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Classification of Bridge Current and Analysis of Heat Transfer Characteristics in Polyvinyl-Chloride-Sheathed Flat Cord Under Tracking

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Abstract – In this study, we examine the tracking happen in a polyvinyl-chloride-sheathed flat cord (PVCSFC), which is widely used as a distribution cord. The study classifies the bridge current via the formed conductive paths during tracking in the PVCSFC. Further, it attempts to distinguish the characteristics of heat generation and heat transfer by kind of bridge current. When the PVCSFC is in the static state, the bridge currents flow only through the electrolyte bridge. In the case of the carbonized PVCSFC, the bridge currents flow through one or more conductive paths. One is the electrolyte bridge, the other is the bridge that is consisted electrolyte and carbonized insulation. Currents flowing through different conductive paths have different heat generation and transfer characteristics. As the bridge current flowing in the conductive path consisting of electrolyte and carbonized insulation increases, the temperature difference between the surface of the PVCSFC and ambient air also increases correspondingly.

Keywords: Tracking breakdown, Conductive path, Bridge current, Heat transfer, Distribution cord

1. Introduction

Tracking breakdown is caused by insulation problems in electric equipments. Several studies have focused on the process of tracking in insulation [1-3].

The test specimens in most tracking studies are prepared with shapes and sizes according to the standards specified the IEC (International Electrotechnical Commission) or the ASTM (American Society for Testing and Materials). However, it is rare that studies tested tracking with electric materials such as cords or cables to analyze the characteristics of tracking depending on the shape of the specimens [3-8].

Various methods — such as the analysis of the surface conditions of the insulation material and type of discharge, analysis of voltage and current waveforms, and the use of light sensors — have been employed for observing the tracking process. One method also includes the detection of tracking carbon paths using thermal images. However, it is not easy to observe tracking with the above-mentioned methods in certain kinds of electrical equipment [9-13].

Especially, it is very difficult to detect tracking that occurs in electric equipments, wires, electric cords, cables etc, that have been installed outdoor. So, this study attempts to analyze the characteristics of the tracking progress in an electric cord. The test sample used for this study was a polyvinyl-chloride-sheathed flat cord (PVCSFC), which is widely used as a distribution cord. Tracking occurs by means of an artificial crack on the surface of the PVCSFC. This study classifies the bridge current by the conductive path while tracking progresses in the PVCSFC. And it attempts to distinguish the characteristic of the heat generation and the heat transfer by the kind of bridge current.

2. Experimental Apparatus and Procedure

Fig. 1(a) shows the experimental setup for observation of the tracking progress in the PVCSFC. This experimental setup is composed on the basis of the test circuit in IEC 60112. The applied voltage was AC 220 V, 60 Hz, non-inductive resistance R was 100 Ω, and the rated current of fuse was 0.5 A at 250V. We regarded the tracking breakdown as this fuse melted.

The voltage and current waveforms were measured using a digital oscilloscope after connecting a 100:1 voltage probe to Ch1 and a current probe (Tektronix, TCPA300 Amplifiers & TCP312 AC/DC Current Probe) to Ch2 in Fig. 1(a).

The test sample (PVCSFC 1.25 $\text{mm}^2 \times 2$ conductors) prepared as shown in Fig. 1(b). The test sample was cleaned with ethyl alcohol and dried over 48 hours with silica gel. The employed electrolyte contained 0.2 % NH_4Cl in de-ionized water. The droplet volume was about 20 mm^3. A droplet of electrolyte was applied at 2 min intervals on the marked ⓧ position on the test sample in Fig. 1(a).

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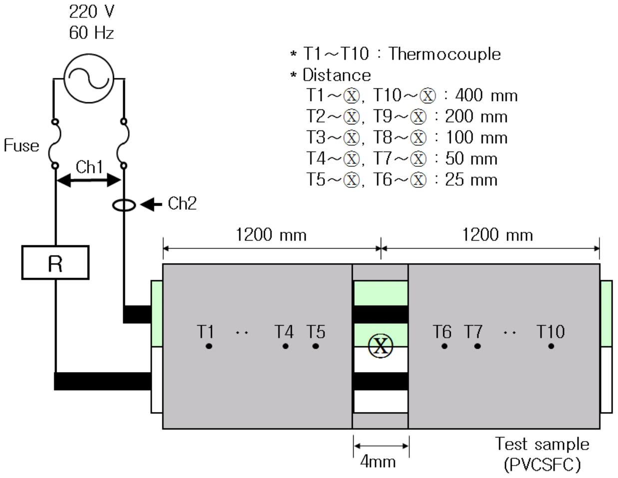
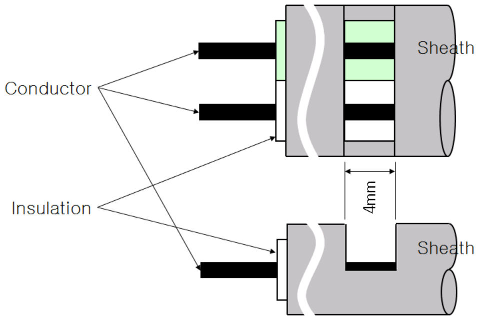


(a) Experimental setup diagram.



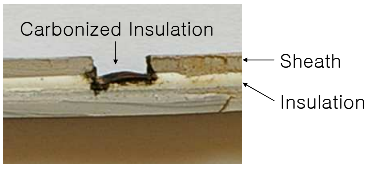
(b) External view of test sample.

Fig. 1. Experimental setup

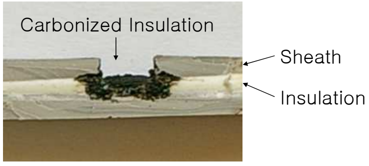
3. Experiment Results

When the electrolyte is dropped on the marked ⓧ position on the test sample in Fig. 1(a), a bridge is formed between the 2 conductors of the PVCSFC. Current flows though this bridge (hereafter, bridge current) and Joule heating occurs. As a result, dry bands having high-intensity electric fields are formed between the 2 conductors. Carbonization is initiated by the discharge occurring in the dry bands. On the surface of the test sample PVCSFC, carbonization begins between the 6th and the 12th droplets.

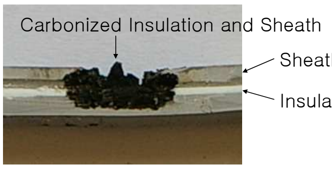
The carbonization progresses from the exposed insulation layer towards the inside, as shown in Fig. 2. In Fig. 2(a), (b) and (c) show the cross section of the test samples after each 1, 2 and 4 hours after the beginning of the experiment. As shown as Fig. 2(a), carbonization begins on the insulation layer. After 2 hour of the commencement of the experiment, the carbonization progresses toward the sheath layer of the PVCSFC as shown in Fig. 2(b). And after 4 hours (of the commencement of the experiment) the carbonized insulation and sheath are piled up on the surface of the PVCSFC, as shown as Fig. 2(c).



(a) 1 hour after the beginning of the experiment



(b) 2 hours after the beginning of the experiment



(c) 4 hours after the beginning of the experiment

Fig. 2. Cross sections of PVCSFC in progressing of carbonization

Table 1 shows the time required for tracking breakdown for 10 pieces of the test samples. The average time to tracking breakdown is 5 hours 33 min in Table 1.

Fig. 3 shows the insulation resistance (IR) values between the 2 conductors of the PVCSFC. The experiment time 0, 1, 2, 3, 4, and 5 in Fig. 3 indicates that the test sample is

Table 1. Time required for tracking breakdown

Sample Number	Time Required	Sample Number	Time Required
1	5 hours 42 min	6	6 hours 2 min
2	4 hours 52 min	7	6 hours 0 min
3	5 hours 28 min	8	5 hours 22 min
4	5 hours 2 min	9	6 hours 38 min
5	5 hours 12 min	10	5 hours 16 min

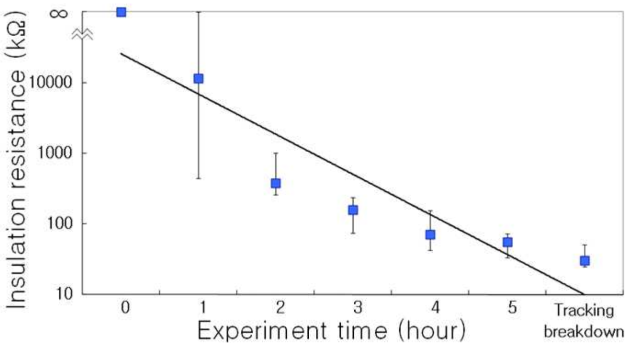
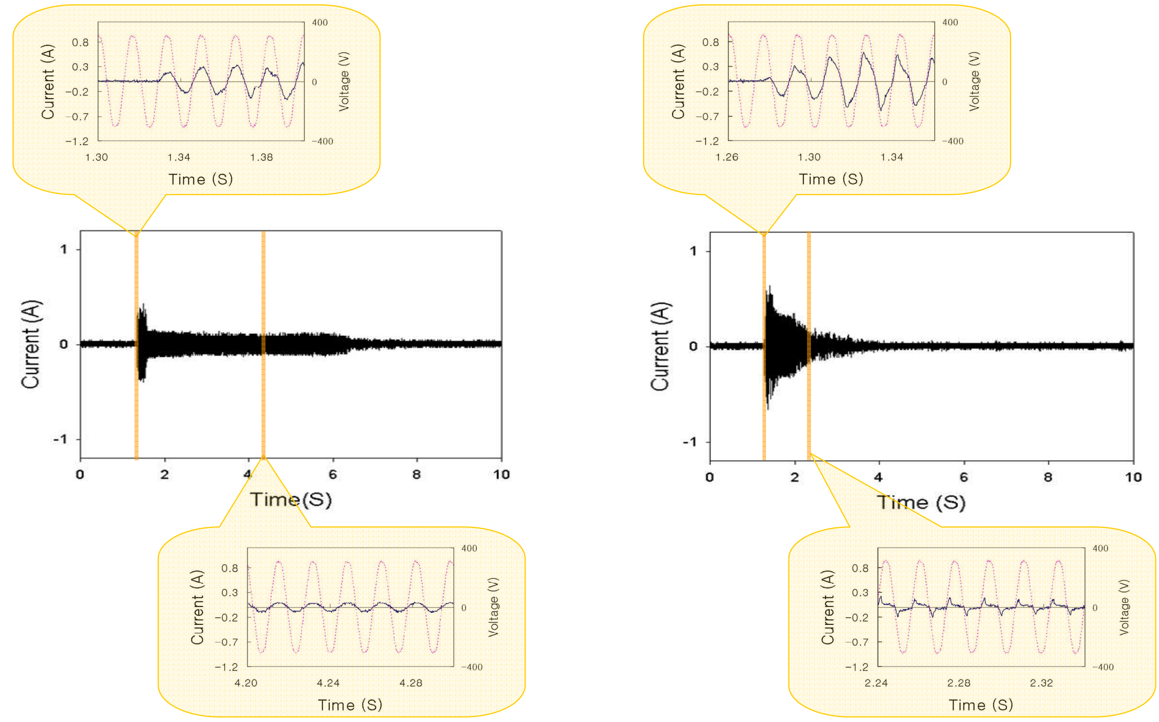
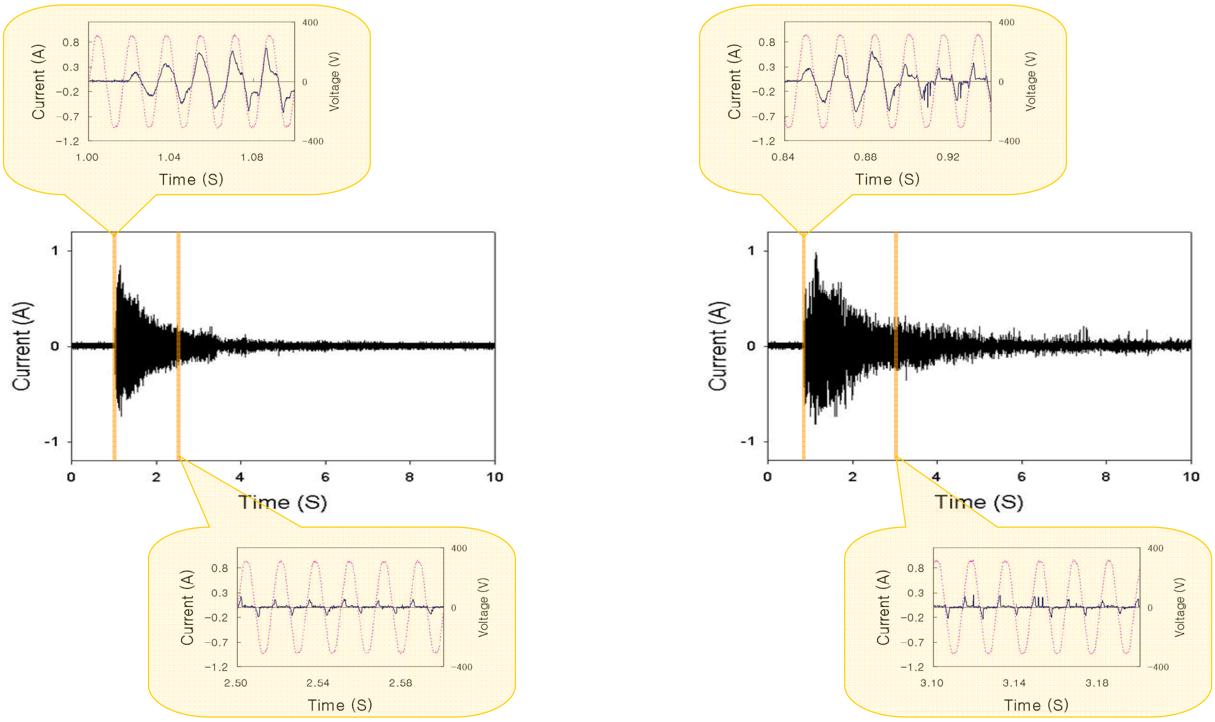


Fig. 3. Variation of IR in PVCSFC



(a) 0 hour after the beginning of the experiment (Static state)

(b) 1 hour after the beginning of the experiment



(c) 2 hours after the beginning of the experiment

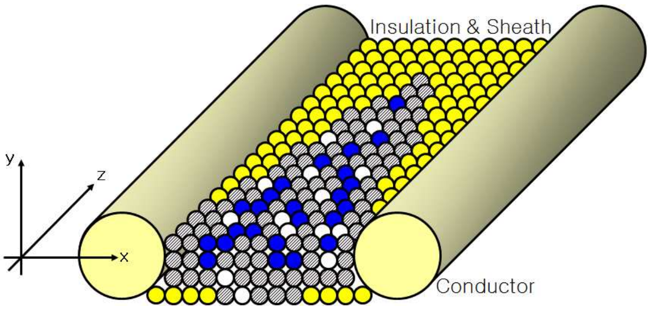
(d) 4 hours after the beginning of the experiment

Fig. 4. Voltage and current waveforms when a bridge between 2 conductors is formed

experimented during 0, 1, 2, 3, 4, and 5 hours respectively. “Tracking breakdown” in Fig. 3 is the test sample that tracking breakdown is occurred. The test sample is dried for over 48 hours with silica gel after the experiment. And the IR value of the test sample is measured after that. The IR values of 70 pieces of the test sample (10 pieces test sample per each experiment time in Fig. 3) are shown in Fig. 3.

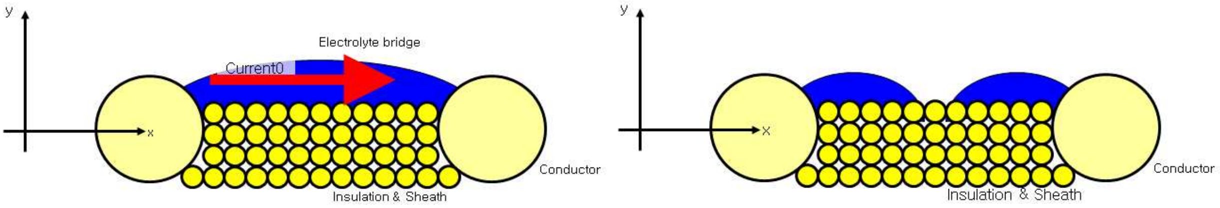
The IR values of 2 samples among the 10 samples experimented for 1 hour exceed the measurement range 500 ㏁, and those of the other 8 samples range from 448 ㏀ to 58,600 ㏀. The average of the 8 samples is 11,574 ㏀. The IR values of 10 samples experimented for 2 hours range from 258 ㏀ to 1,004 ㏀, with a average of 382 ㏀. The average of the IR values is 159 ㏀ for the experiment time of 3 hours, 71㏀ for 4 hours, and 56 ㏀ for 5 hours. The average of the IR value after tracking breakdown is 31 ㏀. As carbonization progresses, the IR value decreases. These results are in agreement with the tracking progression shown in Fig. 2, which shows that the area of carbonization between the 2 conductors increases as it progresses.

Fig. 4 shows the measured current waveforms from Ch2 while a bridge is formed between the 2 conductors. Fig. 4(a) shows the measured current waveform when the electrolyte is dropped onto a PVCSFC whose carbonization has not begun (hereafter, static state). The bridge current has a sinusoidal waveform. Fig. 4(b), (c) and (d) show the measured voltage and current waveforms between the 2 conductors while the test sample is measured at the instant of 1, 2, 4 hours respectively during the experiment. The bridge current waveform has a sinusoidal immediately after the electrolyte’s drop; thereafter, the waveform shape



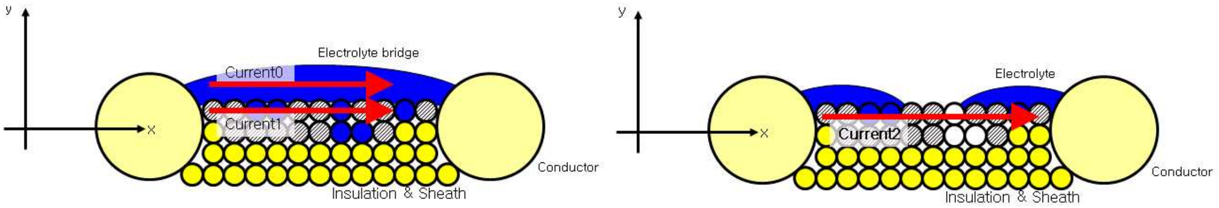
The yellow ball (YB) denotes insulation in static state.
The black ball (BB) denotes a carbonized insulation.
The white ball (WB) denotes a void among carbonized insulations.
The blue ball (BLB) denotes the electrolyte is contained at WB.

(a) The virtual model of the carbonized test sample



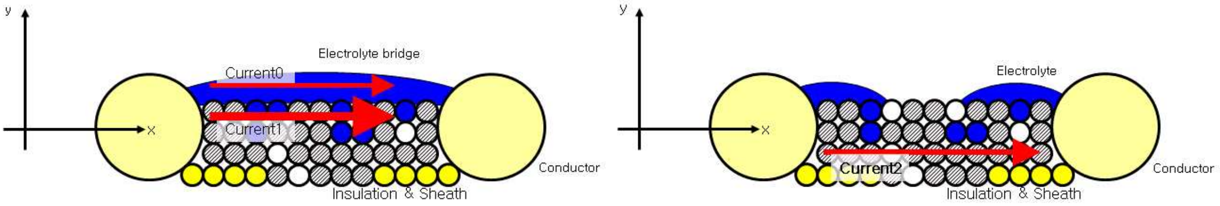
(b) When EB is formed (0 hour, static state)

(c) When dry band is formed (0 hour, static state)



(d) When EB and BLB&BB Bridge are formed (1 hour)

(e) When dry band is formed (1 hour)



(f) When EB and BLB&BB Bridge are formed (4 hours)

(g) When dry band is formed (4 hours)

Fig. 5. The virtual model of the test sample created to explain the waveform phenomena observed in Fig. 4

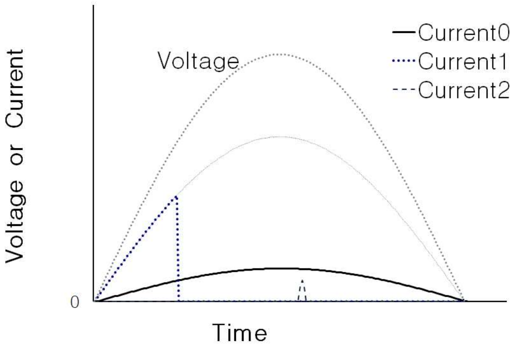
changes to a non-sinusoidal one.

Fig. 5 shows the virtual model of the test sample created to explain the waveform phenomena observed in Fig. 4. In Fig. 5, the yellow ball (YB) denotes an insulation or sheath in the static state, the black ball (BB) denotes a carbonized insulation or sheath, the white ball (WB) denotes a void, the blue ball (BLB) denotes the electrolyte is contained in the WB.

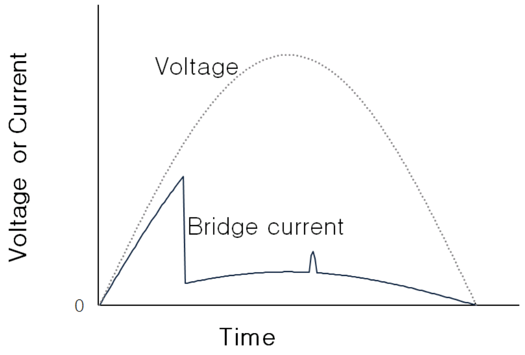
When the electrolyte is dropped onto the PVCSFC in static state, an electrolyte bridge (EB) is formed between the 2 conductors shown in Fig. 5(b). This bridge current flowing through the EB is named Current0. Fig. 4(a) shows Current0 has sinusoidal waveform and Current0 becomes 0 when the dry bands are formed shown in Fig. 5(c). Subsequently, discharge may occur in the dry band.

When the electrolyte is dropped onto the PVCSFC in the carbonized state, 2 kinds of bridges are formed as shown Fig. 5(d). One is the EB, the other bridge is formed by a pathway of BLBs and BBs (hereafter, BLB&BB Bridge). The bridge current flowing through the BLB&BB Bridge is named Current1. So, the bridge current of the carbonized test sample is the sum of Current0 and Current1. Fig. 5(e) shows when the dry band is formed in this carbonized test sample.

The width of the combined bridge formed by the EB and the BLB&BB Bridge together is wider than that of the EB alone. In Fig. 5(f), it is observed that the carbonization is much greater than that in Fig. 5(d). Current1 of (f) is larger than Current1 of (d). As carbonization progresses, as the width of the combined bridge increases and consequently, the bridge current also increases. Therefore, as carbonization progresses, as the amplitude of the bridge current increases like Fig. 4(b), (c) and (d).



(a) Waveforms of Current0, Current1, Current2, and Voltage



(b) Bridge current waveform comprising sum Current0, Current1 and Current2

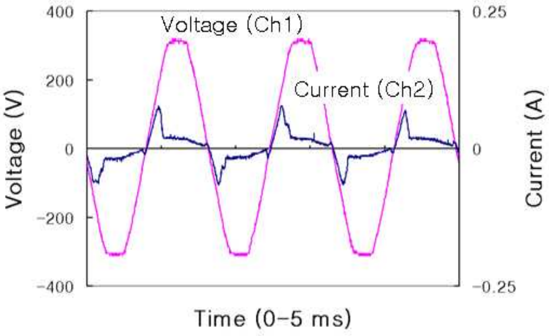
Fig. 6. The bridge current waveforms

In Fig. 5(e) and (g), a dry band is formed in the EB. The BLB&BB Bridge also has a dry band because BLBs are evaporated and they become WBs. The discharge occurs in the WB that has strong electric field intensity. This bridge current is named Current2.

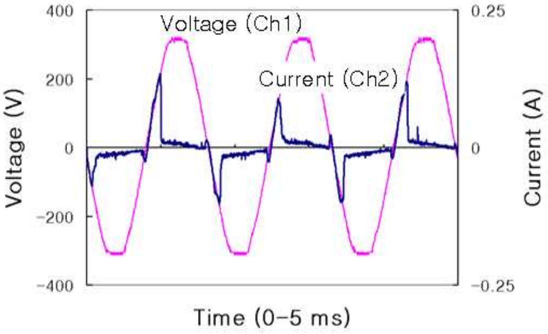
In Fig. 5(d), because the BLB&BB Bridge exists in a surface of test sample, the existence time of Current1 is of short duration like Fig. 4(b). In Fig. 5(f), because the BLB&BB Bridge exists from the surface to the inside of the test sample, the existence time of Current1 is of long duration like Fig. 4(d). As carbonization progresses, several current pulses (Current2) occur after the WBs are formed. As the result, the appearance ratio of the pulse and its amplitude occurring due to Current2 increases in order of (d) > (c) > (b) in Fig. 4.

From Fig. 6, the reason for the non-sinusoidal current waveforms seen in Fig. 4 can be explained. This study classifies the bridge current as Current0, Current1 and Current2. Current0 has a sinusoidal form. Current1 changes as follows during the voltage half-cycle: when the voltage increases, Current1 also increases. BLBs change to WBs in BLB&BB Bridge due to the generated Joule heat. So the value of Current1 approaches 0. Because a few BLBs remain in the BLB＆BB Bridge, BLBs can change WBs within a half-cycle (due to electrolyte evaporation). And when the voltage is high, discharge occurs in WBs. It means that the Current2 flow. But the other case, when the voltage is low, WBs change BLBs again because of the inflow of the electrolyte. The bridge current is the sum of Current0 and Current1 before BLBs change to WBs in BLB&BB Bridge, and it is mostly Current0 and Current2 after BLBs change to WBs. As carbonization progresses, the width of the BLB&BB Bridge increases and Current1 increases. Consequently, the Joule heat generated from Current1 also increases within a half-cycle. So, the need time for BLBs change to WBs is shorter. During WB is existed, Current2 is activated. This is shown in Fig. 7.

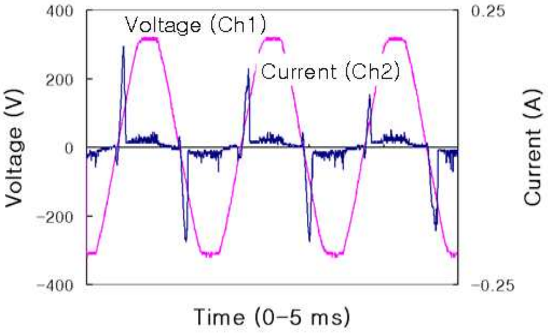
The experimental setup shown in Fig. 1(a) is also used to measure the temperatures of PVCSFC surface and the ambient air. Fig. 8 shows the temperature difference between the surface of the PVCSFC and ambient air (hereafter, TDSA). 10 pieces of K-type thermocouples (T1, T2, …, T10) and recording & data acquisition equipment (Yokogawa MV100) are used for temperature measurement. The thermocouples are set up on both sides of the position marked ⓧ, at distances of 25, 50, 100, 200, and 400 ㎜ from ⓧ in Fig. 1(a). The ambient temperature is maintained at 23±2 ℃.



(a) 1 hour after the beginning of the experiment



(b) 2 hours after the beginning of the experiment



(c) 4 hours after the beginning of the experiment

Fig. 7. Voltage and current waveforms when WBs are existed in the BLB&BB Bridge.

Fig. 8 shows average of TDSA measured in every 10 min after 0, 1, 2, and 4 hours after the beginning of the experiment. As the carbonization progresses, TDSA increases. As shown in Fig. 4, the bridge current flowing time decreases in the order of (a) > (d) > (c) > (b) but TDSA increases in the order of (d) > (c) > (b) > (a). The reason for this phenomenon can be explained as below.

At first, because the Joule heat is generated due to Current0 through the electrolyte, the Joule heat is dissipated via the evaporation heat of electrolyte preferentially and then the remaining Joule heat is conducted through the PVCSFC; there is no more heat generation after the dry band is formed. However, in the case of Joule heat generated due to Current1, a portion of Joule heat is conducted through the electrolyte and the rest of the heat is conducted to the PVCSFC directly. A portion of the heat generated from Current1 will always be conducted through the PVCSFC. Upon comparing Fig. 4 with Fig. 8, the increase in TDSA is found to be correspond to the increase in the amplitude of Current1 in the order (d) > (c) > (b) > (a). Moreover, the duration of Current1 is in the order (d) > (c) > (b) > (a) (Current1 does not exist at the instant shown Fig. 4(a)).

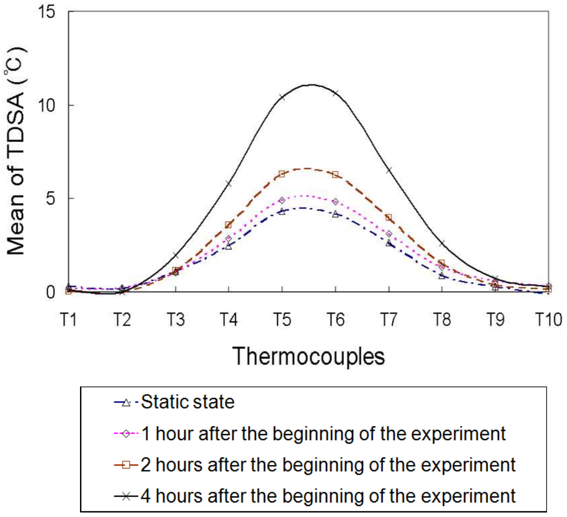


Fig. 8. Temperature difference between PVCSFC surface and ambient air (TDSA)

In second, as shown in Fig. 4, Current1 or Current2 flows over a long time as carbonization progresses. Therefore, Joule heat is also generated and transmitted over this long time and the average value of TDSA increases.

4. Conclusion

This study attempts to analyze the characteristics of the tracking progress in the PVCSFC. It classifies the bridge current by the conductive path while tracking is progressed in PVCSFC. And it attempts to distinguish the characteristic of the heat generation and the heat transfer by kind of bridge current. The main conclusions are as follows:

(1) The average time to tracking breakdown in PVCSFC is 5 hours 33 min.

(2) As a result of the analysis of the bridge current waveforms flowing between the 2 conductors, the bridge current flows through different paths between the 2 conductors according to the carbonization existence of the PVCSFC. When the test sample is in the static state, the bridge currents flow only through the electrolyte bridge. In the case of the carbonized test sample, the bridge currents flow through the electrolyte bridge and the conductive path formed by the electrolyte and the carbonized insulation. Especially, the current flowing in the conductive path formed by the electrolyte and the carbonized insulation is

the cause as carbonization is progressed as the amplitude of the current increases and the bridge current becomes non-sinusoidal.

(3) As the bridge current flowing in the conductive path formed by the electrolyte and the carbonized insulation increases, the temperature of the PVCSFC surface increases above the normal ambient temperature. This is considered to be caused by the current flowing in the abovementioned conductive path. The 1st reason for temperature increase is that the duration and the amplitude of this current increases as carbonization progress. The 2nd reason is the Joule heat generated from this current is conducted to the PVCSFC directly.

We believe that our results can be useful for analysis of tracking progress in PVCSFCs.

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