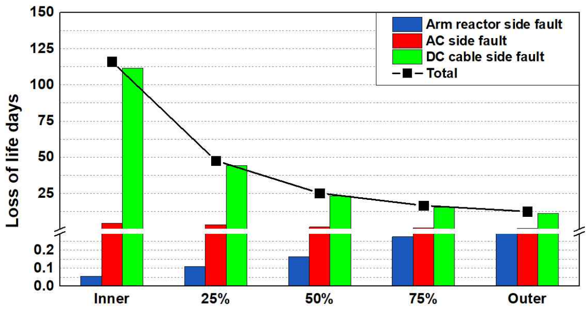


Fig. 12 Number of days for TP cable damage per year due to fault occurrence

5. Conclusions

In this paper, the life loss rate of TP cable insulation due to fault occurrence in the VSC-HVDC system was analyzed. The 250 kV TP cable designed according to CIGRE TB 496 of extruded cable test conditions was analyzed by applying it to the FEM model. Through FEM analysis, changes due to fault were analyzed, and the life loss rate analysis Arrhenius-IPM model was applied to analyze the life loss rate of TP insulation according to the fault scenario.

The change in electric field distribution due to the occurrence of a fault was largely influenced by the fault point voltage. When a voltage higher than the steady state voltage is applied, space charges are generated in the inner insulation. Conversely, when a lower value than the steady state voltage was applied, the movement of space charges decreases, and a high electric field was formed on the outer insulation. The life loss rate of the TP insulation was mostly affected by the electric field, and the life loss when a fault occurred on the arm reactor side was minimal. In contrast, when a fault occurs on the AC and DC sides, overvoltages higher than the steady state 250 kV is applied, resulting in a high electric field formed in the outer insulation and subsequently, a high life loss rate found in the inner insulation.

Applying the life loss rate analysis to the number of annual faults, it was found that faults on the DC cable side accounted for the majority of the impact. Consequently, the insulation lifespan of the TP cable per year was reduced by approximately 116 days. These results can be helpful in remaining life analysis of TP cables for applying to HVDC systems.

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