Verification of the HTS Cable at an Accident

– Protection Against the Ground Fault for 275 kV HTS Cable and Experiment –

Tomohiro Takagi [*1], *Masashi Yagi* [*2]

ABSTRACT The ground fault experiment for the 275 kV HTS cable was conducted, as a part of New Energy and Industrial Technology Development Organization (NEDO) project, where the alternating current simulates the ground fault flowed in a short piece of the cable with an artificial ground fault point. The sample without any protection had a large hole on the inner and outer cryostat pipes with the 3 cycles of an alternating current of 10 kA. Then the sample with the protection layer consisting of the insulating non-woven textile on the cable core and the inner cryostat pipe was tried in order to keep the integrity of the outer cryostat pipe. The cable cores were damaged severely with or without the protection layer on the cable core, however the protection layer on the inner cryostat pipe succeeded in keeping the outer cryostat pipe with the 3 cycles of alternating current of 20 kA.

1. INTRODUCTION

The empirical study regarding the safety of the high temperature superconductor (HTS) cable considered to be introduced in the real line was further developed. It was conducted under the NEDO project of “Demonstration Studies of the Stability / Reliability of Next-Generation Transmission systems” started in 2014 and completed in March 2016. The project related to a verification test for the rapid recovery of the power transmission system from a fault or an accident and to increase its durability including the cooling system. The HTS related projects were newly integrated to the “Technology Development to Promote Commercialization of High-Temperature Superconductivity” in July 2016, and the verification study for the safety of the HTS transmission cable is proceeding as the “Development of Commercialization of High-Temperature Superconductor Cable System for Power Transmission”. We, Furukawa Electric is in charge of the practical research of the 275 kV cable and is implementing the project with Sumitomo Electric Industries, which is in charge of 22 kV and 66 kV cable, and Tokyo Electric Power Company Holdings, Inc. which coordinates the project overall[1), 2)].

We have two kinds transmission cables, the AC and DC cable, the project focuses on the AC cable. Since the HTS wire is used as the conductor of the electric current for the HTS cable, it is possible for the cable to decrease the transmission energy loss taking advantage of reducing the joule loss to its utmost limits. Therefore the superconductor has limitations to the flow of the current, and the ultra-high voltage of several tens or several hundred kV is charging the conductor in the high voltage transmission. The short circuit current accident or ground fault accident are occurring for the HTS cable as well as the conventional cable. Since the HTS cable is different from the conventional cable, with respect to being cooled by the liquid nitrogen to the cryogenic temperature, or rising of the cable temperature leads to loss of the super conductivity during the current flowing, the special fault or phenomena are occurring on the cable. If the HTS cable is implemented in a power system of an important infrastructure connected directly to the public, it is very important to make a careful verification before applying to the real line.

As in the accident of the HTS cable, the short circuit current, the liquid nitrogen leakage due to the cable damage, etc. are considered. This paper is a report focusing on the ground fault accident. The ultra-high voltage is applied on the conductor of the ultra-high voltage transmission cable and the applied voltage is held by the insulation layer on the conductor. In the case of an occurring damage in the insulation due to any cause, the insulation breakdown will occur because it will be unable to withstand the ultra-high voltage. This is the ground fault accident of the transmission cable. The small damage or the small defect in the insulation will be caused of the discharge and the small discharge at the point occurring intermittently makes the damage grow gradually. The arc discharge rises between the ground earth and the conductor. Then it destroys the surrounding structure and then the systemic destructive breakdown will occur. In case the discharge part, that released a huge energy,

[*1] Telecommunications & Energy Laboratories, R&D Division
[*2] Technical Development Department, Power Cable Division

exists inside the cable, the accident leads to a serious result on the cable per se. The purpose of this paper is to discuss, “What situation the accident brings on the HTS cable?” and “To get the guide line or the solution for the restoration of the cable after the accident”. We would like to discuss the two items in detail in Chapter 4.

2. THE HTS CABLE STRUCTURE AND THE SIMULATION TEST SAMPLE

2.1 Structure of the HTS Cable

The 275 kV cable is the power transmission cable in a power grid and the copper core conductor cable is utilized at the present, with insulation types such as the crosslinked polyethylene (XLPE) insulated cable, the oil filled (OF) cable, etc. On the other hand, the conductor of the HTS cable consists of the HTS wire for carrying current. We have two kinds of HTS wires, namely the bismuth strontium calcium copper oxide (BSCCO) wire and the rare earth barium copper oxide (REBCO) wire. The construction and the composition of the two wires are different from each other, but the two have the tape shape in common. We are dealing with the possibility to apply REBCO wire. When the tape is arranged on a round rod, the cylindrical shape conductor layer is formed artificially. Figure 1 shows the structure of the 275 kV HTS cable[3), 4)]. The cable core is stored in the inner cryostat pipe and the liquid nitrogen of the coolant flows around the cable core. As for the HTS cables of less than 66 kV, there is a configuration with three cores for the three-phase alternating current transmission encased in one cryostat pipe, but each of the cable cores of the 275 kV cable is encased in its own pipe. The diameter of the cable core was ϕ 89 mm with an insulation layer with a thickness of 22 mm consisting of the polypropylene laminated craft paper (the half-synthetic paper) between the conductor layer and the shield layer. The conductor layer was wound spirally on the copper former consisting of the copper wire bundle and the former was the bypass of the current in the case of the ground fault accident or the short current flowing. The shield layer cancels the magnetic field from the alternating current in the conductor layer, with an alternating current equal to the conductor's but opposite in phase[5), 6)]. Since the alternating ultra-high voltage was applied only to the conductor layer, the current flows to the shield layer or the cryostat pipe at ground potential from the conductor layer on the ground fault accident.

The rated transmission current for the 275 kV HTS cable is AC 3 kA, but the maximum current for 275 kV cables in the power transmission system will be 63 kA in case of the ground fault current[7)]. In the present transmission system, when the ground fault accident occurs, the main protective relay cuts the current with the current breaker of the transmission side.

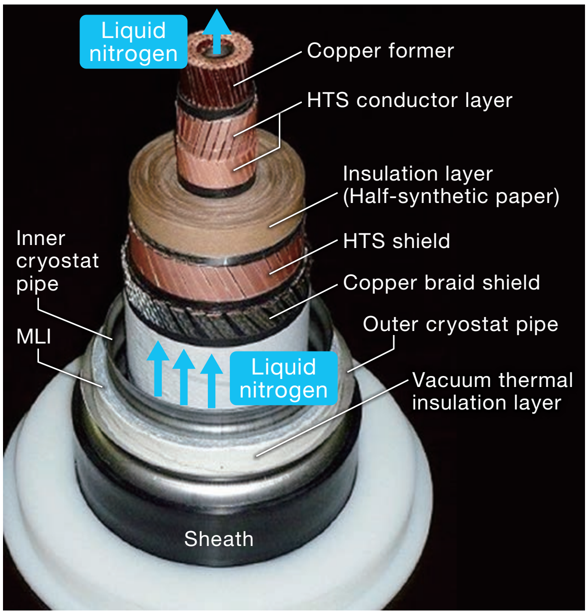


Figure 1 The structure of the 275 kV HTS cable.

2.2 Horizontal Sample and Vertical (standing upright) Sample

Since the ground fault simulated test is a destructive test, every sample is tested once. If we would like to try many samples for different conditions, we need to prepare a multitude of short samples. Since a short cable sample has different considerations from the long cable on several points, we have to decide the experimental method based on clarifying what to evaluate or what to discard. The cable is usually installed horizontally. In the case of laying horizontally short cable samples using the liquid nitrogen as the coolant, we need the end terminal to store the liquid nitrogen on both sides of the cable sample. If we prepare a lot of the experimental samples, we need to have a large amount of budget and labor force. We investigated the vertical sample for the ground fault current test and adopted it for achieving the ground fault simulation test[8)]. The cable core and the cryostat pipe were standing and the bottom of the cryostat pipe was capped and the liquid nitrogen was poured in the tube. The nitrogen liquid was kept and the cable core was cooled without the end terminal. The vacant space of the double cryostat pipe was unable in a vacuum state, but it was possible to keep the sample in the cryogenic state and to keep up the liquid nitrogen as the coolant.

The vertical sample was prepared easily compared to the horizontal sample which was necessary for the storage of the nitrogen, and suitable for carrying out many experiments. It also assumed a good reproducibility of the phenomena of the ground fault accident, such as the arc discharge. We reported the result of the experiments using the vertical sample in this paper. In addition, it should be noted that since the upper end face of the pipe opened, the rising of the pressure of the coolant on the ground fault was not reproduced accurately. In order to get the information regarding the pressure rising, it is more suitable to use the horizontal sample than the vertical sample. We need more of the simulation analysis.

2.3 The Production of the Artificial Ground Fault Point

The sample of the cable core was manufactured in 2014 by the joint venture between Furukawa Electric and Fujikura (VISCAS). The cable core was cut 1 m in length for the experiment. A hole was drilled near one end of the sample and an iron pin was set in the hole. Both ends of the pin were connected to the inner copper former and the copper braid shield respectively. As the copper former and the copper braid shield would represent the bypass of the HTS wire on the ground fault, the pin, which would short circuit them, would be the artificial ground fault point which simulated the defect of the insulation being the trigger of the ground fault in a real line. The conductor current, flowing in the longitudinal direction usually, would flow to the shield layer of the earth potential through the iron pin, and the pin would evaporate at once due to the joule heat. Thus, the arc discharge occurs in the drilled hole, the iron pin set point, and the discharge leads to the huge artificial ground fault. At the other end of the short core sample, the copper former and the copper braid shield were stripped to equip the sleeve electrode with solder. The configuration of the short core sample is shown in Figure 2.

Figure 2 The configuration of the short core sample.

Since the unintentional discharge occurs, if the core has any part with low voltage performance, the voltage withstand test was done for the sample with the drilled hole but no iron pin set. According to the result, the sample withstood at least 12 kV in the air and no discharge occurred anywhere.

3. THE SIMULATED TEST OF THE GROUND FAULT ON THE HTS CABLE WITHOUT PROTECTION

3.1 Experiment

The simulated ground fault energizing current was for 60 milliseconds in 3 cycles of AC 50 Hz. The current time was derived from the time of cutting electricity after starting the main circuit breaker in the transmission grid. The energization was carried out with the current control mode, which keeps the amplitude of the alternating current, and the voltage level of the appropriate current was applied to the sample. Since the arc discharge was able to reach the shield layer, the inner cryostat pipe and the outer cryostat pipe from the conductor layer of the cable core, these three conductors were installed with the electrode and connected to the current source. The three current monitors were set to the three current paths. Figure 3 shows the circuit diagram with the sample schematic and the items to measure in the experiment.

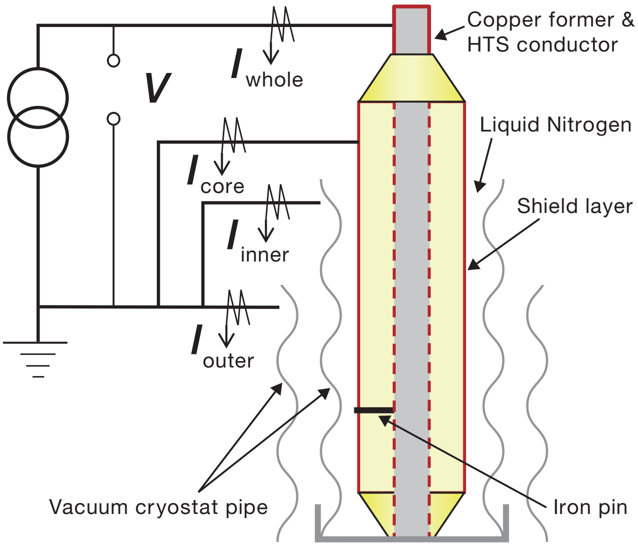


Figure 3 The Circuit diagram for the examination on the short vertical sample.

The cable core was cooled adequately before energizing with the liquid nitrogen poured in the inner cryostat pipe where the bottom at the lower end was capped. Since the insulation layer of the cable component has a high thermal resistivity, it needed a long time to cool adequately the inner parts of the sample. We took around one hour for the cooling period. The ground fault current overwhelmingly exceeded the critical current of the HTS cable in the experiment, as well as the actual ground fault accident. After starting of energizing, most of the current should flow in the normal conducting parts, such as the copper stabilization layer, the copper former of the conductor layer, and heat the current path, and after exceeding the critical temperature of the path, the total current should flow in the normal conducting parts, not in the HTS wire. Therefore, it was not important whether the HTS layer was cooled below the critical temperature or not. However it was desirable for the sample to be cooled sufficiently, since damage of the cable core could change according to the temperature of each part.

3.2 Result of Experiment

The sample was removed after the test and was dissected to check the damage condition. Figure 4 shows the damage appearance of the cryostat pipe of the sample energized at AC 10 kA. The left thinner pipe was the inner pipe and the right thick pipe was the outer pipe. The hole of the outer pipe was bigger than that of the inner. Some metal slugs around the hole on the outer pipe were seen, implying a part of the outer pipe melted and was scattered. The significant deformation was not observed in the remaining parts of both of cryostat pipes and it indicated that the pipes were not exposed to the pressure to deform its shape. The heat of the arc discharge was the main cause of the pipes damage. Since the pipes had no damage except the ground fault point, the joule heat generation by the current flown in the cryostat pipes did not make damage to the pipes.

Figure 4 The Damaged appearance of the cryostat pipe with AC 10 kA. The left is the inner pipe and the right is the outer pipe.

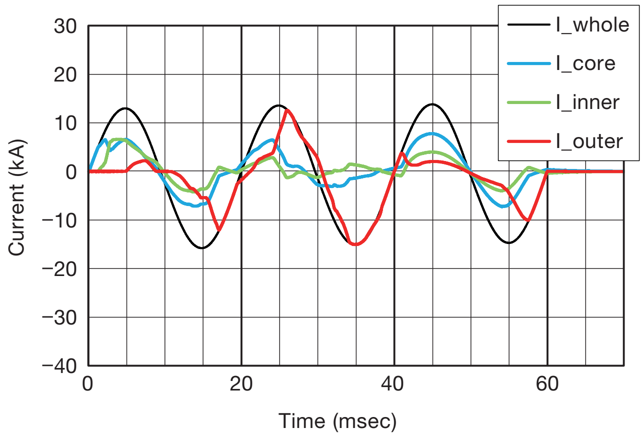
The behavior of the current of the sample at AC 10 kA is shown in Figure 5 (a). In the figure, the black line shows the current flowing up to the ground fault point (total current), the blue line shows the current flowing in the shield layer, the green line shows the current flowing in the inner cryostat pipe and the red line shows the current flowing in the outer cryostat pipe respectively. After the ground fault point, the current flowing in the three paths of the shield layer and both of the cryostat pipes. Since for another sample, when only less than 2 kA current flowed for 4 milliseconds in the outer cryostat pipe, the hole occurred in both of the cryostat pipes. According to these results, we presumed that when the current flowed in the outer cryostat pipe, that means when the arc reached the outer pipe, the cryostat pipe lost its integrity.

The behavior of the circuit voltage for the sample is shown in Figure 5 (b), in which the current of AC 10 kA flowed. The voltage relatively stabilized regardless of the current modulation, and showed a slightly high value before and after the polarity inversion.

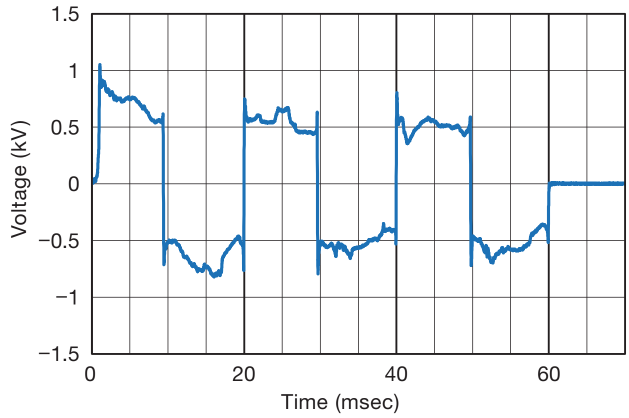
No voltage was observed for 1 millisecond after the start of the current. This indicated that the current flowed in the iron pin that embedded in the core at the artificial ground fault point. After that time, the iron pin evaporated due to the joule heat, and the arc discharge had taken over the current. In the alternating current, the arc discharge paused on the polarity reversal. When the ionized plasma being in responsible for the arc discharge is lost by the electric charge recombination, it is impossible to make a re-ignition by the voltage application of around 10 kV, according to the previous paper[8].

In the current experiment shown in Figure 5, both of samples were energized the current as the setting condition. It was presumed to need slightly high voltage to maintain the arc discharge before and after the polarity reversal, because the plasma concentration (the arc conductivity) decreased with the current decreasing. The relative stability of the voltage, except the polarity reversals, might be explained by the change in the arc discharge cross section or plasma density to follow the current intensity.

Going back to the behavior of the currents, the measured current intensity should show the scale of the arc discharge in each current path from the center part of the conductor layer, except just after the energizing start at the time when the current flowed in the iron pin.



(a) Behavior of the currents



(b) The Behavior of the circuit voltage

Figure 5 The Behavior of the currents and the voltage for the sample at AC 10 kA.

4. THE INVESTIGATION OF THE CABLE PROTECTION

4.1 The Purpose of the Cable Protection

In the case of a huge ground fault accident of the HTS cable, a hole may form on the cryostat pipe as described in the previous chapter. The situation makes the liquid nitrogen leak from the hole of the pipe and may result in a deficiency of the oxygen to the ambient around the HTS cable. On the other hand, if the ground fault is small, the hole may not form on the pipe and the coolant pressure increases due to the discharge and fills in the cryostat pipe, and the pressure propagating far may affect adversely on the circulation mechanism of the liquid nitrogen, etc. We have to investigate both cases, forming the hole or not, and find a solution and a recovery plan to both cases in order to improve the reliability of the HTS cable. This is the main goal of the project and the ground fault examination has to get the above information for the project.

It is supposed that one cable is stored in one vacuumed cryostat pipe for the construction of the 275 kV HTS cable, the three cables of the same structure are installed in parallel in the three phases of the power transmission system. When the cable experiences a ground fault, the cable can be replaced, but it is desirable to avoid the influence of the ground fault on the cables or the apparatus installed around the accident cable. If the integrity of the outer cryostat pipe is kept at the ground fault accident, it is avoidable not only for the above situation but the leakage of the liquid nitrogen from the pipe. The 275 kV HTS cable is supposed to be installed in the urban underground cable tunnel. The liquid nitrogen leaking out of the cable which means the leakage in the underground tunnel is difficult for us to make a recovery operation, and it is meaningful to prevent the leakage from the perspective of the recovery of the power transmission. The maintenance of the integrity of the outer cryostat pipe is the target to consider when designing the cable protection to the ground fault accident.

4.2 The Addition of a Protection Layer to Ground fault

As a protection of the cable to the ground fault accident, the following two items were considered: the addition of the protection on the cable core and the addition of the protection on the inner cryostat pipe. We did not think that the protection layer added on the outer cryostat pipe was effective on the maintenance of the outer cryostat pipe. As for the sample of the ground fault simulation test, we prepared two samples, which were the sample with the above two protection layers (type A) and with only the protection layer on the inner cryostat pipe (type B). The protection layer of 12 mm thickness consists of the laminated structure of the electrically insulating non-woven textile. Table 1 shows the thickness of each of the parts for the type A and the type B and the schematic drawing for the cross section of the type A is shown in Figure 6.

Table 1 The Diameters of type A and type B.

Structure		ϕ (mm)	
		Type A	Type B
HTS conductor layer		35.4	35.4
HTS shield layer		88	88
Core diameter (include sheath)		112	89
Inner cryostat pipe (include MLI, etc.)	Inner diameter	127	106
	Outer diameter	172	148
Outer cryostat pipe	Inner diameter	200	155

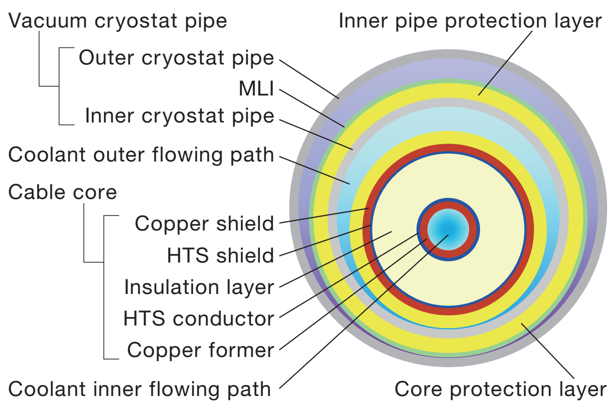


Figure 6 The Schematic drawing of the cross section of type A.

5. THE EFFECT OF THE PROTECTION

5.1 The Damage of the Sample

The two samples were examined with a current of AC 20 kA-3 cycles, and the samples were removed and taken down to be investigated. There were no damage on the appearance of the outer and inner cryostat pipe for both of type A and B, when examining the whole sample. Since the target of the examination is securing the integrity of the outer cryostat pipe, it showed that the protection system of both of type A and type B was effectively kept. On the other hand, the cable cores for both types were damaged, especially around the artificial ground fault point. The protection layer on the cable core of type A was damaged and appeared like a cleavage in the circumferential direction at the artificial ground fault point. The damage of the cable core of the type A is shown in Figure 7. As for the insulation layer, the conductor layer and the copper former located on the inner side of the protection layer, they had larger opened holes than the drilled hole at the artificial ground fault point. However the damages looked slight comparing with the outer protection layer. The damage of the cable core of the type B is the same as the type A.

Figure 7 The Damage appearance of the cable core of the type A.

The inner cryostat pipe was removed and taken down to be investigated. The pipe had a multi-layer insulation (MLI) as the most outer layer and the protection layer inside of the MLI. The layers were removed in order. According to the result, the MLI of both samples were completely without damage and the outer part of the protection layer had also no damage. But removing the protection layer furthermore, the thermal damage was observed in the inner part of the layer, such as carbonization, melting and re-solidification, and the non-woven textile per se was lost in the more inner layer. However at a point a little bit apart from the damaged area, there was no damage for even the non-woven textile of the most inner protection layer.

When all of the protection layers were removed from the inner cryostat pipe, there was a big hole formed on the corrugated pipe made of the SUS steel. The result was the same as the result of the simulated ground fault examination mentioned in the chapter 3. The periphery of the hole looked to be cut by the heat and the hole around area got no clear deformation. The shape and size of the hole on the corrugated pipe was consistent with the lost area of the protection layer. Figure 8 shows the appearance of the corrugated pipe damaged by the current test.

Figure 8 The Appearance of the damaged inner corrugated pipe.

5.2 The Verification of the Effect of the Protection Layer

The behavior of the current flowed in the three paths, the shield layer and both of cryostat pipes, for the type A sample is shown in Figure 9. Comparing with the current behavior of the sample without the protection layer shown in Figure 5 (a), the clear difference was the current in the outer pipe indicated in the red line. The current in the outer pipe accounted for a substantial share of total current in Figure. 5(a), however no current flowed in the outer pipe during the energizing period of 3 cycles in Figure 9. The behavior of the current in the outer pipe indicated that the relative huge arc discharge reached the outer pipe for the sample without the protection layer on the inner pipe shown in Figure 5 (a), on the other hand, the arc discharge did not reach the outer pipe for the sample (type A) with the protection layer on the inner pipe shown in Figure 9. The protection layer which consisted of the lamination of the insulating woven textile prevented the arc discharge from extending, that means the protection layer on the inner pipe protected the outer pipe from the ground fault current. The inside of the multi-layer close to the artificial ground fault point was lost or damaged by heat, however the outside of the layer was as-made. Since the protection layer consisted of the multi-layer of lots of non-woven textile and there were lots of the interface proportional to the numbers of the multi-layers, the heat conductivity in the stacking direction was decreased and the heat generated by the discharge did not transfer to the outside of the multi-layer.

The amount of the arc energy obtained from the product of the total current and the voltage was around 0.3 MJ for the sample without the protection layer when energized by 10 kA and 0.8 J for type A when energized by 20 kA. Since the average voltage of the latter case was a little bit higher than the former, the ratio of the released energy was higher than the current ratio of 1:2.

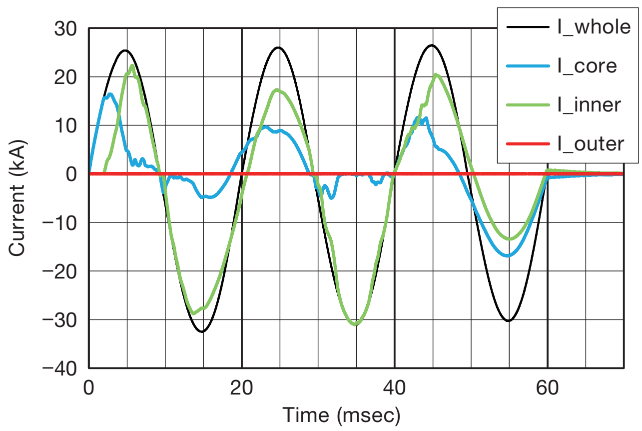


Figure 9 The Behavior of the currents for the type A sample.

Then the effect of the protection layer on the cable core was investigated. The behavior of the current for the sample of the type A which had the protection layer consisted of the insulating non-woven textile (the half-synthetic paper) on the cable core was shown in Figgure 9, the behavior of the current indicated that the arc discharge broke the protection layer in 2 to 3 milliseconds after energizing. The damage appearance of the cable core shown in Figure 7 suggested that the protection layer was broken not by heat gradually but by an impact at once. Since the shield layer which was the destination of the arc discharge was located inside of the protection layer, in the case of the protection layer being reliable, the first arc discharge heated strongly the surrounding coolant. We presumed that the gasified coolant generated a large pressure and it broke the protection layer on the cable core as the role of a "lid" at once.

Why the protection layer on the inner pipe did not break under the pressure mentioned the above? The pressure which broke the protection layer on the cable core did not break the metallic inner corrugated pipe, and released after the coolant was push out longitudinally. The arc discharge and the generation of heat with the discharge continued later on, and the inner corrugated pipe was lost partially with the heat and the protection layer of the inner pipe would be exposed to the high temperature heated coolant molecule and plasma finally. However the density of the coolant decreased and the high pressure situation did not remain compared to the initial stage of the discharge starting, and the protection layer on the inner pipe exposed to the coolant was not damaged by the pressure. The protection layer on the inner pipe was reinforced by the impact resistance with the metallic inner corrugated pipe and produced an effective protection performance.

However the above discussion was considered under the special condition of the vertical sample. It is not easy to push out the pressurized and filled coolant from the real cable. In the above case, it is presumed that the inner cryostat pipe was exposed to the strong inner high pressure for a long time. It is limited to solve the following items on the basis of the result from the experiment this time, "What kind of phenomena occurs under the above situation?", "How effective for the solution?" It is our future work to pursue the phenomena and find the solution for the ground fault accident in the long cable with the simulation measure.

6. CONCLUSION

The current test of the ground fault simulation for the 275 kV HTS cable was done. In the case of no protection, the large hole on the inner / outer cryostat pipes was formed with the current test under AC 10 kA-3 cycles. As the solution for the defense of the outer cryostat pipe, the sample with the protection layer consisting of the insulated non-woven textile on the cable core and the inner cryostat pipe was examined. According to the result, the protection layer on the inner cryostat pipe succeeded to keep the integrity of the outer cryostat pipe from the current of AC 20 kA-3cycles. It indicated that the effective protection on the ground fault current was obtained.

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