Interfacial space charge characteristic of PPLP insulation for HVDC cables

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Abstract: High-voltage DC (HVDC) cables show more efficiency than high-voltage AC cables over the long distance power transmission and have attracted significant attention recently due to rapid developments in off-shore wind farm. Polypropylene laminated paper (PPLP) insulation based HVDC cables have provided a reliable operation for many years and are the highest voltage level in operation at the moment. In this study, the authors intend to understand the electrical performance of PPLP insulation system by examining space charge in detail, especially at the interfaces. It has been found that the interface between polypropylene and Kraft paper acts as trap for charge carriers, resulting in an optimal electric field distribution in PPLP insulation system. The optimal electric field distribution enhances overall electrical performance of PPLP insulation, including higher dc breakdown strength and lower electrical conductivity.

1 Introduction

Compared to the high-voltage AC system, high-voltage DC (HVDC) technology may offer several advantages like more efficient power transfer over long distance [1]. Technically, there is no limit to the length of HVDC cable. Mass impregnated (MI) cable has been developed for decades because of the fact of non-draining and no need for feeding in comparison with oil-filled cable [2]. For example, 580 km long NorNed submarine HVDC cable is still the longest submarine cable with the paper lapped MI cable [3, 4]. HVDC MI cable with PPLP insulation has been applied in different commercial projects with further improvement of voltage and conductor temperature. For example, the Western link submarine HVDC submarine cable is the first subsea link at 600 kV level using PPLP MI cable [3, 5]. Until now, there are not many reported insulation faults for the existing HVDC MI PPLP cables around the world. However, to maintain high reliability of such cables especially at higher voltage levels, it is essential to understand why the PPLP insulation performs so well.

Space charge is the major issue for HVDC insulation system and has attracted more attention for HVDC power transmission. The issue has been highlighted in the extruded HVDC cables and limits the current operative HVDC cable to 320 kV [1]. For HVDC PPLP insulation cables, the effect of space charge dynamics in PPLP insulation system on the electrical performance is not clear. Interfaces are an essential part of lapped insulation system [2]. It becomes more and more important to understand space charge characteristics at interfaces of PPLP insulation impregnated with insulation oil.

In the present paper, charge dynamics with different type of insulation interfaces in MI PPLP insulation have been studied. The pulse electroacoustic (PEA) technique has been used to measure charge accumulation at the interface. The corresponding electric field is estimated to study the potential influence of charge on electrical performance such as electrical conductivity and electrical breakdown of PPLP insulation system.

2 Sample preparation and experimental details

PPLP laminated insulation consists of one layer of polypropylene sandwiched by two layers of Kraft paper, typically in a form of tape. The PPLP tape is wound around the conductor under controlled environment with a consistent tension in cable manufacture process (as shown in Fig. 1a) and impregnated with oil under vacuum at elevated temperature. Fig. 1b shows the layered structure of the PPLP tape. The butt gaps are established during the winding process which allow oil flow freely during the oil impregnation process to ensure the Kraft paper is fully impregnated with oil. For a typical PPLP insulated cable, there are different types of interfaces which are described as A to D in this paper. Interface A is between two layers of impregnated Kraft paper with good contact. Interface B means the interface between Kraft paper and PP in PPLP tape. Interface C represents the interface between PPLP. Interface D is between the PP-Kraft paper and Kraft paper-PP, which may represent the condition of the outer layer Kraft paper is destroyed by mechanical force in two adjacent PPLP tapes.

Another key feature in PPLP MI cable is the high viscosity impregnated compound, which stays in the insulation paper and butt gaps during operation. The impregnated compound used in our study is T2015 high viscosity DDB oil. Both PPLP tape and compound were treated in vacuum oven at 100°C for 24 h before impregnation. The impregnation was carried out under the same environment over 2 days to ensure the full impregnation. The samples were kept in vacuum to reduce the moisture absorption until tests.

Two types of PPLP were used in this study, one is commercial insulation PPLP, and another one was laminated in our laboratory using insulation Kraft paper and polypropylene film. Meanwhile, two types of Kraft papers were also used in the tests, one was peeled from commercial PPLP and another was the same Kraft paper used for laminating PPLP. PP sample present in the tests was the single layer peeled from PPLP.
Space charge distributions were measured by the PEA technique which is a mature technology of charge measurement widely used for different size of insulation. It relies on the interaction of the applied pulsed electric field and the charge in the insulation sample, launching acoustic waves that will be detected by a transducer attached onto bottom electrodes and converted into charge information across the sample. The PEA system used for the present study has a good spatial resolution of 10 µm for charge distribution. The space charge measurements were carried out about 30 min under the external applied voltage and further 10–30 min decaying test after the removal of the external voltage.

Electrical conductivity for oil impregnated PPLP sample was measured for 60 min under different applied voltages. All the tests have been done at room temperature.

3 Results

3.1 Charge distribution in single film of Kraft paper

To understand charge dynamics in PPLP insulation, space charge distributions in single layer of oil impregnated Kraft paper and PP were measured. Fig. 2 shows the charge distribution in single layer impregnated Kraft paper under 10 kV/mm. The anode peak is a bit wider and smaller in magnitude than the cathode peak due to the attenuation and scattering of acoustic waves through the insulation sample. Homo-charge injection from both electrodes occurred after the external voltage is switched on and increased gradually as shown in Fig. 2a. The almost symmetrical homo-charge distribution after the removal of the applied voltage changes little over the time as shown in Fig. 2b. It is known from the other research work [6–8] that the charge dynamic in oil impregnated Kraft paper is highly dependent on the oil property. For a low viscosity mineral oil, it has been found that charge decay rate after the removal of the applied voltage is much quicker [6–8]. However, as the impregnate oil used in this study has a very high viscosity, it seems to have a significant impact on charge movement reflected in the rate of charge injection and decaying in the impregnated Kraft paper.

3.2 Charge distribution in single film of PP

Fig. 3 shows the charge movement in single layer of PP film peeled from the PPLP tape measured under the 10 kV/mm. Charge injection occurs obviously and moves into the sample with time. As the sample is peeled from PPLP, a tiny thin layer of cellulose might be left on both surfaces of PP and the surface condition is not smooth as well. This may have some influence on charge injection from the electrodes.

Compared with Fig. 2, it can be seen that the injected charges stay closely to the electrodes and decay quickly after removal of the applied voltage. From results shown in Fig. 3b, more than 50% amount of charge accumulated close to electrodes disappears in 10 min.

3.3 Interface A between two Kraft paper

3.3.1 Thinner Kraft paper sample: As illustrated in Fig. 1, there are different types of interfaces in a typical PPLP insulated cable. Firstly, we study the interface A between two layers of oil impregnated Kraft paper, described in Fig. 1. The sample consists of two layered Kraft papers peeled off from the commercial PPLP tape after it was fully impregnated with T2015 compound. From the results shown in Fig. 4a, there is a smooth transition of charge distribution at the interface between two Kraft paper layers under an applied electric field of 10 kV/mm. A small amount of negative charge found accumulated in the area near to the interface of two Kraft papers. As the PEA technique only measures the net charge, the captured charges are the sum of positive and negative charges. From the result shown in Fig. 4b, which is the charge information after removing the applied voltage, the charges left at the interface are negative and charges in the bulk of Kraft paper layers close to anode are positive. Not a lot of negative charge found in the Kraft paper layer close to cathode.

3.3.2 Thicker Kraft paper sample: The Kraft paper used for lab lamination has 80 µm thickness and it was impregnated with high viscosity oil T2015 as before. Two layers were overlapped and placed between two electrodes in the PEA system and measured under 10 kV/mm as well. In this case, the surface of the Kraft paper is smoother than the one peeled from PPLP and each layer is also thicker. Space charge distribution across the sample is shown
in Fig. 5. Apparently, an obviously negative charge peak can be found at the interface and a small amount of negative charge next to the cathode and a large amount of positive charge close to the anode. They all increased gradually over the duration of voltage application. The homo-charge injection from both cathode and anode is confirmed from the decay result shown in Fig. 5b. The amount of positive charge left in the Kraft paper layer close to the anode is much more than that of negative charge left in the layer close to the cathode. Compared to the thinner Kraft paper in Section 3.3.1, the oil paper layer in this case made it possible to prolong the traveling time of charge carriers under the external electric field. That allows us to observe the dynamic of space charge across the sample. Negative charge accumulation at the interface plays a crucial role at the interface of two layers high viscosity impregnated oil Kraft paper. Positive charge only found out in the oil Kraft paper layer close to anode.

### 3.4 Interfaces B between Kraft paper and PP at single tape of PPLP

PPLP is formed by laminating Kraft paper-PP-Kraft paper at elevated temperature, resulting in two interfaces between PP and Kraft paper with a probably vague boundary as melt PP will be pushed into pore structure of the Kraft paper. The diagram and sandwich structure of PPLP sample with different PP ratio has shown in Fig. 6. In Fig. 6a, the sample with low PP ratio was made in laboratory and impregnated with the high viscosity oil T2015. The sample of PP and Kraft paper used for lamination are 25 and 80 μm thickness, respectively. The laminated PPLP thickness is 180 μm, less than the total thickness of three layer. Some of the PP was pushed into the cellulose of Kraft paper and the sample is opaque. However, the sample with a high PP ratio in Fig. 6b shows a semi-transparent as evident from the fact that the word ‘Test’ underneath the PPLP tape can be read clearly. The whole thickness of PPLP is 110 μm. After un-laminating the sandwich sample, the Kraft paper is 35 μm, the rest part of one Kraft paper sticked with PP is 100 μm and the middle layer PP without both side sandwich paper layer is 100 μm. It is believed that the PP has been squeezed into Kraft paper.

The interface for PPLP is not the clear boundary but a region of mixture of PP and Kraft paper. The distance from electrode to the interface for low PP ratio PPLP sample will be longer and very short for high PP ratio sample.

#### 3.4.1 PPLP sample with lower PP ratio:

The impregnated PPLP sample was tested under an electric field of 10 kV/mm. Charge distribution in Fig. 7 shows a continuous homo-charge injection from both electrodes to the impregnated Kraft paper following the external voltage application. There are two interfacial charge peaks clearly recognisable. They increase with time and have the same polarity as the closer electrode. The decay results present in Fig. 7b confirm the charge accumulation inside the PPLP sample. The two interfacial charge peaks decrease slowly after the removal of the external voltage, indicating the charges are deeply trapped at the interfaces. Homo-charge peaks close to the electrodes become obvious and decay slowly with time. The charge movement in the layer of Kraft paper next to the cathode is similar to that in the impregnated Kraft paper shown in Fig. 5. The thicker layer of impregnated Kraft paper provides a better opportunity to study charge movement. It seems that the negative charges move easily through the impregnated Kraft paper but are partly trapped at the interfaces.
interface. It is believed that negative charges are injected from the electrode and move to the interface between the impregnated Kraft paper and PP under the influence of the applied electric field. During the decay stage, the accumulated charges release from the interface, either travelling slowly back to its respective electrodes or neutralising with positive charge in the PP layer. It is similar pattern for positive charges, but the speed of charges movement is slower.

3.4.2 PPLP with higher PP ratio: Space charge dynamics in the commercial PPLP sample with a high PP thickness ratio was measured under 8.5 kV/mm as shown in Fig. 8. It can be seen that the two charge peaks on electrodes decrease quickly while the two interfacial charge peaks increase rapidly (about three times peak value from 5 min 30 min). The charge distribution shows a symmetrical feature for positive and negative charge with charge polarity at the interfaces same as the adjacent electrode. The charge distribution is generally consistent with the results shown in Fig. 7 where a low PP thickness ratio of PPLP sample is used. The significant difference is the rate of charge accumulation at the interfaces which is much faster in the sample with a high thickness PP ratio. It looks like the electrodes shift to the interface positions. Correspondingly, as described in the layer diagram of PPLP shown in Fig. 6, the oil Kraft paper thickness is thin in higher PP ratio PPLP. It is hard to separate the charge accumulate near the electrode or at the interface. The injected charges are quicker arriving at the interface.

The decay result in Fig. 8b shows the remaining charge dissipation across the multilayer sample after removing the applied electric field. It is hard to tell where the charges move away based on this result. Charges either dissipate from the impregnated Kraft paper to the electrode or neutralise with positive charges moving from the other side of PP layer. The decay rate is comparable to the charge accumulating rate.

3.5 Interfaces C between two layers of PPLP

Fig. 9 shows the space charge distribution in two layered PPLP sample under the same applied electric field. The negative peak on the cathode decreases with time during voltage application which is consistent with the single layer PPLP sample. The negative charges migrate across the impregnated Kraft paper and are partly blocked at the left-hand side of Kraft paper/PP interface.

From the anode side, marked in red line in Fig. 9, the expected positive peak is not observed. Two possible reasons may lead to this observation. Significant accumulation of positive charge at the interface close to the anode side results in cancellation of the induced charge on the anode. Additionally, the acoustic signal generated from the anode would travel through the whole structure of sample and its magnitude becomes smaller due to the attenuation effect.

There are two charge peaks of opposite polarity in the middle. They both increase with time initially, but the positive charge peak reaches to ‘steady state’ earlier than the negative peak. Based on the information of sample thickness and acoustic wave velocity, it can be confirmed that two opposite polarity charge peaks are the position of the interface between impregnated Kraft paper and PP. The charge distribution has a smooth transition between these two
The impregnated Kraft paper is the weak part in the PPLP. Kraft paper is peeled. Space charge in such a structure is measured as shown in Fig. 10.

However, from the results shown in this section, it seems that arrangement in Section 3.5 has been used but with two Kraft paper gets damaged when subject to mechanical stress, it has no barrier effect on charge movement.

The electrical property of oil insulation paper is highly dependent on the oil condition. The ionisation may take place under the external voltage application. As a result, positive charge will move to the cathode and negative charge to the anode. However, from the results shown in this section, it seems that charge injection from the electrode dominates the process.

### 3.6 Interfaces D between two layers of PPLP without outside Kraft paper

The impregnated Kraft paper is the weak part in the PPLP insulation system in terms of mechanical and electrical property. If the Kraft paper gets damaged when subject to mechanical stress, it will result in the PP exposed. To mimic this scenario, similar arrangement in Section 3.5 has been used but with two impregnated Kraft papers peeled. Space charge in such a structure is measured as shown in Fig. 10.

Unlike the situation in Fig. 9, here both cathode and anode charge peaks are clearly shown and change a little over the duration of the voltage application. Only a small amount of charge in the middle two layers of Kraft paper. From the results in Fig. 4, it is known the peeling off PP layer from PPLP shows the homo-charge injection. It is also known that the ionisation in impregnated Kraft paper under the external electric field may also contribute towards charge accumulation in Fig. 9. In Fig. 10, the small amount charge distribution in each impregnated Kraft paper shows the pattern of positive appear on the side of the cathode and negative on the side of the anode. That is the moving direction of the positive and negative ions under the external electric field. Therefore, it is assumed that the small amount of charges captured in this area is the sum of the injected charge and the ions produced in impregnated Kraft paper. Based on this hypothesis, the results of two layers of PPLP, shown in Fig. 9, prove that the charge accumulated at the interface of Kraft paper and PP adjacent to both electrodes should be most of trapped at a physical interface, less inside the PP layer. Most of the accumulated charges are hard to migrate through PP layer and further arriving at next interface. The decay results in Fig. 10b confirm the injected homo-charge in PP layer close to the both electrodes.

### 3.7 DC conductivity of oil impregnated PPLP

The DC conductivity for PPLP impregnated within high viscosity oil T2015 were measured at room temperature under different electric field. The interesting and surprising result in Fig. 11 shows that the conductivity value of PPLP is very low even under 50 kV/mm. It shows that the conductivity of sandwich structure PPLP is independent on the applied electric field under room temperature.

### 4 Discussion

When designing the insulation of MI cable, the better electrical performances of PP are main reason of replacing Kraft paper with PPLP. Due to the resistivity of PP film is much higher than that of Kraft paper, DC electric stress is supposed to mostly impose on the PP film to which also happen to have a higher DC breakdown strength [9–11]. It has been demonstrated the insulation structure of PP film combination with Kraft paper gives higher DC breakdown strength than conventional Kraft paper insulation [2, 12, 13]. Unfortunately, the detailed mechanisms have not been fully understood and the effect of space charge distribution in such a lapped insulation has not been taken into consideration. Our recent works have shown space charge dynamics under various conditions in this laminated insulation [8, 14].

Although the information of charge accumulated at interfaces in PPLP insulation system has been obtained, the processes of charge movement across the interface are complicated and affected by many factors, including the oil. Here a simple schematic explanation is put forward to account for the charge accumulated at the interface. As the viscosity of impregnated oil used in this study is very high under room temperature, it may be feasible to treat it as solid state. In addition, the energy depth of the interface trap whether for negative or positive charges carriers is assumed to be the same level.

Based on the energy band theory, the band gap between highest level of valence band and lowest state conduction band is closely related to the electrical conductivity of a material. The jump of electrons from the valence band to the conduction band and moving along the conduction band creates the electric current. For the combine insulation made of two layers, the principle of electrical conductivity is complicated but at the ease of electrons. A schematic energy diagram for two materials is shown in Fig. 12, which is mixing up the energy state of two materials. It is big difference between schematic and actual but give us a general view of the interfacial effect on electric carriers movement. For the material of low conductivity, M1 the bottom energy level of conduction band is higher than that of material with high conductivity, M2. In that case, the occupied electrons in valence band need a lot of energy to be excited to the conduction band.

Charge injection from the electrode to the insulation is often described by the Schottky mechanism. A potential barrier is
formed at the interface between the electrode and the insulator which depends on the work function of electrode and electron affinity of insulator. The shape of the barrier (height and width) can be modified by the external applied electric field. Once injected, the charge carriers will drift across the insulation material under the influence of the electric field and arrived at the interfaces built between two insulation films. If the interface works as a trap centre, the trap energy level would be localised within the forbidden gap shown in Fig. 12. For instance, the electrons trapped at interface from M1 would need sufficient energy to jump to the conduction band of next layer M2 to be free. The free charge at trap level jump to M2 need less energy than to M1.

The illustration of the charge accumulation at interface is shown in Fig. 13. When the interface was built by the film of same material, the charge carriers injected from the electrodes would be easily arrived at this trap centre and captured by the trap, we describe this as trapping process. At the same time the trapped charges can move from the interface and into the next layer of insulation. This process of de-trapping from the interface and re-trapped into material needs more energy. It is more difficult than the charge extraction from first layer. The interfacial traps are more complicated than the traps produced by impurity in polymer. It seems that the de-trapping is harder than trapping process. This may explain negative charge captured at the interface of two oil Kraft papers.

If the two layered samples M1 and M2 are not homogeneous with different conductivities, i.e. \( \sigma_{M1} \leq \sigma_{M2} \), and the electrons trapped at the interface from either material, would be easy because the physical interface would stop charge carriers. If the electrons travel from M1 to the interface and want to jump to conduction band of M2, it is easier and possible. Most of the electrons can travel to the next layer. If electrons travel from M2 to the interface, they get captured there. More energy is required to move them into the higher conduction band level of M1. This process is harder to complete, resulting in that the charges are being held at the interfaces.

The above description of electrons can also be applied to holes. For example, holes drift from the anode and arrive at the interface trap centre. It is easier for them to escape from trap and move into the high conductivity material than to the low conductivity material.

To validate the above proposed explanation, the space charge dynamics from a sample consisting of only PP and Kraft paper under 10 kV/mm were measured as shown in Fig. 13. The sample was produced by peeling one layer of Kraft paper from a normal PPLP tape. When PP was in contact with the cathode as shown in Fig. 14a, it can be seen that negative charges are injected from the cathode and easily travel through the interface because of \( \sigma_{PP} < \sigma_{KP} \). At the same time, the injected positive charge is hard to pass through the interface. As a result, more positive charges are accumulated at the interface area. When Kraft paper was in contact with the anode as shown in Fig. 14b, the charge movement of the injected charges is opposite. The injected negative charge from the cathode move across the oil impregnated Kraft paper and but hardly pass through the interface due to the low conductivity of PP, resulting in negative charge accumulation. On the other hand, the injected positive charges from the anode drift through PP and easily pass the interface due to the high conductivity of Kraft paper. The charge distribution in Fig. 14 is in general agreement with the schematic representation shown in Fig. 13.

It has to be stressed here that the real situation is more complicated than the one described above. The ionisation may take place in the insulation oil which will affect charge dynamics and make contribution towards the final charge formation. The exact role of ions needs further investigation.

The presence of space charge in the insulation system will alert the electric field distribution, hence impact on the electrical performance. It is necessary to examine the local electric field distribution in PPLP insulation from measured charge results.

The electric field distribution along the lapped sample can be calculated based on space charge distribution as

\[
E(x) = \int_0^d \frac{\rho(x)}{\varepsilon r} \, dx, \quad 0 \leq x \leq d
\]

where \( \rho(x) \) is the charge density, \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_r \) is the relative permittivity of insulation sample, \( d \) is the thickness of the sample. Due to the very similar relative permittivity between high viscosity oil impregnated Kraft paper and polypropylene film, an average \( \varepsilon_r \) has been used to calculated the electric field for simplicity purposes.

In PPLP symmetry insulation, positive and negative charges inject from both electrodes, and can be blocked at the interface of Kraft paper and PP film. Fig. 8 shows the symmetry results at both interfaces. The electric field across the PP layer will be enhanced by the accumulated charge at two interfaces. The more the charge accumulated at the interfaces, the higher the electric field across PP layer.

Fig. 15, for example, shows the electric field distribution in the PPLP sample with a thicker PP. It can be seen that the electric field within both impregnated Kraft paper decreases over the period of voltage application while the electric field in PP layer rises up rapidly. For comparison, the electric distribution in the PPLP
sample with a thinner PP is shown in Fig. 16. The electric field across PP layer is also enhanced by the accumulated charge at the interfaces but the field enhancement is much less. The decrease in the electric field in Kraft paper is very small. It can be found that after 50 min, the electric field reduction in the Kraft paper is about 80% for a high PP ratio PPLP and about 20% for a low PP ratio PPLP sample.

The amount of charge accumulated at the interfaces of PPLP sample increases before reaching to quasi-equilibrium. This will lead to electric field distortion in both PP (enhancement) and Kraft paper (reduction). However, due to its good dielectric property of PP including higher breakdown strength and low conductivity, it is capable of enduring higher field. Conversely, the distortion of electric field across the PP is less in the PPLP sample with a lower PP ratio. That means the reduction of electric field across Kraft paper is not significant. This will increase the burden of impregnated Kraft paper as it has a lower breakdown strength. That may explain why the DC breakdown strength in high PP ratio PPLP sample is higher than low ratio sample observed in [9].

Also, the interface trap centre hypothesis and electric field distortion might explain the reason of low conductivity of the laminated PPLP sample with sandwich structure. The charges from both electrodes accumulated will reduce the electric field across the Kraft paper. The electric field reduction of Kraft paper will slow the speed of charge injection and accumulation. The amount of electric carriers that can overcome the interface trap into the PP layer is limited. Therefore, the flow of electrons through PP layer is smaller and that make the whole electric current through PPLP smaller as well.

5 Conclusions

Space charge dynamics in PPLP insulation used for HVDC MI cables have been investigated in this paper with the emphasis on the interfaces. The following conclusions can be drawn.

Charge distribution in the high viscosity oil impregnated Kraft paper under room temperature is similar to that in polypropylene film. It has different behaviour compared to traditional mineral oil impregnated Kraft paper which shows an easy charge injection and fast charge movement.

The interface works as a trap centre for both positive and negative charges. For the interfaces between two oil Kraft papers, negative charges dominate the accumulation. For the interface between different materials in the sandwich structure, e.g. in PPLP, the charge accumulated at the interface has the same polarity as the closer electrode. The different PP ratio of PPLP will impact the amount of charges accumulated at the interfaces.

By parity of reasoning, the electric field distortion across the PPLP is different. The charge trapped at the interface of multilayer sample will distort the electric field distribution in each layer. The direct consequence of the interfacial charge in PPLP sample result in the higher field across PP and lower field across Kraft paper. The pattern of charge distribution in two-layer PPLP repeats. These characteristics make such an insulation system adjust the electric field distribution to achieve the great overall performance including low electrical conductivity and high DC breakdown strength.

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