High Performance HVDC Polymer Cable

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This Paper describes the modified HDPE (into which a small amount of acid group is grafted as modified group) insulated cable as a high performance HVDC polymer cable.

It has been confirmed that the high performance DC and impulse breakdown strength of modified HDPE results from the two aspects : (1) the improvement in intrinsic breakdown strength due to high crystallinity of HDPE, and (2) the restriction of space charges due to introducing the acid modified group. For instance, space charge distribution in modified HDPE cable(insulation thickness : t=3.5mm) measured by using pulsed electroacoustic(PEA) method shows a small amount of homo space charges near both electrodes under the DC field of several tens kV/mm. Also, DC and impulse breakdown strength of the modified HDPE cable (t=12mm) exhibits the high level of 130～140kV/mm even in the temperature of 90℃. In addition, because of the high crystallinity of base polymer (HDPE), the modified HDPE shows the smaller values of thermal resistivity and thermal expansion than conventional XLPE, which also serve as reduction of cable diameter for long-length DC cables. As for long-term DC characteristics, it has been proved that modified HDPE cable (t=3.5mm) endures DC 90kV/mm×2,500hours at 90℃. Moreover, over the range of maximum 10,000hours under the DC field of 30kV/mm, the changes in volume resistivity and space charge distribution(by PEA) of modified HDPE cable (t=6.0mm) have been verified. The insulation design applying above-mentioned properties can be achieved to give the insulation thickness below 20mm for 500kV class DC cables.

1. Introduction

Polymer insulated HVDC cables have not been realized until now. Over ten years ago, we commenced on searching polymer insulating materials for HVDC cables. And then modified high density polyethylene(modified HDPE),into which a small amount of acid groups was grafted as modified group, was discovered as the promising material with excellent DC characteristics[1].

Because of the following features, this modified HDPE cable can be used as a substitute for oil impregnated paper cables (oil-filled(OF)cable, mass impregnated non-draining (MIND)cable),which are served as long-length DC submarine cables at present. The features of modified HDPE insulation are ;

(1)Due to the polymer insulation, there are no needs to have counter plans for oil, maintenance systems in OF cables and oil draining(in case of heat cycles, altitude difference)in MIND cables.

(2)The high level of DC and impulse breakdown strengths almost equal to those of PPLP OF cable which shows the highest values among present DC cables[2].

(3)Maximum permissible conductor temperature : 80～90℃(MIND cable→50～60℃, OF cable→85℃).

(4)Smaller values of thermal resistivity(approx. 60% compared with oil impregnated paper) and thermal expansion(approx.70%compared with XLPE),which serve as the increase of current capacity and the reduction of cable diameter.

(5)Because of non-crosslinking, very long-length cable will be possible without jointing.

The evaluations of the feature of modified HDPE cable as stated above, are summarized in this paper.

2. DC Mechanism for Modified HDPE

As mentioned later in sections 3 and 4, modified HDPE cable shows a superiority in DC and impulse (Imp.) breakdown strength, space charge distribution and long-term DC characteristics. In chemical structure, modified HDPE has a small amount of acid group (less than 1%) as modified group, which is acted as grafted side chain. DC and Imp. breakdown strength(E_B) have been evaluated in term of

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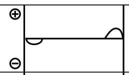
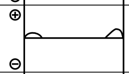
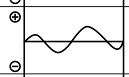
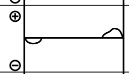
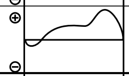
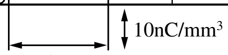
Table 1. Effect of Modified Group and Additives for DC Characteristics

Sample	Grafted acid group	Antioxidant	Chlorine catcher	Space charge distribution*1 (90℃, 40kV/mm,1h)	DC E_B *2 (kV/mm)
Modified HDPE (standard)	○	○	○		450
Base HDPE	–	○	○		310
Modified HDPE (non-additive)	○	–	–		400
Modified HDPE (chlorine catcher)	○	–	○		440
Modified HDPE (antioxidant)	○	○	–		250

*1 : t=1.5mm sheet · measured by PEA
*2 : t=0.2 – 0.3mm recess sheet



parameter such as density of base polyethylene and the content of the grafted acid group, indicating that Imp. E_B increased with the density of base polyethylene and DC E_B enhanced when modified group existed[1)3)].

In addition, modified HDPE contains phenolic antioxidant and chlorine catcher (neutralization agent for chlorine as HDPE polymerization catalyst residue) as additives, and these additives also largely affect the DC E_B and space charge distribution[4)5)].

For instance, Table 1 shows the effect of modified group and additives for DC E_B and space charge distribution (measured by pulsed electro-acoustic (PEA) method) by using sheet samples. Standard modified HDPE gives the best superiority showing a small value of homo space charge distribution and the highest DC E_B, which is considered to be the synergistic effect caused by both grafted modified group and additives.(in the same evaluation, the space charge of conventional XLPE gives the large hetero distribution near both electrodes and its DC E_B is about half compared with modified HDPE)

Therefore the excellent DC and Imp. E_B of modified HDPE results from two aspects : (1) the improvement in intrinsic E_B due to high crystallinity of HDPE, and (2) the restriction of space charges due to introducing modified group.(Fig.1)Namely, the latter((2)) seems due to a trapping effect of injection charges from the electrode to a grafted acid modified group, that is to say, the formation of space charge is considered to be restricted by an offset between ionic hetero space charges caused by bulk impurities etc. and homo injection charges trapped by the modified group. As the similar results, it is recently reported that the restriction effect of space charges is remarkable in some kinds of acid group grafted polyethylene[6)7)].

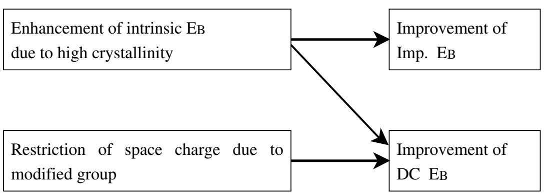


Fig. 1. The Reason for Excellent E_B of Modified HDPE.

3. Breakdown Strength of Modified HDPE Cable

The modified HDPE cables with different insulation thickness(Table 2, Fig. 2)were produced and their DC, DC polarity reversal, Imp. and DC+Imp. (reversed polarity superposition)breakdown characteristics were measured.

The completely dry method(passing through a catenary type heating zone and cooling zone filled with silicone oil just after triple layer common extrusion ; FZCV manufacturing line[8)]) was employed as a cable production process. The heating zone functions as a cross-linking zone in the case of XLPE cable production while being used as a heat

Table 2. Modified HDPE Cable with Different Insulation Thickness for Breakdown Test

Insulation thickness(mm)	Conductor size(mm^2)
3.5	60
6.0	200
9.0	400
12.0	800
20.0	800

Fig. 2. Modified HDPE Cable Sample(20mmt, 800mm^2).

Table 3. Results of Breakdown Tests for Each Cable (at 90℃)

Applying voltage		3.5	6.0	9.0	12.0	20.0
	Insulation thickness (mm)	3.5	6.0	9.0	12.0	20.0
	Conductor size(mm^2)	60	200	400	800	800
DC(kV/mm)		170	140	136	137 (1,650kV OK)	73 (1,450kV OK)
DC polarity reversal(kV/mm)		131	132	122	117	38 (750kV OK)
Imp.(kV/mm)		146	143	133	128	108
DC+Imp.(kV/mm)		111*1	107*2	104*3	−	95*4

*1 : DC= − 100kV+Imp.(+) · *2 : DC= − 200kV+Imp.(+)
*3 : DC= − 300kV+Imp.(+) · *4 : DC= − 500kV+Imp.(+)

treatment zone after extrusion process in the case of modified HDPE cable production.

The breakdown test results of individual cables(at 90℃)are shown in Table 3. Fig. 3 shows the relationship of DC and Imp. breakdown strength(E_B)vs. insulation thickness compared with data[5] from other kinds of insulated cables. The level of the DC and Imp. E_B can be seen to be close to those of the PPLP OF cable which has the highest insulation performance among current HVDC cables[2].Although the XLPE cable shows a considerable deterioration of DC E_B with increasing insulation thickness, the modified HDPE cable exhibits little deterioration of DC E_B, which ensures high DC characteristics despite of an increase in insulation thickness. As already mentioned, as space charges in the modified HDPE become a small amount of homo space charge distribution, DC+Imp.(reversed polarity) and DC polarity reversal characteristics have the tendency to decline, but their absolute values remain at satisfactory levels.

4. DC Long-term Characteristics

Fig. 4 shows the test results of DC V-t characteristics using the modified HDPE cable with the insulation thickness t=3.5mm. Each measured point shows the breakdown time at constant DC voltages (conductor : negative polarity) of 80%, 70%, 60%, 50% of the initial DC breakdown value(170kV/mm) at 90℃. The V-t curve tends a drooping characteristic at n=14 assuming that $V^n \cdot t$ =constant. At the lowest test field of about 90kV/mm, breakdown still did not occur at 2,500 hours when the test was stopped.(Residual DC breakdown value of 140kV/mm reached nearly 80% of the initial breakdown value.) If we assume that the working DC stress is a maximum of 40kV/mm including the field deformation and n =14, the equivalent theoretical life becomes $L = (90/40)^{14} \times 2{,}500$ hours = 24,000 years, showing excellent long-term DC characteristics.

In the DC application of HVDC cables, it is important to confirm the long-term variation in volume resistivity and space charge characteristics that may lead to field deformation.

Using the modified HDPE cable with the insulation thickness t=6.0mm, the variation in volume resistivity and space charge distribution(by EPA)were measured simultaneously under the continuous DC application of 30kV/mm at room temperatures and

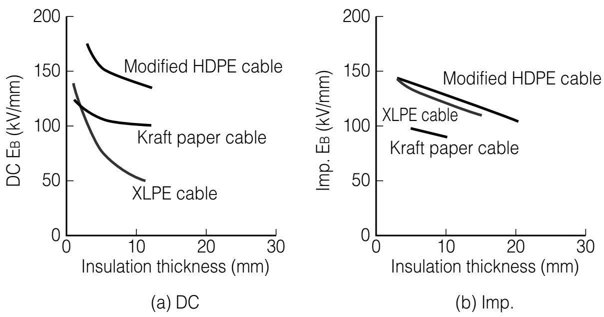


Fig. 3. DC and Imp. E_B in Modified HDPE Cable Compared with Other Cables.

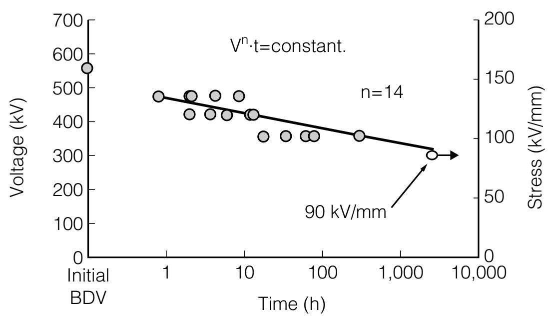


Fig.4. DC V-t Characteristics of Modified HDPE Cable (3.5mm).

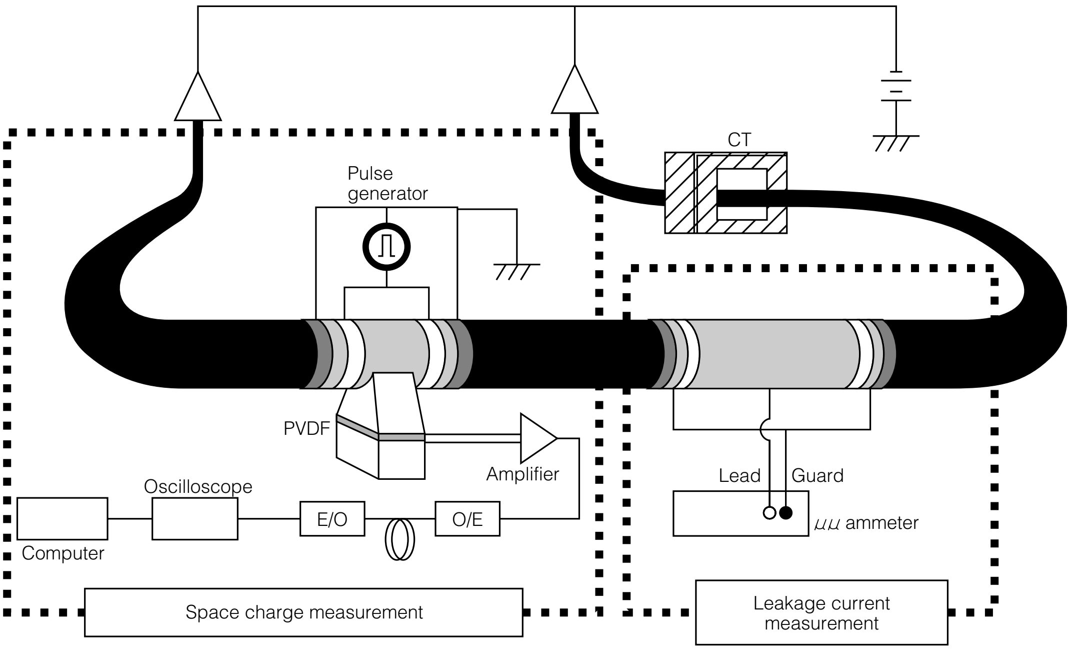


Fig. 5. Space Charge and Leakage Current Measurements.

high temperature(conductor 80℃, ΔT=20℃) up to a maximum 10,000 hours. (Apparatus : Fig.5) The variation in volume resistivity and space charge distribution with time is shown in Figs. 6 and 7 respectively. In a polymer insulation,

Table 4. General Properties of Modified HDPE

Item		Conditions	Modified HDPE	XLPE
Density(g/cm^3)		20℃	0.95	0.92
Melting point( )		–	130	105 – 110
Tensile strength(TS) (MPa)		20℃	27	25
Elongation(El)(%)		20℃	520	560
Retention after again	TS(%)	120℃×13day	110	110
	El(%)	120℃×60day	130	105
Bending strength(TS) (MPa)		20℃	37	15
Deformation under heat(%)		120℃	5.8	38
Coefficient of linear thermal expansion		25℃	1.4×10^{-4}	2.6×10^{-4}
		90℃	7.3×10^{-4}	1.0×10^{-3}
Thermal resistivity (℃·cm/W)		20 – 35	222	278
		60 – 75	238	286
		85 – 100	263	313
ε		–	2.3	2.3
tanδ(%)		RT	0.05	0.03
		90	0.04	0.03

as some carriers may have very small mobility, volume resistivity increases slowly with time and remains constant after 1,000 to 2,000 hours.(Fig. 6) Although volume resistivity continues to change up to 1,000 to 2,000 hours, Fig. 7 shows that long-term field deformation due to space charge has a limited effect since the change in the induced charge density of the both electrodes (inner and outer semiconductive layers) is small over time. (Precisely, Fig. 7 shows that the field near the outer layer hardly changes and the field near the inner layer has the tendency to be weakened by the homo space charge.)

5. Thermal-mechanical Characteristics

The general properties of modified HDPE are shown in Table 4 in comparison with those of

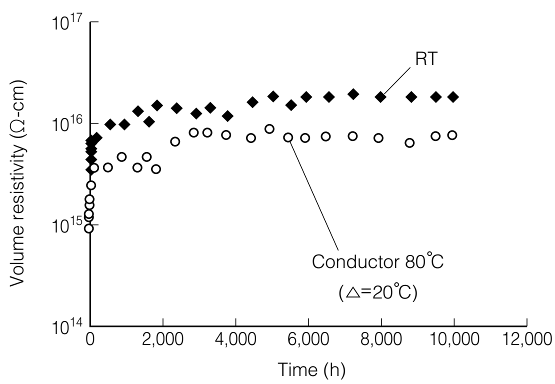


Fig. 6. Volume Resistivity under Long-term DC Voltage (30kV/mm× Max. 10,000h).

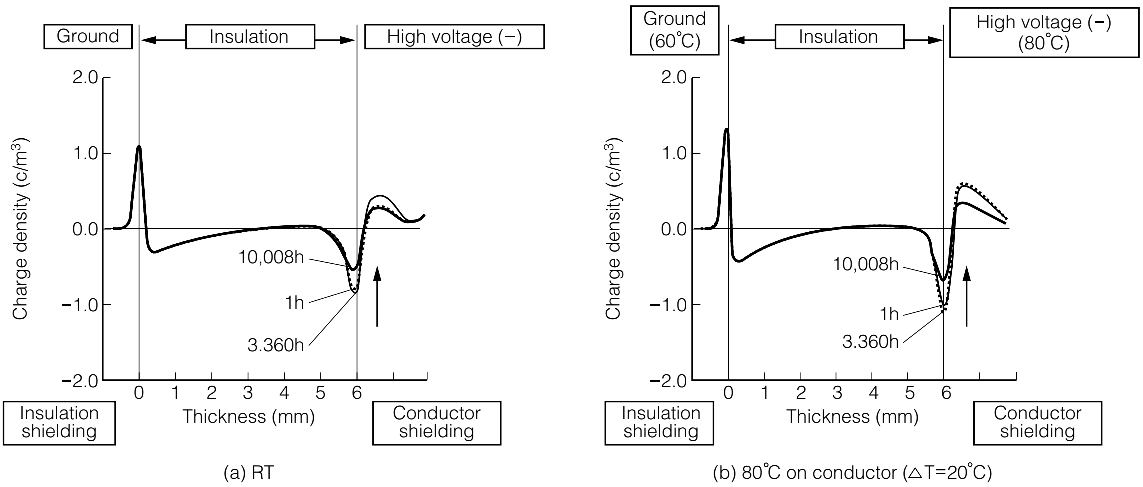


Fig. 7. Space Charge under Long-term DC Voltage (30kV/mm×Max 10,000h).

Table 5. Bending Properties

Item	Modified HDPE	XLPE	Remark
Bending strength (MPa)	37	15	Insulating material
El of cable core (N · mm^2)	4.1×10^9	2.4－3.2×10^9	Cable core t=12mm, 800mm^2

Table 6. Design of HVDC Submarine Cable (500kV DC 1,600mm^2)

Item	Modified HDPE cable	MIND cable
Cross-section of conductor(mm^2)	1,600	1,600
Insulation thickness(mm) (including shield layer)	Approx. 21	Approx. 22
Approx. overall diameter(mm)	140	140
Approx. weight(kg/m)	50	53
Transmission capacity(MVA)	1,051	698
(ratio)	(151)	(100)

XLPE. Emphasis is on the thermal characteristics (thermal resistance, thermal expansion, thermal deformation), especially thermal resistance is shown to be about 80% of XLPE and 60% of oil-impregnated paper.(Fig. 8) This permits an increase in current capacity based on the excellent heat dissipation of the material. The excellent thermal characteristics come from the base HDPE polymer which has high crystallinity. As the base polymer is HDPE, the bending elastic modulus of the material itself is about 2.5 times larger than that of XLPE, but the bending rigidity(EI) of a modified HDPE cable core (t=12mm) including conductor(800mm^2) is about

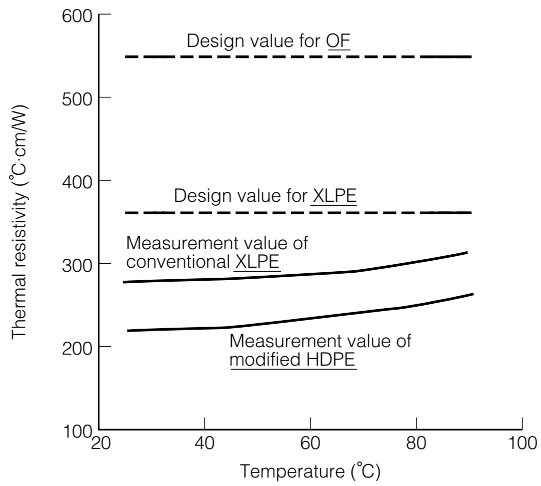


Fig.8. Comparison of Thermal Resistivity.

1.5 times larger than that of an equivalent sized XLPE cable. (Table 5)

Dielectric properties (ε, tanδ) of modified HDPE are similar to those of XLPE because the amount of acid grafted modified groups remain low (less than 1%).

6. Trial Cable Design Applying Modified HDPE

Although insulation design methods for polymer insulated DC cables have not yet been established, two methods are proposed[9)10)]. One method is similar to that for AC XLPE cables using DC V-t characteristics($V^n \cdot t$ = constant)to give the required lifetime[9)]. The other takes into account the DC electric field deformation resulting from space charges[10)]. Whichever method is applied, the insulation thickness of modified HDPE cables is determined depending on the Imp. characteristics(reversed polarity Imp. superposition) because the cable has outstanding DC characteristics. For example, for a 500 kV HVDC cable, the insulation thickness determined from Imp. characteristics is 19 to 20mm including a margin for safety.

Table 6 shows the comparison between a modified HDPE cable, at 500kV and with a conductor cross section of 1,600mm^2, and a similarly structured MIND cable which is currently used for long distance submarine DC transmission. The modified HDPE cable has a transmission capacity about 1.5 times larger than that of the MIND cable, reflecting the advantages in the higher allowable temperature of the conductor and lower thermal resistance of insulation.

7. Conclusion

With regard to a high performance HVDC polymer cable that may replace oil-impregnated insulation cables, the modified HDPE cables display the following features.

(1)Outstanding DC, Imp. breakdown characteristics similar to those of PPLP OF cables resulting from increased intrinsic breakdown strength due to the high crystallinity of the base polyethylene and space charge suppression based on the small amount of grafted modified groups.

(2)As for DC long-term characteristics, it was confirmed that the cable can endure DC 90kV/mm × 2,500hours(at 90 ℃). In addition, from a study of volume resisitivity and space charge characteristics over time at DC30kV/mm × max 10,000hours, it was found that the long term effects of DC has a small influence on field deformation.

(3)Excellent thermal characteristics, especially, thermal resistance which is about 80% of XLPE and 60% of oil-impregnated paper, permitting an increased current loading. The bending elastic modulus of modified HDPE is about 2.5 times larger than that of XLPE but the bending rigidity(EI)of the cable core (where t=12mm, and cross-section of conductor 800mm^2) is about 1.5 times larger than that of XLPE.

(4)For 500kV HVDC, a theoretical insulation thickness of 19 to 20mm with a transmission capacity about 1.5 times larger than that of a similarly structured MIND cable (500kV, 1,600mm^2) is achievable.

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