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Reliability Evaluation of Software Filters Applied to Conduction Current in HVDC Power Cables

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ABSTRACT For design and operation, the conduction current of insulation must be obtained in high-voltage direct current (HVDC) power cables. The measured noise from the environment and equipment can have a significant impact on the reliability of the conduction current. To obtain an accurate conduction current, software filters of the moving average filter (MAF) and moving median filter (MMF) are employed. This study aimed to develop an evaluation method that can quantify the noise reduction of the conduction current measured in HVDC power cables. In addition, we proposed a new software filter with excellent performance. The conduction current was measured at various temperatures using an applied electric field, and the noise reduction rate of the filtered conduction current was evaluated using a statistical method. The experimental results showed that the maximum noise reduction rate of the software filters is 94 %, and the newly proposed filter is up to 26 % more effective in reducing noise than MAF and MMF. This demonstrates the development of a reliable new software filter and evaluation method.

INDEX TERMS Moving average filter (MAF), moving median filter (MMF), high voltage direct current (HVDC).

I. INTRODUCTION

Polymeric materials have been continuously developed as high-voltage insulators. Recently, cross-linking polyethylene (XLPE) has been applied to the insulation of high-voltage direct current (HVDC) extruded cables owing to its excellent insulation properties. The XLPE is widely used owing to its electrical, thermal, and mechanical properties. Obtaining the conduction properties of XLPE has emerged as an important part of the reliable design and diagnosis of HVDC power cables. The DC conduction current is considered as a key parameter for the operation and design of HVDC power cables. The electric-field distribution of HVDC cables changes according to the DC conductivity related to the conduction current [1].

Several researchers have used conduction current to diagnose the aged condition and calculate the DC conductivity in insulation materials [2]–[5]. The intrinsic characteristics of the conduction current, such as the data distribution, shape, and slope, are useful in diagnosing polymeric materials [6]. However, there is a problem in using the conduction current to diagnose the insulation and to calculate the DC conductivity. The magnitude of the conduction current depends on the temperature and the applied electric field, and it is significantly small (10^{-13} to 10^{-7}A). Therefore, it is affected by noise generated from various sources, environment, and measuring device [7]. Hardware and software filters can be used to reduce the noise generated by measuring the conduction current. The hardware filter is a low-pass filter composed of a resistor and a capacitor. It is intended for ripple reduction by a high-voltage source [8]. The software filters of the moving average filter (MAF) and moving median filter (MMF) are used to remove unexpected noise generated by the measurement environment [9], [10].

The noise of raw data can be processed using software filters to improve the readability of the aging analysis. However, as the noise reduction rate of the filtered conduction current has not been quantitatively considered, it is difficult to determine whether the change in the conduction current of aged XLPE samples after using the filter is within the range of intrinsic characteristics [8]. The software filters of the conduction current have been discussed; however, the noise reduction rate has not been focused [11]. The software filter was applied statistically, and the original data

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lost its intrinsic characteristics as the number of uses and data acquired increased [11]. Therefore, it is necessary to clarify the statistical characteristics of the software filter, noise reduction rate, number of uses, and number of data collected. However, this clarification has not yet been considered. In addition, no studies have evaluated the reliability of software filters applied to the conduction current.

In this study, we developed a new method to evaluate the software filters applied to the conduction current measured in an HVDC XLPE cable. This method determines the software filter with an excellent noise reduction performance for the conduction current.

The contents performed to evaluate the reliability of the software filters applied to the conduction current are as follows: First, the conduction current was measured in an HVDC XLPE model cable manufactured for research according to the temperature and electric field. Second, the measured original data were processed using MAF, MMF, and the newly proposed filter. Third, the noise reduction rate of the filtered conduction current in the test sample was calculated quantitatively. Finally, the reliability and robustness of the new filter were verified using standard deviation.

The contribution of this study is the improvement of the readability and reliability of insulation diagnosis in HVDC XLPE power cables.

The remainder of this paper is organized as follows. Section 2 presents a discussion of the theory for filtering the conduction current of the XLPE model cable and the evaluation of the noise reduction method. In Section 3, we propose a circuit to measure the conduction current. In Section 4, we present the reduction rate of the filtered conduction current and the optimized filter method.

II. THEORY

A. CONDUCTION CURRENT

The polarization and depolarization current (PDC) was measured using a time-domain method to obtain the conduction current of the material. This technology is based on the characteristics of the DC voltage applied to the insulation of power cables. When a high voltage is shared across to the insulation for a tc, the polarization current is obtained. In addition, when the high voltage is withdrawn, the depolarization current can be measured, and the conduction current becomes the steady-state current, which can be calculated from the mathematical relationship between the polarization current and the depolarization current. However, note that these concepts of conduction current are approximations that are used when the charging time is quite long in insulation. The conduction current can be written as in [3]:

$$I_{Conduction}[t] = I_{polarization}[t] - I_{depolarization}[t] \quad (1)$$

B. SOFTWARE FILTERS

The software filter is a digital low-pass filter mainly used to process the raw data. It assumes M samples of input data at once and uses statistical methods to produce a single output data. As the use of the software filter increases, the softness of the output increases, on the other hand the sharp changes in the raw data become gradually dull [12].

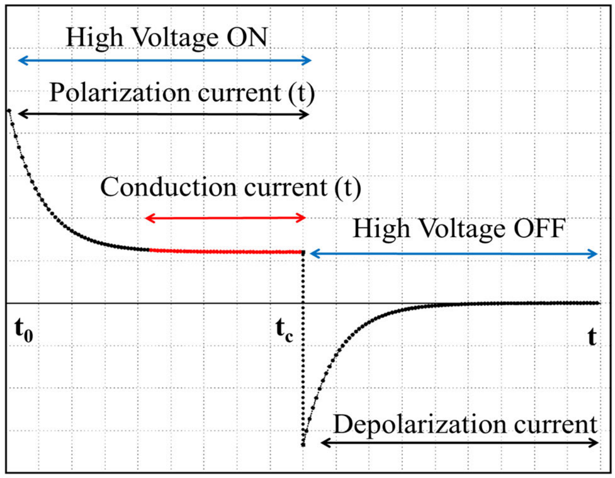

FIGURE 1. Principle of conduction current using PDC.

There are two most commonly used filters: moving average filter (MAF) and moving median filter (MMF), and they use the average and median of the data, respectively. MAF can be mathematically expressed as follows [9]:

$$a[i] = \frac{1}{M}\sum_{J=0}^{M-1} Y[i+j] \quad (2)$$

The MMF can be written as in [10]

$$m[i] = median\,(Y[i] : Y[i+M-1]) \quad (3)$$

where a[i] and m[i] are the filtered output signals using MAF and MMF, Y[i] is the input signal and data, including noise, and M is the number of samples obtained for average and median. The noise of the measured data is affected by the statistical characteristics of the average and median values. The MAF is a commonly used filter, but it is not effective in removing noise when the signal is sporadic, far from the average. As the amount of data increased, the noise removal performance improved. The MMF is effective for removing sporadic and unexpected noise, but is affected by the number of measured data. Therefore, it is necessary to select an appropriate filter based on the type of noise. The principles of MAF and MMF are shown in Fig. 2. Y1-6 is the input signal, and a1-4 and m1-4 are data processed using MAF and MMF. In addition, the number of samples taken was 3. Figure 2 shows that the data are statistically processed as they move to the right.

The concept of approximation is used to propose a new filter method. Generally, the mathematical definition of the approximation can be expressed as (4):

$$\text{Approximation} = \text{true value-error} \quad (4)$$

An approximation is similar to a true value, but is not the same because of an error. As the equation shows, the smaller

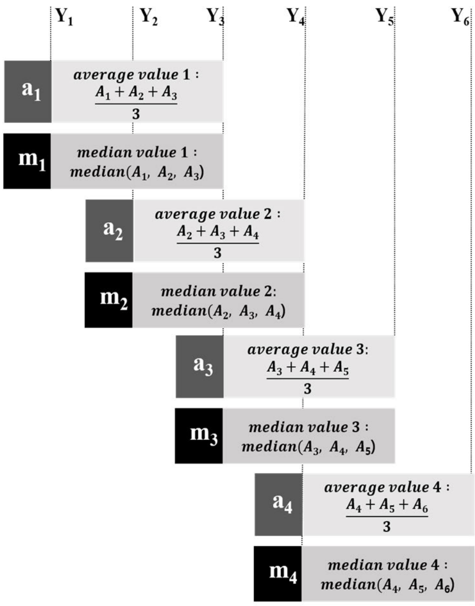

FIGURE 2. Principle of moving average filter and moving median filter: Y_{1-6} is input data, a_{1-4} and m_{1-4} are filtered data using MAF and MAF, The M applied to the filter is 3.

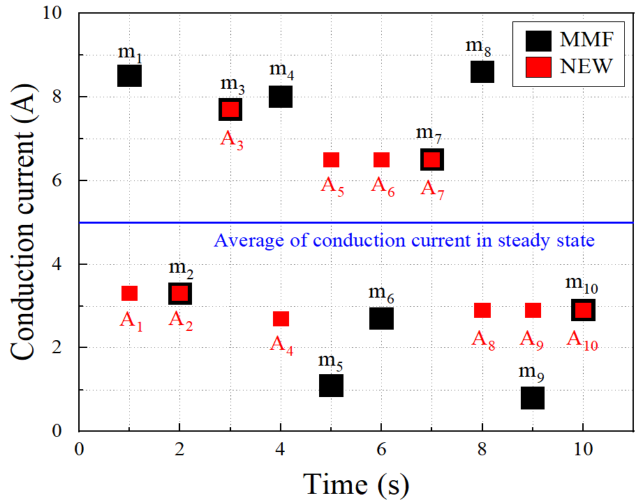

FIGURE 3. Principle of new software filter: m_{1-10} is filtered data using MMF, A_{1-10} is filtered data using NEW method, The M applied to the filter is 3.

the error, the closer the approximation is to the true value, and the greater the reliability.

We applied this concept to the new filter. In (4), the approximation is the data group of m[i] processed from the raw data through the median filter, and the true value is the average of the conduction current. Therefore, when the average value of the conduction current is subtracted from m[i], the data with the smallest error are acquired as the data processed with the new filter.

A new method to increase the reliability of the noise reduction rate can be expressed as

$$A\,[i] = \text{Approximation}_{smallerror}\,(m\,[i] : m\,[i + M - 1]) \quad (5)$$

In (5), m[i] is the filtered data using MMF, as shown in (3). In addition, an approximation$_{\text{small error}}$ can be defined as the value with the smallest error when the average of the conduction current is subtracted from m[i].

The application of the new filter is divided into two stages. The first step is processing the unfiltered raw data into the MMF. The second is considering an approximation with the smallest error in m [i]. As shown in Fig. 3, when the number of data acquisitions M is three, the average value of the conduction current is 5, m_1 is 8.5, m_2 is 3.2, and m_3 is 7.8; the value of m_2 has the smallest error and becomes A_1 produced by the new filter.

This technique guarantees success only when the measured data has a constant value, such as the conduction current, for a long period. The approximation of (5) is defined by the average, which is a statistical method that guarantees the performance as the number of data increases and the deviation is small. Therefore, the characteristics of this average are suitable for the conduction current. However, when the data rapidly decreases or increases rapidly with time, the accuracy of the average decreases because the data deviation increases, which may eventually cause the failure of the new filter. For example, the success of a new filter cannot be guaranteed in transients in which data are rapidly changed when a voltage is applied or removed. Therefore, it is important to understand the nature of the data used to determine the success or failure of this filter. By comprehensively applying the advantages of median and average, the new filter is effective in removing noise from sporadic and unexpected conduction currents, and performance improves as the number of measured data increases. The new filter uses an approximation of the average, thus the characteristics of the data applied to the filter are important.

The principle of the proposed noise reduction filter is illustrated in Fig. 3. m_{1-10} is filtered data from the raw signal using MMF, and A_{1-10} is processed using a new filter. To obtain the filtered data, the number of samples taken was 3. Among m_1, m_2, and $_3$, A_1 is an approximation that is close to the average of the conduction current in steady state. It moves to the right while processing the data in this manner.

C. NOISE REDUCTION RATE

The standard deviation is a statistic that represents the amount of dispersion or variation of measured data. A low standard deviation means that the values are clustered around the average of the set, whereas a high standard deviation represents that the data are more spread out over a large scale. This was calculated using the average and variance of the data. The formulas related to the standard deviation can be expressed as follows:

The average can be expressed as

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (6)$$

The variance can be written as

$$v = \frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n} \quad (7)$$

The standard deviation can be written as [13]

$$SD = \sqrt{v} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n}} \quad (8)$$

where n is the number of data points, Xi are the values of the data, $\overline{X}$ is the average of X_i, and v is the variance of the measured data.

The noise reduction rate was calculated as the ratio of the standard deviation of the raw data to the filtered data. A high noise reduction rate indicates that the values tend to be effective for noise reduction of the raw data. The noise reduction rate can be mathematically expressed as:

$$NRR(t) = \left| 1 - \frac{SD_{raw}(t) - SD_{filtered}(t)}{SD_{raw}(t)} \right| \times 100 \quad (9)$$

where SD_{raw} is the standard deviation of the unfiltered signals and $SD_{filtered}$ is the standard deviation of the filtered data using a software filter. In (9), the time t represents the section in which the conduction current of the XLPE model cable is stabilized and has a constant value.

III. EXPERIMENTAL SECTION

A. TEST SAMPLE

To obtain the conduction current, the test object was a miniature cable, which was produced by triple extrusion into the semiconductor layers and XLPE insulation for research on HVDC applications. Figure 4 shows the geometry of the XLPE model cable. The thickness of the XLPE insulation was 2.53 mm and the outer diameter of the test sample was 12.79 mm.

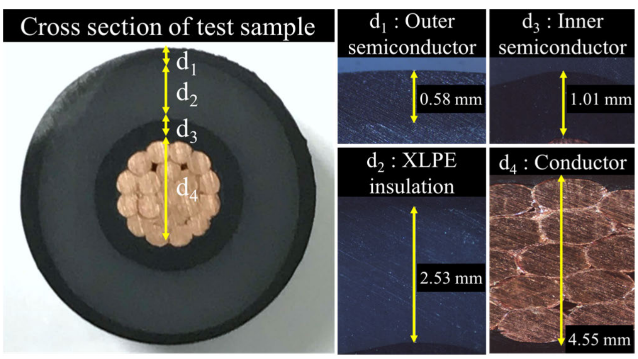

FIGURE 4. Cross section of the test sample: d_1 of outer semiconductor = 0.58 mm, d_2 of XLPE insulation = 2.53 mm, d_3 of inner semiconductor = 1.01 mm and d_4 of conductor = 4.55 mm.

Figure 5 shows the HVDC XLPE model cable considering the measurement of the conduction current. The test sample was thermally preprocessed at 60 °C for 72 h to reduce the byproducts generated from crosslinking. The outer semiconductor of the termination was removed by 1300 mm to prevent the partial discharge generated from the high voltage. The length of cable termination was considerably increased to apply high voltages from 25 to 62.5 kV in the test sample. The guard electrodes were composed of a 100 mm copper tape to prevent stray current in the XLPE terminations of the test sample. The measuring electrode was constructed using a 1300 mm copper tape. The total length of the test sample was 4500 mm to obtain the conduction current. A–I show the different parts of the XLPE model cable in Fig. 5. A and I are the copper conductors to which HVDC is shared; B and H are the XLPE terminations from which the outer semiconductor was pealed; C and G are the guard electrodes; D and F are the gaps between the guard and measuring electrodes; E is the measuring electrode.

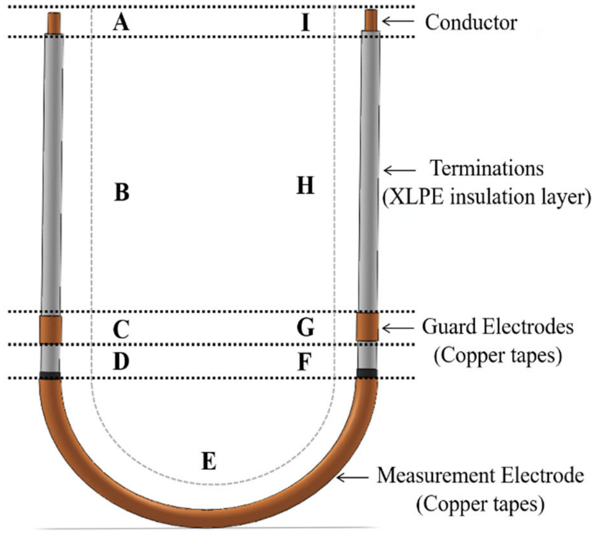

FIGURE 5. Test sample considering measurement of conduction current: A and I = 100 mm, B and H = 1300 mm, C and G = 100 mm, D and F = 100 mm and E = 1300 mm.

B. EXPERIMENTAL SETUP

Figure 6 represents the circuit for measuring the conduction current. When a high voltage is applied to the test sample of the cable structure, unexpected noise is generated from the HVDC power supply. To reduce this noise, the resistor and capacitor with high withstand voltage were constructed in parallel to act as a low pass filter. The resistor of the RC filter must be constructed by considering the combined resistance of the voltage divider and the test sample. The noise-reduced voltage was shared between the test sample and the voltage divider. The voltage applied to the XLPE of the model cable was measured using a voltmeter. An ampere meter was used to measure the conduction current owing to the volume resistivity of the XLPE insulation.

Figure 7 shows schematic and photo representation of experimental setup for measuring conduction current. The temperature of the test sample was controlled using the reference loop method [14]. Because high voltage is applied

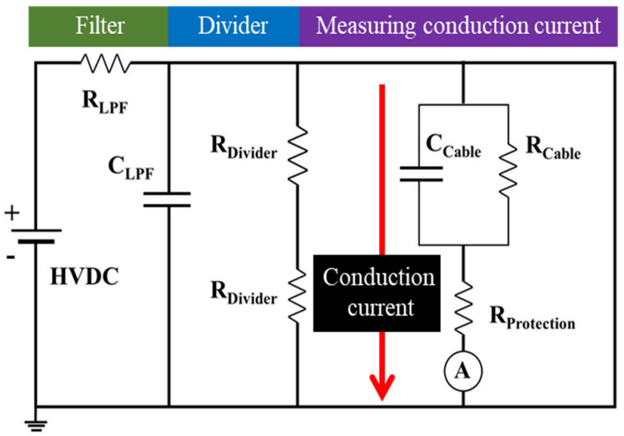

FIGURE 6. **Circuit for measuring conduction current.**

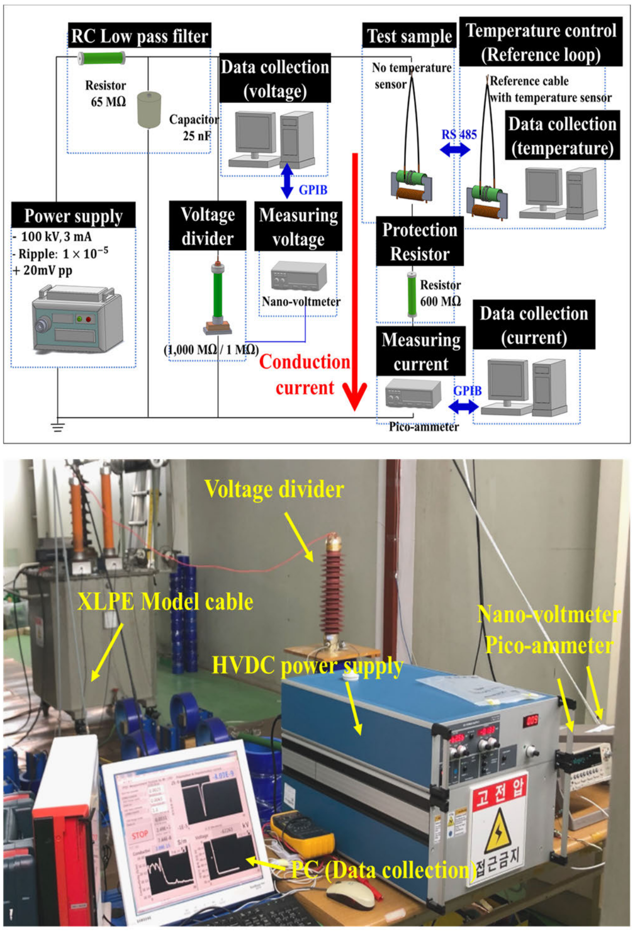

FIGURE 7. **Schematic and photo representation of experimental setup for measuring conduction current in the HVDC XLPE model cable.**

to the test sample, if the temperature sensor is installed on the conductor of cable, the high voltage is connected to the sensor and the measuring device is damaged. Therefore, the temperature sensor is installed only on a reference cable is similar to the test sample. The temperature of the test sample is controlled by flowing the amount of induced current that passes through the reference cable using recommended standard (RS) 485 installed to a computer. Furthermore, for protection of device, the resistor was connected to test sample and pico-ammeter in series. The protection unit was set to be 1000 to 10000 times less than the resistance of model cable. The conduction current was obtained via the pico-ammeter. The sampling rate of the measured current is one per second.

To apply voltage to the HVDC XLPE model cable, the fug HCP 350-100,000 was used as a negative high-voltage power supply. The ripple of the source and the voltage stability were $\leq 1 \times 10^{-5} + 20$ mV$_{P-P}$ and $\leq 1 \times 10^{-5}$ for 8 h. To remove noise and ripple from DC power supply, a hardware filter was composed of RC ($R_{LPF} = 65$ MΩ, $C_{LPF} = 25$ nF) with a cut off frequency of 0.1 Hz [15]. The voltage applied to the test sample was measured at the resistors of the divider (1,000 MΩ, 1 MΩ). The conduction current and voltage were collected using a pico-ammeter (Keithley 6514) and a nano-voltmeter (Keithley 2182A) that were controlled via the GPIB. In addition, to control the conductor temperature of the test sample and reference cable, the current transformer was connected to RS 485. The protection unit ($R_{protection} =$ 600 MΩ) was used to protect the instrument from overvoltage and overcurrent in the case of the failure of the test sample [16].

C. MEASUREMENT PROCEDURE

The conduction current was measured by applying an average electric field of 10 kV/mm, 15 kV/mm, 20 kV/mm, and 25 kV/mm at temperatures of 30°C, 60°C, and 90 °C for 3 h. Table 1 shows the conditions for measuring the conduction current of the electric field and temperature. To obtain an accurate conduction current, the voltage source applied to the test sample should be stable. The temperature error range of the test sample for measuring the conduction current was maintained within ± 0.5 °C at 30 °C, within ± 1 °C at 60 °C, and within ± 2 °C at 90 °C. Figure 8 shows the voltage stability and temperature for measuring the conduction current.

TABLE 1. **Measuring conditions to obtain the conduction current.**

E-field (kV/mm)	Temperature (°C)	Measuring time (s)
10, 15, 20, 25	30, 60, 90	10,800

For insulations with the DC conductivity of higher than $\sim 10^{-10}$ S/m, the steady state is generally reached within 1 min. However, insulations with a less DC conductivity require longer electrification times to obtain that the conduction current continues for several hours, days, weeks or even months [17]. The measuring time was set to 10800 s to reach the steady state of the test sample during the application of voltage. The actual stabilization time of the conduction current was after 7200 s, except for 10 kV/mm in Fig. 10.

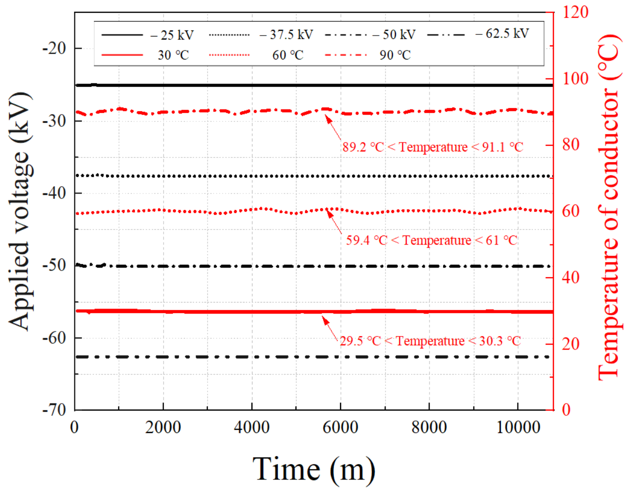

FIGURE 8. Stability of the test voltage and conductor temperature for measuring conduction current.

IV. RESULTS AND DISSCUSION

A. UNFILTERED DATA

Figures 9, 10, and 11 represent the conduction current of the raw data without filtering. The conduction currents are measured for applied electric fields of 10 kV/mm, 15 kV/mm, 20 kV/mm, and 25 kV/mm at conductor temperatures of 30 °C, 60 °C, and 90 °C, respectively. The evolution of the conduction current with time depends on the applied electric field and the temperature of the conductor. The conduction current increases as the applied electric field and temperature increases. As shown in Figs. 9 and 11, when the temperature of the cable is compared at 30 °C and 90 °C, it can be observed that the noise deviation of the conduction current decreases as the temperature increases. Among Figs. 9, 10 and 11, the most noise is contained in conduction current measured at a conductor temperature of 30 °C and 15 kV / mm. In addition,

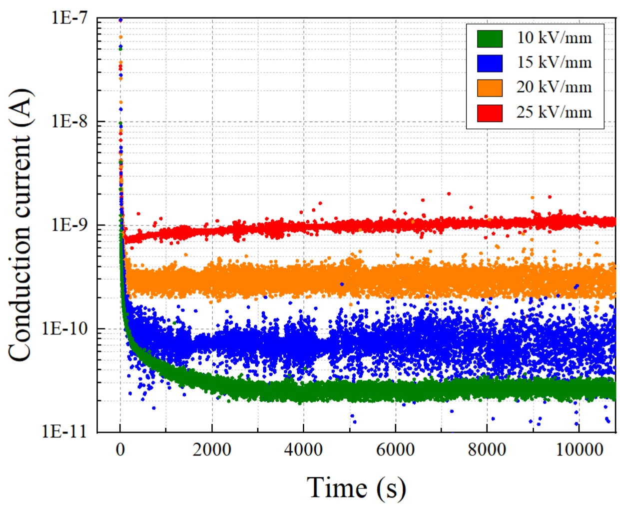

FIGURE 9. Results of the unfiltered conduction current of the test sample as a function of time at 30 °C.

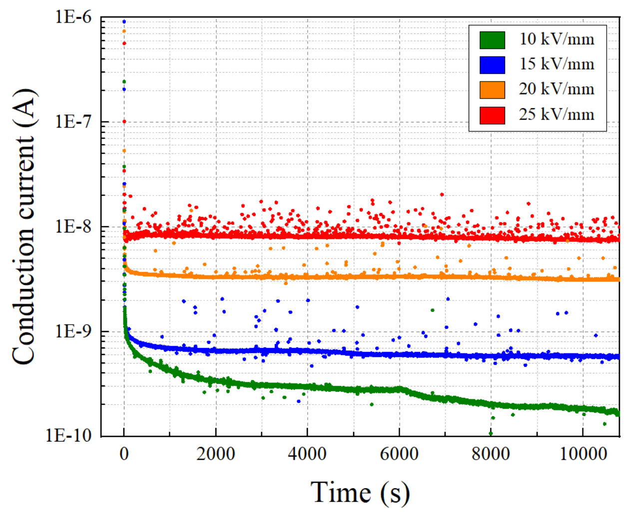

FIGURE 10. Results of the unfiltered conduction current of the test sample as a function of time at 60 °C.

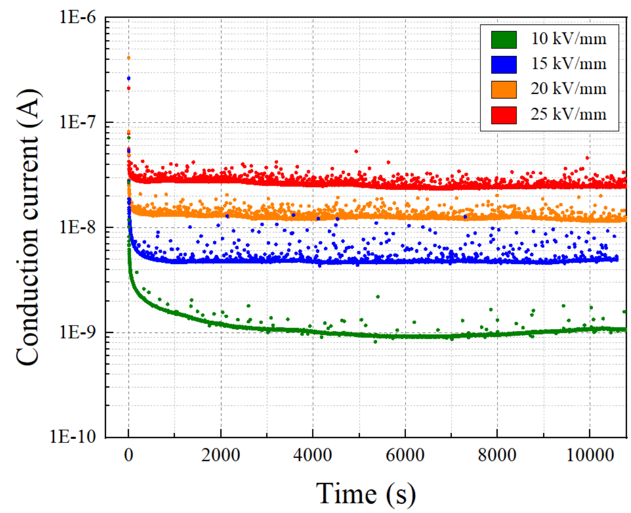

FIGURE 11. Results of the unfiltered conduction current of the test sample as a function of time at 90 °C.

more sporadic noise can be observed under the condition of an electric field of 15 kV/mm. Figures 10 and 11 show that the noise increases at 25 kV/mm compared to that at 10 kV/mm. The temperature and applied electric field affect the noise generated when measuring the conduction current, but it is difficult to determine the exact correlation.

B. DATA PROCESSING USING FILTERS

Unexpected noise from various sources can significantly affect the measurement of the conduction current. Therefore, along with the hardware filter (RC filter), a software filter should be applied to obtain accurate data measurements [7]. The raw data must be processed using software filters to ensure the effectiveness of the measured conduction current. Generally, as the number of M that acquires data increases, the reduction in noise increases, but the inherent characteristics of raw data deteriorate. Therefore, a software filter with high efficiency should have a small amount of acquired data and a high noise reduction.

In Figs. 9, 10, and 11, the noise deviation of the unfiltered conduction current is most sporadic under the conditions of conductor temperature 30 °C with an electric field of 15 kV/mm, conductor temperature of 60 °C with an electric field of 25 kV/mm, and conductor temperature of 90 °C with an electric field of 15 kV/mm.

Figures 12, 13, and 14 visually show the extent of noise reduction by applying a software filter to the conduction current under these conditions. When software filters are applied to the conduction current measured in HVDC XLPE model cables, the performance of noise reduction is approximately 50 % or more.

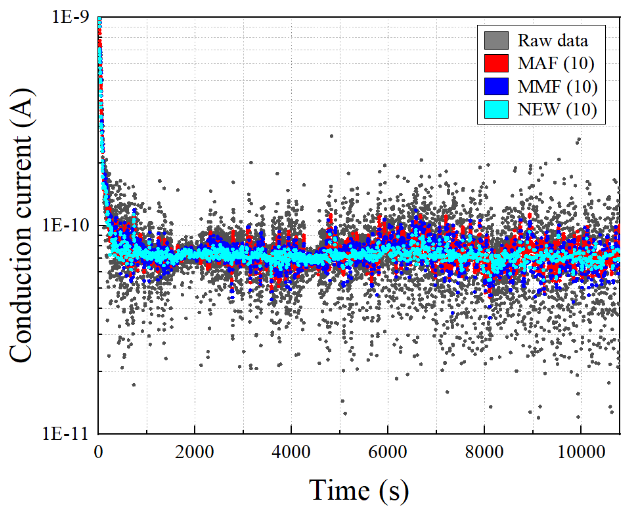

FIGURE 12. Data processing using software filters for conduction current measured as 15 kV/mm at 30 °C.

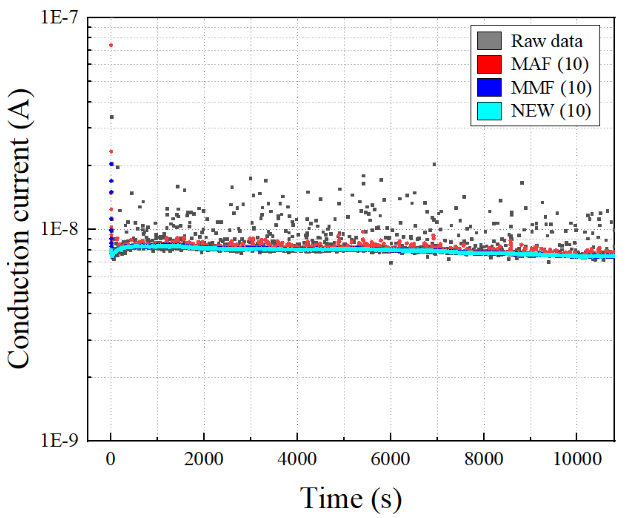

FIGURE 13. Data processing using software filters for conduction current measured as 25 kV/mm at 60 °C.

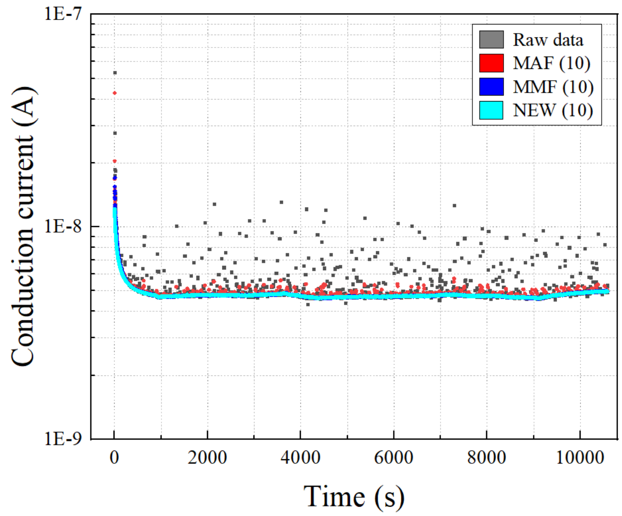

FIGURE 14. Data processing using software filters for conduction current measured as 15 kV/mm at 90 °C.

In Figs. 12, 13, and 14, the number of data acquired for the filter is 10, and the noise reduction rate of the conduction current through the MAF, MMF, and the newly proposed filter method is visually shown. In the figures, gray represents the raw data of the conduction current containing noise, red represents the data filtered using MAF, blue represents the data filtered using MMF, and light blue represents data filtered by a new method that statistically combines MAF and MMF.

In Fig. 12, the variation of the light blue data according to the measurement time was the smallest, thus the newly proposed filter was more effective in removing noise than MAF and MMF. In addition, when using the newly proposed filter method in Fig. 12, it can be observed that the noise of the raw data is reduced by approximately 80 %. In Figs. 13 and 14, the red data using the MAF have a larger deviation of noise than the light blue data. Thus, it can be observed that the newly developed filter is more effective in removing noise from the conduction current than the MAF. However, it seems difficult to visually evaluate the performance of MMF and the new filters in Figs. 13 and 14. To accurately evaluate the filter performance, the noise reduction rate of the MMF and the newly developed filter should be calculated numerically using (9).

C. CALCULATION OF NOISE REDUCTION RATE

The standard deviation is a statistical technique that indicates the degree of variance of a statistical group. Therefore, it is possible to quantitatively express the degree of noise reduction before and after using the filter by employing standard deviation. The time domain for obtaining the noise reduction rate is between 7200 s and 10800 s when the conduction current of the HVDC XLPE model cable is considerably stabilized. The noise reduction rate using the standard deviation is effective in the section where the conduction current is stabilized and has a constant average. The noise reduction rate of the filtered data was quantitatively calculated using (9).

As shown in Figs. 9, 10, and 11, it stabilizes after 7200 s under most conditions except for the temperature of 60 °C with an electric field of 10 kV/mm. Figures 15, 16, and 17 show the noise reduction rate of the filtered conduction current measured at conductor temperatures of 30 °C, 60 °C, and 90 °C with applied fields of 10 kV/mm, 15 kV/mm, 20 kV/mm, and 25 kV/mm. In addition, the software filters applied to the conduction current to reduce noise are the MAF, MMF, and NEW methods. As the noise reduction rate increased, the deviation and noise of the conduction current decreased. It can be observed that the noise reduction rate increases as the amount of data acquired for use in the software filter increases.

D. EVALUATION OF FILTERS

If the noise reduction rate is used, the noise of the raw data can be calculated quantitatively, and a filter optimized for the conduction current can be selected. In general, a software filter with excellent performance has a small amount of data acquired and has a high noise reduction rate.

The newly developed filter has the highest noise reduction rate with 10 data acquired by the filter at conductor temperatures of 30 °C, 60 °C, and 90 °C, as shown in Figs. 15, 16, and 17. Moreover, even if the amount of data to be acquired increases, the noise reduction rate of the newly developed filter for each measurement condition is high.

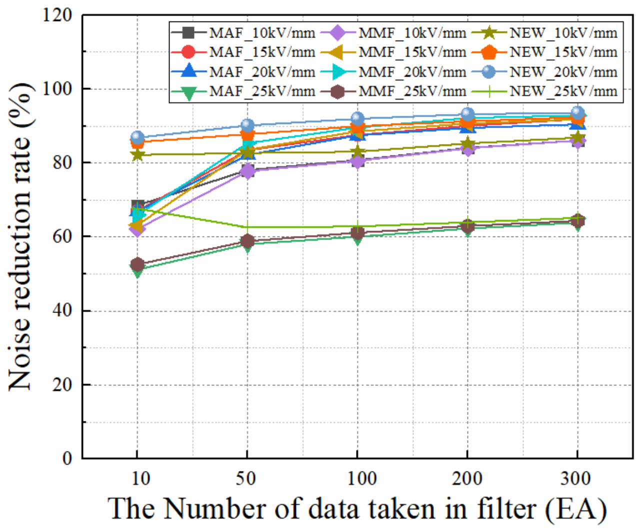

FIGURE 15. Results of the noise reduction rate of filtered conduction measured as 10, 15, 20 and 25 kV/mm at 30 °C.

Figure 16 shows that the newly developed filter with 10 data acquired at an electric field of 25 kV / mm and a conductor temperature of 60 °C has up to 26 % higher noise removal performance than MAF and MMF. Even under other conditions, the noise reduction rate of the new filter is higher than that of the MAF and MMF methods. A new

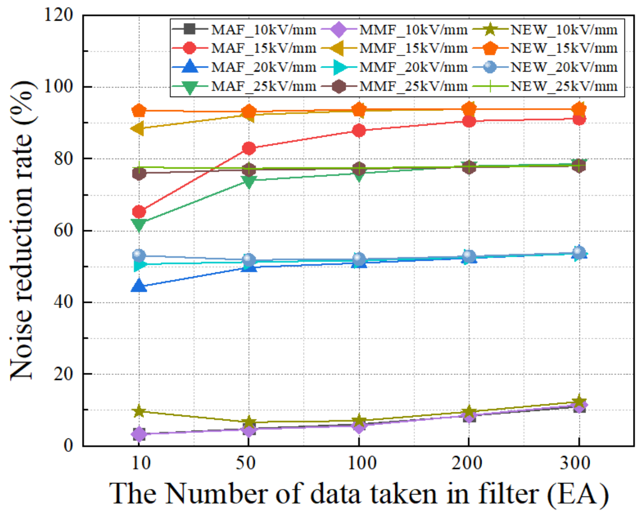

FIGURE 16. Results of the noise reduction rate of filtered conduction measured as 10, 15, 20 and 25 kV/mm at 60 °C.

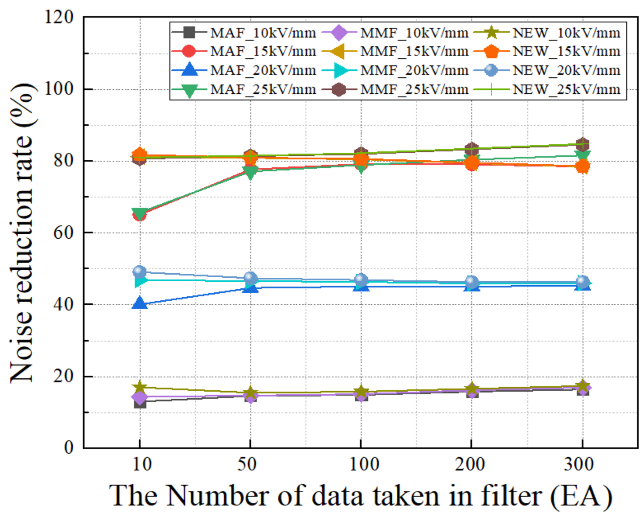

FIGURE 17. Results of the noise reduction rate of filtered conduction measured as 10, 15, 20 and 25 kV/mm at 90 °C.

filter method that statistically combines MAF and MMF is an optimized filter for the conduction current of HVDC XLPE model cables.

E. DISCUSSION

When measuring the conduction current in an HVDC power cable, noise is generated from high voltages and various causes. For the effectiveness of the measured data, a software filter is used to process the conduction current.

Previous researchers have not numerically shown the noise reduction rate before and after applying the software filter of the conduction current. In addition, to the best of our knowledge, there has been no research or mention on the selection of an optimized filter when software filters are applied to conduction currents, including noise.

TABLE 2. Noise reduction rate according to temperature and electric field with the filters that takes 10 data.

E-field (kV/mm)	Temperature (°C)	Noise reduction rate (%)		
		NEW	MAF	MMF
10	30	86	69	62
15	30	88	67	63
20	30	90	67	66
25	30	69	51	52
10	60	10	3	3
15	60	89	65	88
20	60	53	44	50
25	60	88	62	76
10	90	18	13	14
15	90	80	65	81
20	90	52	40	47
25	90	83	66	81

In this study, the conduction current of the HVDC XLPE model cable was measured at temperatures of 30 °C, 60 °C, and 90 °C with electric fields of 10 kV/mm, 15 kV/mm, 20 kV/mm, and 25 kV/mm. As shown in Figs. 15, 16, and 17, the noise reduction rate according to the number of data acquisitions 10, 50, 100, 200, and 300 is quantitatively specified by applying MAF, MMF, and newly proposed software filters to the raw data of the conduction current. We also compared the noise reduction rates between the filters applied to the conduction current to prove the reliability and excellence of the newly proposed filter. The noise reduction rate of the newly proposed filter is up to 20% higher than that of MAF and MMF at 30 °C, 20 kV/mm, and 10 data acquisitions.

There are also limitations and improvements to the new filter proposed in this study. This filter is effective for data with a large amount of data and a characteristic with a constant value. In particular, an effective performance cannot be guaranteed in the case of rapidly changing data. However, it is believed that the performance can be improved by adjusting the number of data for averaging the transient state. Therefore, it is necessary to set the optimal average in the new filter.

The temporal process, size, and shape of the conduction current are used when analyzing the aging state and diagnosing insulation in HVDC power cables. Therefore, quantitatively clarifying the noise reduction rate before and after the application of filters increases the reliability of the aging analysis in HVDC power cables. In the future, studies must be performed on aged HVDC XLPE model cables using DC conduction characteristics applied with reliable software filters.

V. CONCLUSION

In this study, we introduced the concept of noise reduction rate and evaluated the commonly used filters for the conduction current measured in HVDC power cables. In addition, we proposed a new software filter that statistically combines MAF and MMF, and then proved its performance reliability. The newly proposed filter has up to 26 % better performance in terms of noise reduction rate than MAF and MMF at a temperature of 60 °C and an electric field of 25 kV/mm.

The implications of this study are summarized as follows: First, we acquired a mathematical formula that can evaluate the performance of the software filters when measuring the conduction current in HVDC power cables. Second, the conduction current of the materials required for HVDC cable operation and design can be surely obtained using the noise reduction rate and the newly developed filter. Third, the newly proposed filter is expected to contribute to research on improving the reliability of the insulation diagnostic system for HVDC cables.

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