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Remarkable Tanδ Suppressin of Oil Filled Cable Insulation with Extremely Degraded Tanδ Oil

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ABSTRACT

The following two effects ((1)&(2)) cause the peculiar phenomena of the remarkable tanδ suppression in oil impregnated paper with extremely degraded tanδ oil.
(1)Tanδ decrease in high electrical stress (including operating stress of oil filled (OF) cable) region by so-called Garton effect.
(2) Tanδ decrease due to the absorption of ionic substance in oil to the insulating paper.

These effects were also confirmed in OF cable splice box insulation flowed by extremely degraded tanδ oil, together with the locally degraded tanδ portions such as the boundary layer between cable paper and joint paper.

KEYWORDS: oil filled cable, degraded tanδ oil, Garton effect, absorption effect

1. Introduction

Many of oil filled (OF) cable (self contained fluid filled cable) has been applied for 66~500kV extra high voltage cable system for a long time. Extremely high dielectric loss (tanδ) of oil (several tens % of tanδ, for example) is occasionally observed in splice box etc.

The relation between oil tanδ and oil impregnated paper tanδ according to simple combination model of oil/paper expressed as equation (1) is shown in Fig.1.

$$\tan\delta = (\theta_f \varepsilon_f^K \tan\delta_f + \theta_o \varepsilon_o^K \tan\delta_o)/\varepsilon^K \cdots (1)$$

(subscript : f→paper fiber, o→oil,
ε &tan δ : value for oil impregnated paper
θ→volume fraction, ε →relative permittivity
k=-0.5 for insulating paper structure)

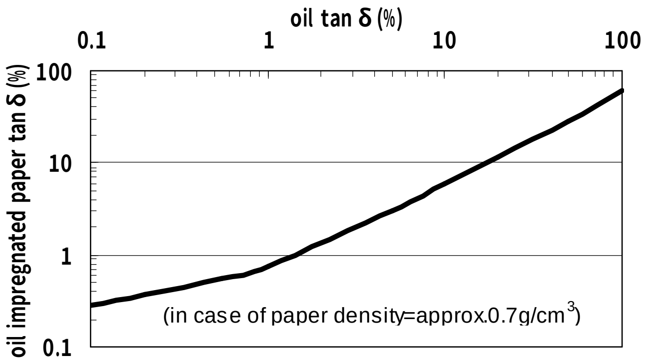

Fig.1 Relation between oil tanδ and oil impregnated paper tan δ according to simple comibination model (equation(1))

Naturally when oil tanδ is extremely high, oil impregnated paper tan δ is also extremely high. (for example, oil tanδ =10%⇔oil impregnated paper tanδ =5.5%, oil tanδ =50%⇔ oil impregnated paper tanδ =30%) In that case, thermal breakdown by the dielectric loss must occur. However, such an event has never taken place so far. This fact suggests that some tanδ suppression mechanism has acted in the oil impregnated insulation.

In this paper, tanδ characteristics of extremely degraded tanδ oil impregnated paper was investigated in detail and the feature of tanδ in OF cable splice box insulation flowed by degraded tanδ oil was also examined.

2. Tanδ characteristics of extremely degraded tanδ oil impregnated paper

The degraded alkyl-benzene oil (AB-oil) and mineral oil (M-oil) used for OF cable with the tanδ level of approx. 10% and 50% (at 80℃) were prepared by the thermal oxidation of oil combined with the organic material coated copper tape. As shown in Fig.2, after the insulating paper was set into the plate electrode and was dried by the vacuum heating, degassed and dehydrated degraded tanδ oil was introduced. Oil impregnated paper tanδ (50Hz, temperature: RT～120℃, electrical stress:0.1～20kV/mm) was measured under the oil pressure of approx. 0.5kg/cm^2.

insulating paper: : thicknes=200 μm、density=approx.0.7g/cm^3
kind of oil : alkyl-benzene oil(AB-oil)、mineral oil(M-oil)
oil tan δ : tan δ =0.01% ↓ (new oil)、tan δ =10%、tan δ =50%

Fig.2 Plate electrode for oil impregnated paper tan δ measurment (just after setting insulating paper& before intoduction of oil)

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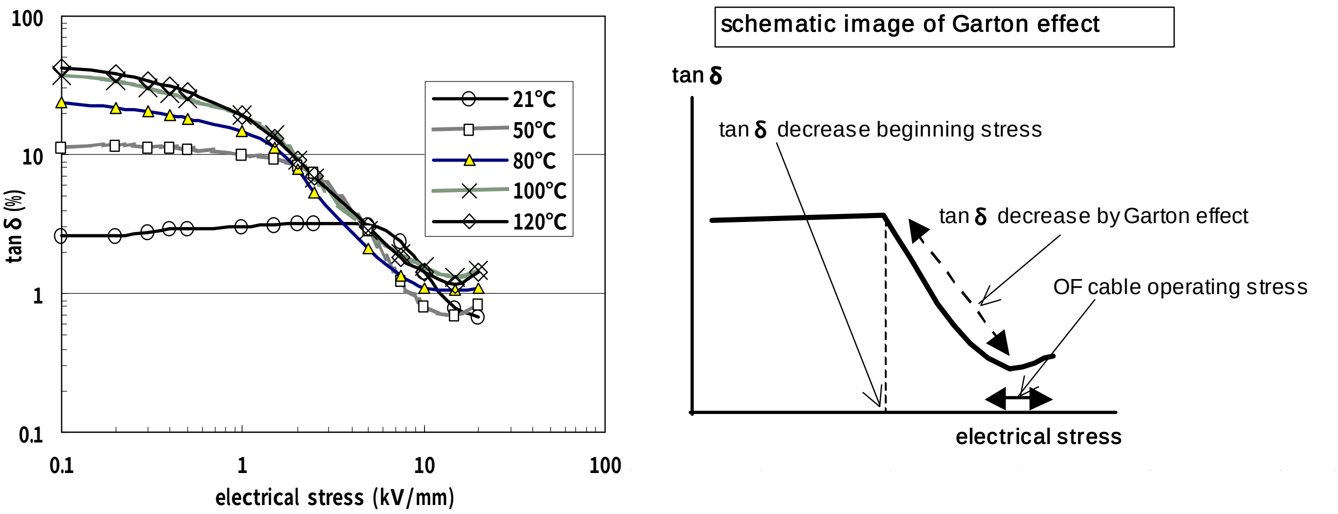


Fig.3 Temperature&electrical stress dependence of tan δ for AB-oil (tan δ =50%) impregnated paper

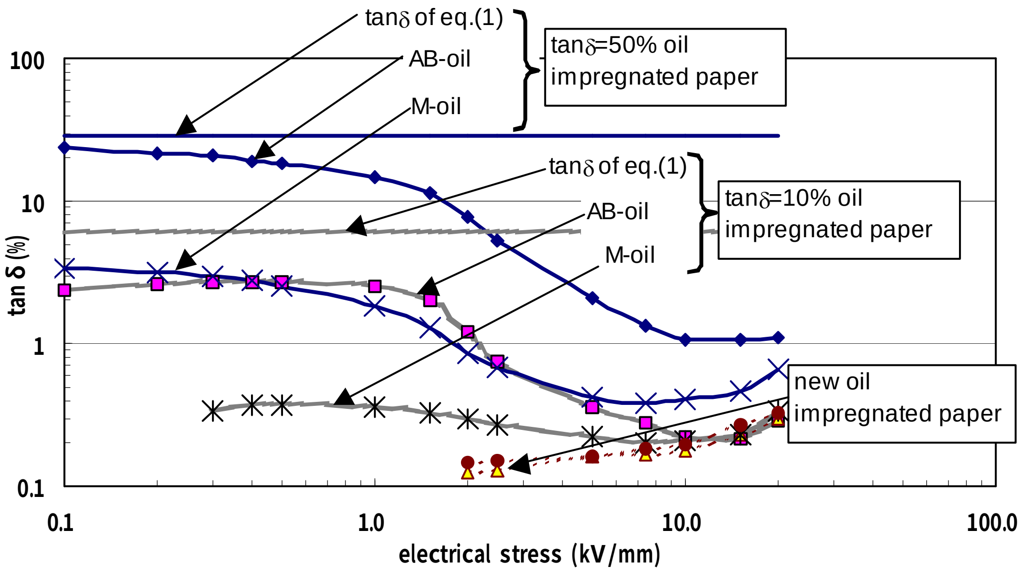
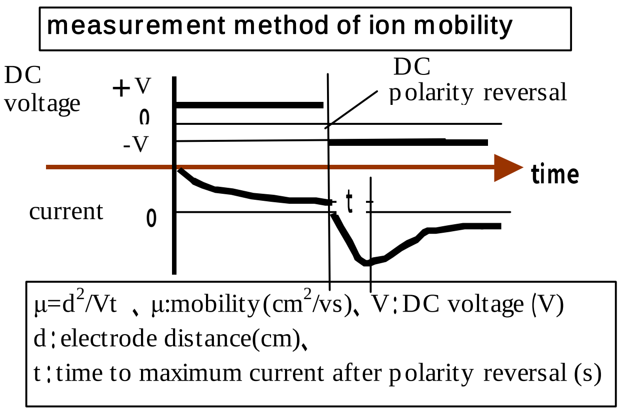


Fig.4. Oil impregnated paper tanδ for various kind of oil (at 80°C)

Fig.3 indicates temperature & electrical stress dependence of AB-oil (tanδ=50%) impregnated paper.
The favorable phenomenon of a remarkable tanδ decrease is recognized in the high electrical stress region including OF cable operating stress (5〜15kV/mm). This tanδ decrease is estimated to be the so-called Garton effect[(2)], which is caused by the ion movement in oil between paper fibers (that has the space of several μm) within the time of AC half cycle. In this effect, tanδ decrease becomes more distinctive on the higher electrical stress because of the larger ion mobile velocity v=μE (μ→ ion mobility, E→electrical stress). The tendency that the electrical stress where tanδ begins to decrease (called here "tanδ decrease beginning stress") shifts to the lower stress at higher temperature can be noted, because the ion mobility becomes larger in the higher temperature with smaller oil viscosity, as described later (Fig.5). The gradual tanδ increases in the much higher electrical stress (~10kV/mm or more) as seen in Fig.3 are thought to be due to the multiplication of ionic careers dissociated by electrical stress.

The comparison of oil impregnated paper tanδ in case of changing the kind of oil (AB-oil & M-oil and tanδ level) is shown in Fig.4. In the all electrical stress region, tanδ values are much smaller than the calculated values obtained from oil/paper combination model (Fig.1), though the larger tanδ in low electrical stress ought to agree with the calculated values. As mentioned later, there is another tanδ suppression mechanism except for the Garton effect, that is, the effect of the absorption of ionic substance in oil to the paper, and this effect is more distinctive in M-oil than in AB-oil. Moreover, lower tanδ decrease beginning stress in M-oil compared with AB-oil is considered to correspond to the lager ionic mobility of M-oil.



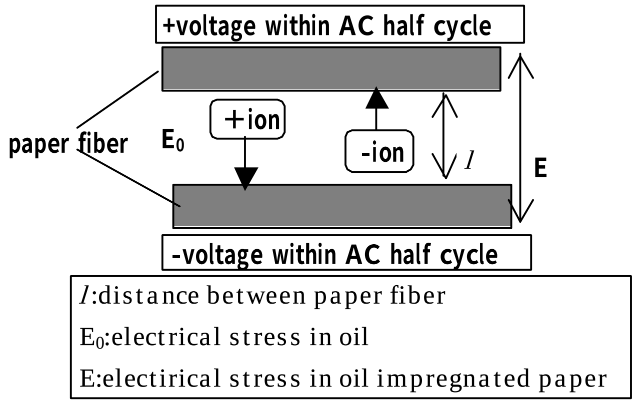


Fig.6 Mechanism of Garton effect

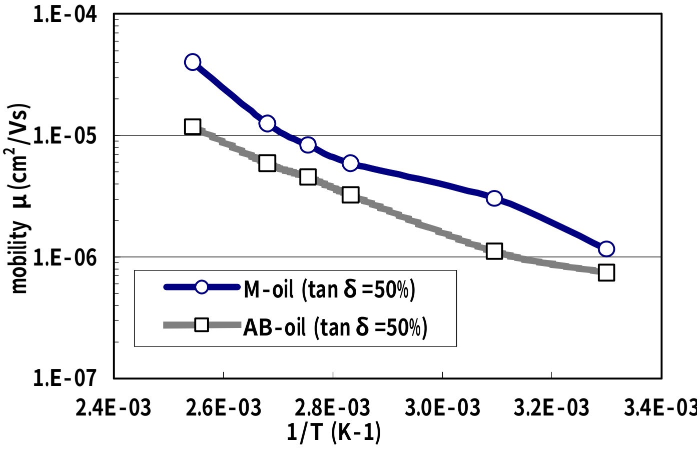


Fig.5 Ion mobility of degraded tanδ oil

Fig.5 exhibits the example of mobility for degraded tanδ oil obtained by the current measurement under polarity reversal of DC voltage[3]. The mobility is M-oil>AB-oil agreeing with the tendency of tanδ decrease beginning stress in Fig.4. By way of contrast, both activation energies obtained from the temperature dependence of mobility $\mu = \mu_0 \exp(-\Delta E_\mu / RT)$ and the temperature dependence of viscosity $\eta = \eta_0 \exp(-\Delta E_\eta / RT)$ is almost similar. ($\Delta E_\mu = 7.5\,\mathrm{kcal/mol}$ & $\Delta E_\eta = 6.4\,\mathrm{kcal/mol}$ for AB-oil and $\Delta E_\mu = 6.5\,\mathrm{kcal/mol}$ & $\Delta E_\eta = 5.7\,\mathrm{kcal/mol}$ for M-oil)

In the oil impregnated paper, the ion in oil will collide with paper fiber within the time of AC half cycle when ion movement distance in AC half cycle is larger than the oil space (l) (several microns) between paper fibers, as illustrated in Fig.6. When ion velocity $v = \mu E_o$ (E_0:electrical stress in oil, μ :ion mobility) and $E_o = E_p \sin\omega t$, movement distance (d) at the time of half cycle (π/ω) is express as equation(2).

$$d = \int_0^{\pi/\omega} v dt = \int_0^{\pi/\omega} \mu E_p \sin\omega t dt = 2\mu E_p/\omega \cdots\cdots (2)$$

Tanδ decrease beginning stress (E_s) is regarded as the electrical stress where d=l, and then E_s (in term of effective value) is as follow.

$$E_s = (\omega l / 2\sqrt{2}\,\mu) \cdot (\varepsilon_{oil}/\varepsilon_i) \cdots\cdots (3)$$

ε_{oil}:relative permittivity of oil =2.2
ε_i:relative permittivity of oil impregnated paper =3.4

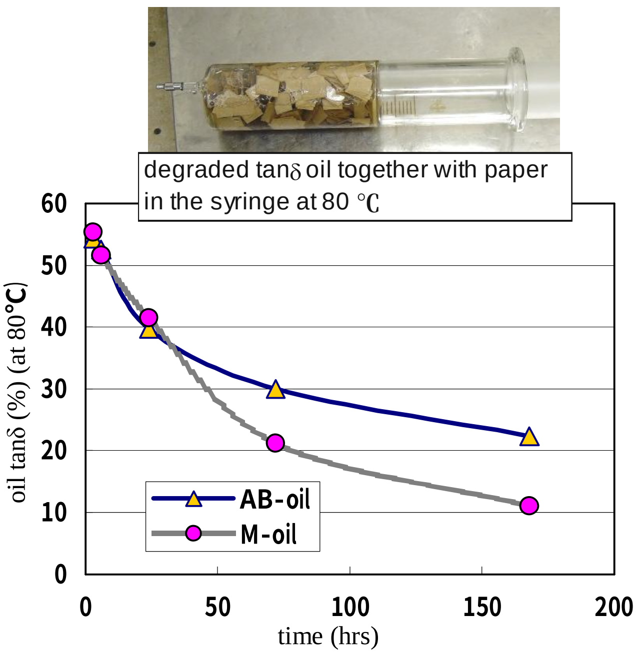


Fig.7 tanδ change for the oil together with paper

For example, E_s=0.47kV/mm when μ=3.2×10^{-6}cm²/V・s (80℃ value of AB-oil (tanδ=50%) in Fig.5) and $l = 2\mu m$ [1] are substituted in equation (3). Thus it can be understood that the tanδ decrease by Garton effect becomes especially remarkable in high electrical stress region of several kV/mm or more including OF cable operating stress.

In order to examine the absorption phenomena of ionic substance in oil to the paper, after 125cc degraded tanδ oil together with 25g paper cut in piece was left in the syringe at the temperature of 80 ℃, oil tanδ was measured periodically. As indicated in Fig.7, considerable tanδ decrease due to the absorption effect where its effect M-oil>AB-oil can be recognized, explaining the tendency in Fig.4.

3. Tanδ characteristics of OF cable spice box insulation flowed by extremely degraded tanδ oil

154kV 800mm^2 OF cable splice box was supplied for the verification of tanδ suppression caused by the Garton and absorption effects described in paragraph 2. AB-oil of tanδ=about 50% was offered to the box oil (25L). The oil of 800cc (approx. 6% of total oil) /time between box oil and conductor oil was flowed by the cylinder with piston (which is installed in conductor side) during 1120 times (4 times /day=280 days), as pictured in Fig.8.

Fig.9 shows the tanδ change of oil (box oil and conductor oil) during splice box oil flow experiment. The cause of oil tanδ comes from ionic substances in oil, so that "tanδ× amount of oil" is regarded as the value which is proportional to the amount of degraded tanδ source, assuming that oil tanδ ∝ ion concentration. As the ratio of degraded tanδ source by this method is also presented in Fig.9, about 80% of degraded tanδ source concentrates on oil impregnated paper insulation after oil flow experiment, which means the noticeable absorption phenomenon to the paper.

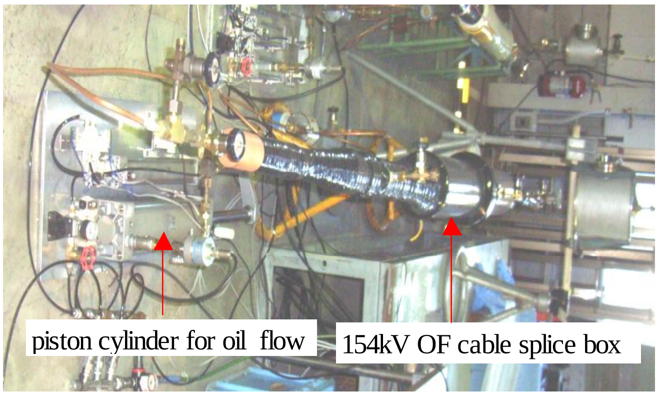


Fig.8 Scene for the degraded tanδ oil flow experiment using OF cable splice box

The radial tanδ for each part of splice box insulation after oil flow experience is indicated in Fig.10. The peculiar radial tanδ feature can be seen, showing the local permeation of degraded tanδ oil in splice box insulation, as filling the arrows in Fig.11. The permeation of degraded tanδ oil in the boundary between cable paper and joint paper is largest and the second largest part is near the surface of joint slope. Because the boundary of cable paper / joint paper is thought to be the looser layer in comparison with

ratio of degraded tanδ source (∝oil tanδ ×amount of oil)

each part of oil in splice box	before oil flow		after 1120 times of oil flow	
	oil tanδ	ratio(1)	oil tanδ	ratio(1)
splise box oil (25L)	48.3%	100%	10.6	21.9%
insulation oil (3.2L)(2)	-	0%	-	76.6%
conductor oil (2.3L)	0.06%	0%	7.84	1.5%

(1)ratio：ratio of degraded tanδ source (∝oil tanδ ×amount of oil)

(2)insulation oil = oil impregnated paper oil

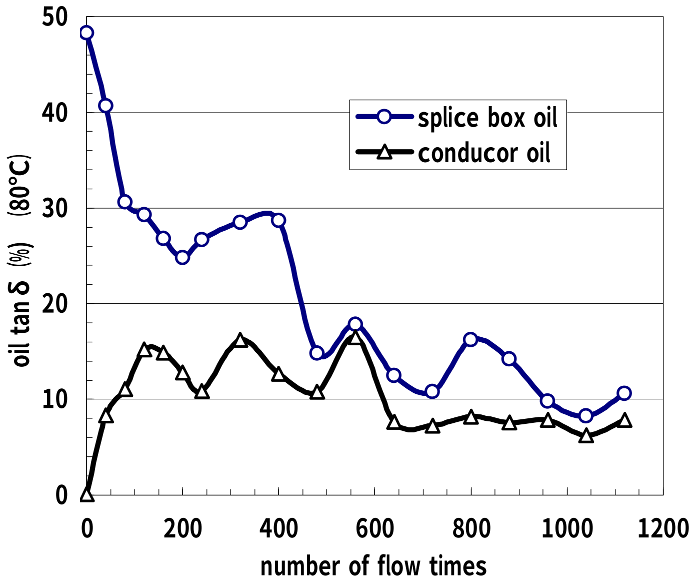


Fig.9 Change of oil tanδ during oil flow expriment

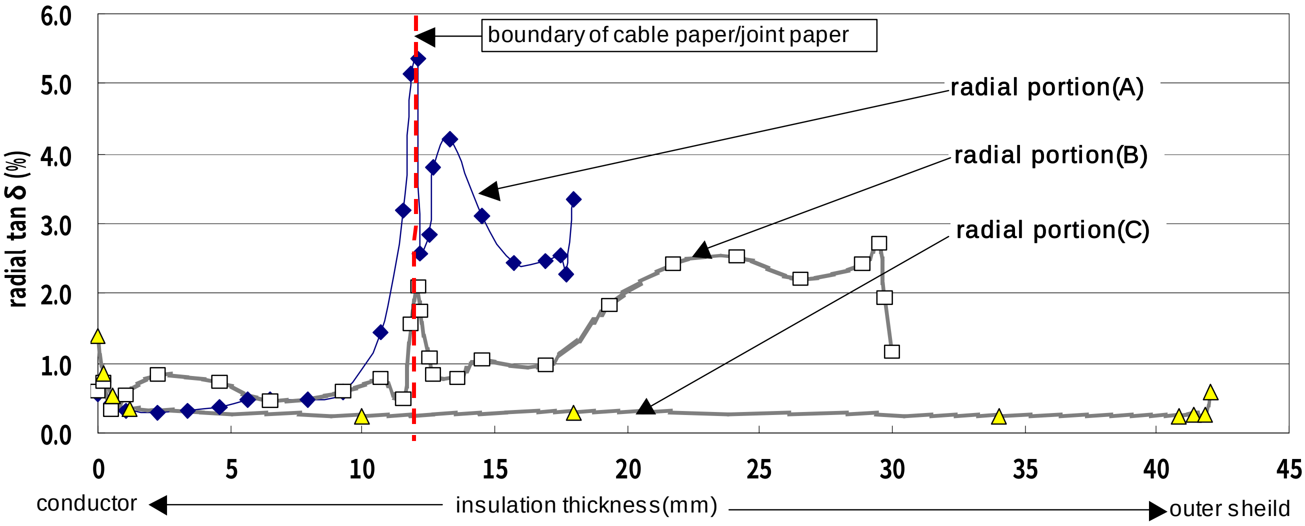


Fig.10 Radial tanδ of splice box insulation (RT, 8kV/mm) (radial portion (A)&(B)& (C):see Fig.11)

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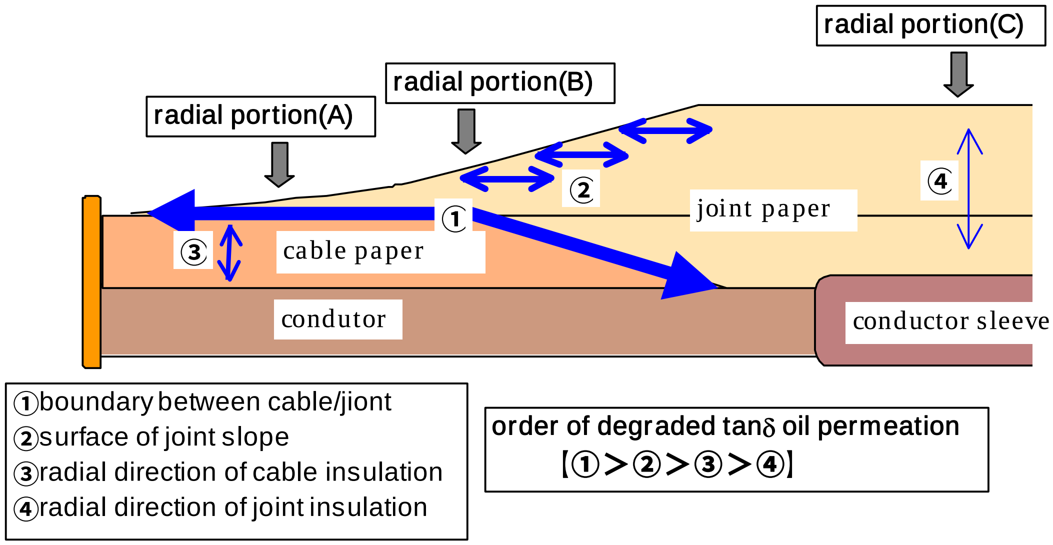

Fig.11 Sampling part for radial tanδ measuremnt and the permeation part of degraded tanδ oil in splice box insulation (radial portion (A)&(B)&(C); see Fig.10)

normal part, oil flow between box and conductor can also be largest along this boundary.

However even in case of tanδ maximum part in boundary layer of cable/joint paper, the vale of tanδ is about 5% which is farther smaller than the value (tanδ=30%) obtained by equation (1) (simple combination model of oil/paper), proving that remarkable tanδ suppression by the Garton and absorption effects. Incidentally, in case of applying tanδ=about 10% AB-oil to similar splice box oil flow experience, maximum tanδ of splice box insulation is about 0.5%, showing the same tendency of tanδ profile as is shown in Fig.10[(4).]

Accordingly it is thought that the locally degraded tanδ parts in splice box insulation in addition to the above-mentioned tanδ suppression effects will prevent a heat generation caused by dielectric loss.

4. Conclusion

The remarkable suppression of tanδ in oil filled (OF) cable insulation with extremely degraded tanδ oil is confirmed due to the following reasons.

(1)Tanδ decrease in high electrical stress (including operating stress of OF cable) region by so-called Garton effect which is related with the ion mobility of oil.
(2)Tanδ decrease due to the absorption of ionic substance in oil to the insulating paper.
(3) The tanδ suppression caused by item (1)&(2) is more distinctive in the mineral oil than in the alkyl-benzene oil.
(4) The above-mentioned tanδ suppression was also verified in the real use OF cable splice box insulation, accompanying the locally degraded tanδ parts such as boundary between cable paper/ joint paper.

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