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Monitoring Electrical and Thermal Characteristics of HTS Cable Systems via Time-Frequency Domain Reflectometry

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***Abstract*—A HTS cable system with the 22.9 kV, 50 MVA, and 410 m length is installed and operated at 154 kV Icheon substation of Korea Electric Power Corporation (KEPCO). Unfortunately, it is a difficult task to diagnose and monitor electrical and thermal characteristics of the HTS cable system in a real-time manner. In order to protect operational failures of grid-connected HTS cable systems, this paper proposes a time-frequency domain reflectometry (TFDR) and analysis techniques, i.e., time-frequency cross-correlation and instantaneous frequency (IF) estimation. To verify the performance of the proposed method, the temperature is changed via cryogenic refrigeration system and the status of grid-connected HTS cable is monitored via TFDR in a real-time manner.**

***Index Terms*—High-temperature superconducting (HTS) cable systems, instantaneous frequency (IF), joint box, time-frequency domain reflectometry (TFDR), Wigner-Ville distribution.**

I. Introduction

HIGH temperature superconducting (HTS) cable systems require insulation performance which provides durability and reliability to operate at low temperature and high current levels [1]–[4]. If the HTS cable system fails to meet the insulation performance, it leads to quench phenomenon and massive amount of power outage in the connected grids. In particular, most of insulation failures are found at joint box and termination in case of conventional cables, and it is also expected that the most vulnerable parts of the HTS cable system will be joint box and termination. Moreover, the temperature of the HTS cable system is an important factor for electrical characteristic of insulation performance. Thus, in order to guarantee safe and reliable operation of the HTS cable system, electrical and thermal characteristics of the HTS cables insulation need to be monitored in a real-time manner.

However, after activation of cryogenic refrigeration system, the monitoring electrical and thermal characteristics can be conducted at the termination only. Furthermore, composite insulation which consists of liquid nitrogen and polypropylene laminated paper (PPLP) makes it challenging to monitor the electrical and thermal behaviors of the HTS cable system by conventional cable diagnosis methodologies such as partial discharge (PD) test in real-time manner.

In this paper, we discuss on electrical and thermal characteristics of the HTS cable system including joint and termination via time-frequency domain reflectometry (TFDR). The TFDR methodology analyzes the electrical signal in time and frequency domain, simultaneously [5]–[8]. We conduct an experiment with using the real-world HTS cable system installed in the Icheon substation located in near Seoul, Korea. As the temperature of the HTS cable system changes between 77 K and 69 K via cryogenic cooling system, we monitor reflected signals from impedance discontinuity points such as the joint box and terminations. The analysis of time-frequency characteristics of reflected signals from the joint box and termination shows the relationship between electrical and thermal properties of the HTS systems.

The structure of the paper is organized as follows: in Section II, the description of experimental setup for HTS cable system diagnostics is introduced. Also, the theoretical background of TFDR is presented. Based on the cross Wigner-Ville Distribution (XWVD), instantaneous frequency (IF) estimation method is introduced. The results of experiments are discussed in Sections III including comparison with time domain reflectometry (TDR), respectively. Finally, the paper is concluded in Section IV. Based on the time-frequency domain reflectometry, this paper presents applications of the proposed technique to real-world HTS cable systems for monitoring electrical and thermal characteristics.

II. Experimental Setup and Theoretical Background

A. Description of HTS Cable Systems and TFDR System

Fig. 1 shows the diagram of three-phase 22.9 kV/50 MVA HTS cable (2G) system which is installed at the 154 kV Icheon substation of Korea Electric Power Corporation (KEPCO) and TFDR system which monitors the electrical and thermal characteristics of HTS cable systems. The HTS cable system is connected to the secondary side of the main 154 kV/22.9 kV transformer and 23 kV switchgear. As shown in Fig. 1, 267 m of HTS cable, part-A, and 150 m of HTS cable, part-B are electrically connected by the cable joint box. During the installation of the joint box, 7 m of cable is removed, therfore,

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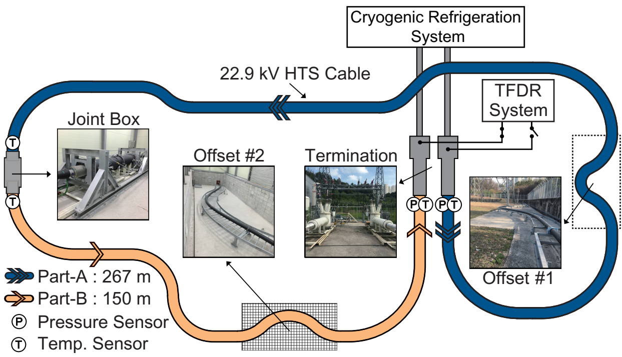

Fig. 1. The diagram of HTS cable system and the TFDR system.

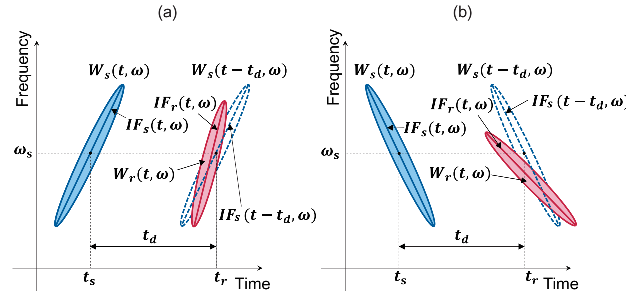

Fig. 2. Time-frequency distributions of the reference signal, time-delayed signal, and propagated signal using up-chirp signal in (a), using down-chirp signal in (b).

the total length of installed HTS cable is 410 m. Liquid nitrogen flows from the source-sided termination at part-A to the load-sided termination at part-B. Also, as shown in Fig. 1, structures of snake-shaped offset are constructed at both part-A and part-B for thermal contraction and expansion [2], [3].

The TFDR system is composed with an arbitrary waveform generator (AWG), a digital phosphor oscilloscope (DPO), and a distinctive signal processing system. The AWG generates a reference signal which is applied to the HTS cable. The DPO measures both the reference and reflected signals, and the signal processing sytem analyzes the signal via TFDR algorithm [5]–[7]. The TFDR algorithm will be discussed in Section II-*B* in detail.

In this paper, load-sided termination (part-B) is used as an input port of the TFDR system because the joint box is located closer to the load-sided termination. The spatial proximity to the joint box makes TFDR analysis easier since attenuation of the reflected signal from the joint box is less compared with the reflected signal measured at the source-sided termination.

B. Theoretical Background of TFDR

TFDR uses Gaussian enveloped chirp signal which is linearly modulated. The reference signal is written as

$$s(t) = (\frac{\alpha}{\pi})^{1/4} e^{-\alpha(t-t_0)^2/2 + j\beta(t-t_0)^2/2 + j\omega_0(t-t_0)} \quad (1)$$

where time duration and frequency sweep rate are determined with the coefficients α and β respectively. Also, t_0 is time center and ω_0 is frequency center of the reference signal.

An appropriate determination of the coefficients is essential in TFDR methodology. Length and attenuation characteristics of the HTS cable including terminations and the joint box are needed. Conventionally, high frequency signal which has high spatial resolution is used for the reference signal. However, it is not desirable to apply high frequency signal to a long-distance cable because of high attenuation characteristics. In this paper, lower frequency than previously used in [5] is selected as the reference signal which is designed with a bandwidth of 5.8 MHz, a frequency center of 3.8 MHz, and a time duration of the reference signal is set to 850 ns based on the uncertainty principle [7], [8].

In TFDR, Wigner-Ville distribution (WVD) is used to analyze the reference signal and reflected signals from points of impedance discontinuity in time-frequency domain. The WVD of the reference signal, $s(t)$, is obtained as follows:

$$W_s(t,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} s^*(t-\frac{1}{2}\tau)s(t+\frac{1}{2}\tau)e^{-j\tau\omega}d\tau. \quad (2)$$

Fig. 2 exhibits time-frequency distributions of the reference signal, $W_s(t,\omega)$, an ideally delayed signal, $W_s(t-t_d,\omega)$, and an actual propagated signal, $W_r(t,\omega)$ on time-frequency plain. In an ideal condition, the time-frequency distribution of propagated signal will be shown as time-delayed version of the distribution for the reference signal. However, structures of the HTS cable itself and accessories such as the joint box and terminations cause distortion including attenuation and dispersion of the reference signal. Therefore, as depicted in Fig. 2, distribution of the actual propagated signal, $W_r(t,\omega)$, suffers the frequency-dependent attenuation and dispersion.

For detection, localization, and characteristic analysis of the HTS cable's impedance discontinuities, TFDR methodology uses time-frequency cross-correlation between the WVD of the reference signal and the reflected signal [8]. Time-frequency cross-correlation result evaluates the similarity between the reference signal and the reflected signal notwithstanding attenuation and dispersion of the signal. In Section III-*A* and *B*, the signal propagation characteristics with the temperature change will be discussed using the result of time-frequency cross-correlation.

C. IF Estimation

IF is a typical index for time-frequency analysis of physical phenomenon such as attenuation and distortion due to frequency-dependent wave characteristics [9], [10]. In general, the WVD is one of the most effective methods to make the signal energy concentrate along the IF in time-frequency domain. Because the characteristics of superconductivity appear only when the temperature of the HTS cable is below its critical temperature, the IF of propagated signal through the HTS cable will be also dependant on the temperature of the HTS cable.

The local peak of the WVD is typically an optimal IF estimator, but the estimation is difficult when the effects of noise are increased and signal-to-noise ratio (SNR) is reduced. In this paper, in order to solve noise problems in the experiments, the XWVD proposed in [10] is used. The procedure

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of the estimation is as follows. Firstly, the distribution of the reference signal, $W_s(t,\omega)$, is obtained as the distribution which has an initial estimate of the IF. Using the initial estimate, XWVD could be calculated between the incident signal and the reflected signal. The peak of the XWVD is extracted as a new IF estimate. The XWVD calculation process between the new IF estimate and reflected signal is repeated until the difference of IF estimates from successive iterations is less than a specified amount. Finally, IF which has information of the HTS cable will be obtained. Using this IF estimation method based on XWVD, in Section III-*C*, IF analysis of the HTS cable with the temperature variation will be discussed.

III. Experimental Results and Discussion

A. Results of TDR and TFDR

TDR using a rectangular TDR step pulse is performed in order to compare the results of TFDR. As shown in Fig. 3(a), at around 1.6 μs, a rapid attenuation part due to probe accessories and structure of load-sided termination is found at the beginning, and the magnitude of voltage is gradually increasing after the joint box point at around 3.5 μs. Also, the source-sided termination of the HTS cable system is easily detected at around 5.5 μs. However, it is highly selective to localize and detect the joint box and there is no difference with change of temperature (inlet temperature of the joint box) in time domain.

Figs. 3(b) and (c) show time series of the reference signal and reflected signals of TFDR when using a up-chirp signal, and time-frequency cross-correlation values, respectively. In enlarged version of reflected signals at the joint box and the source-sided termination, chirp-shaped signals are found with the attenuation and dispersion of the reflected signal. Distortion at 300 K causes a low similarity between the reference signal and the reflected signal, and a relatively small value, 0.33, of the time-frequency cross-correlation at around 3.25 μs and 5.5 μs. Also, in the vicinity of 3.25 μs, the value, 0.69, which is calculated using the reflected signal from the joint box at 69.8 K is bigger than the value, 0.64, at 76.6 K. Inversely, large energy of reflected signal at the joint box makes small energy of transmitted signal and arrived signal at the termination, therefore, the time-frequency cross-correlation value calculated at the termination is bigger at 76.6 K.

In Fig. 4, the cause of the peak points which are located on between the joint box and the source-sided termination is illustrated. As mentioned in Section II-*A*, the HTS cable system has snake-shaped structure on part-A and part-B. The time-frequency cross-correlation values which are located at between the joint box and the source-sided termination, from 4 μs to 5 μs, indicate the reflection at offset #1 and the multiple reflection of the joint box. Because the radius of curvature; which makes the impedance change; for offset #1 is longer than that for offset #2, only the location of offset #1 is detected. As shown in Figs. 5(a) and (b), when using a down-chirp signal, similar results are found in comparison to use up-chirp signal. In this paper, the analysis of time-frequency characteristics of reflected signals from the joint box is objective and we focus on the time-frequency cross-correlation values at the joint box.

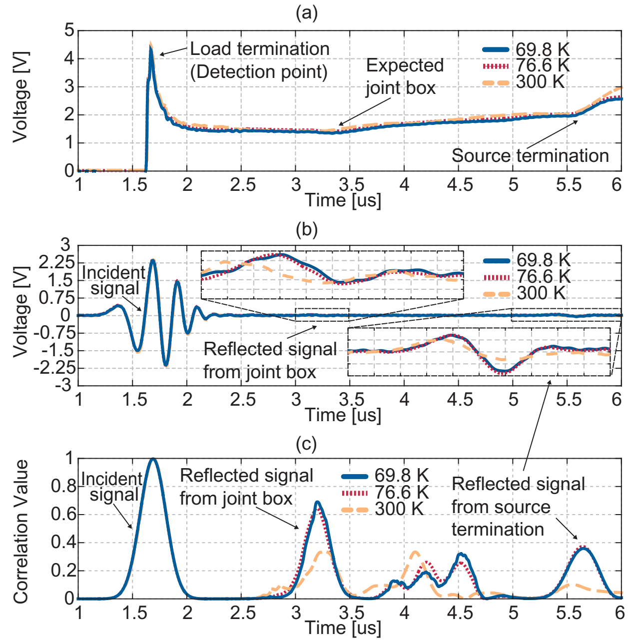

Fig. 3. TDR for the detection and localization in (a), time series of the reference and reflected signals in (b), and time-frequency cross-correlation in (c) using up-chirp signal.

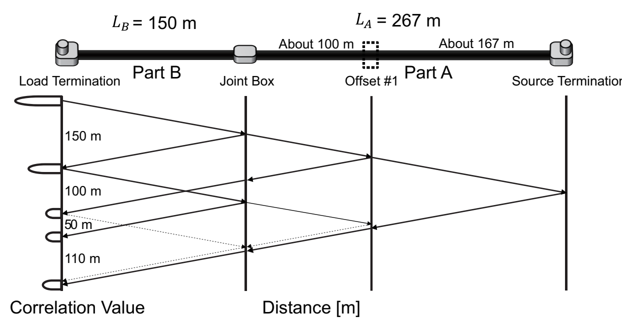

Fig. 4. Lattice diagram for the HTS cable system in Icheon substation.

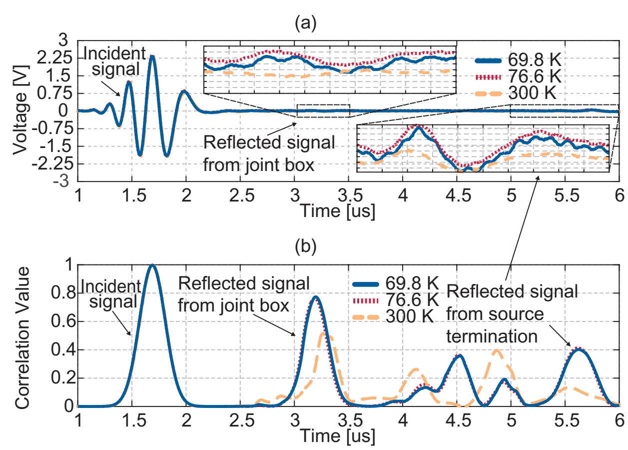

Fig. 5. Time series of the reference and reflected signals in (a), and time-frequency cross-correlation in (b) using down-chirp signal.

B. Monitoring Time-frequency Cross-correlation Result and Discussion

To analyze changes of property for the reflected signals at the joint box with the change of temperature, we control the

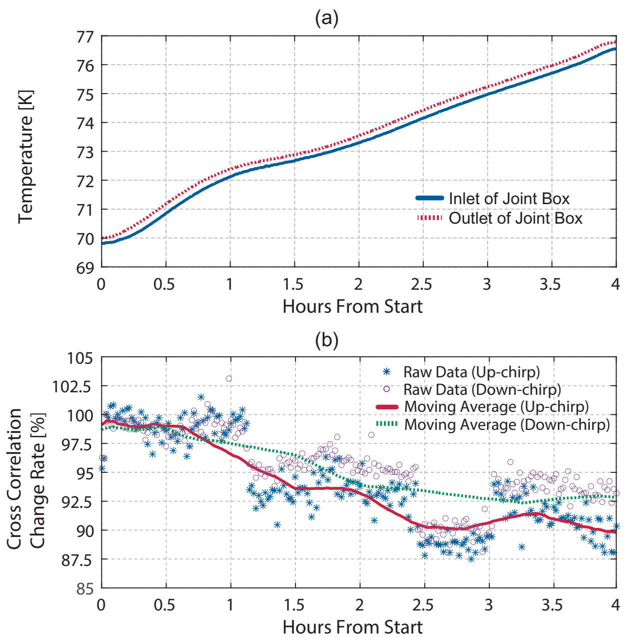

Fig. 6. Increasing temperature profile in (a) and time-frequency cross-correlation change rate in (b).

inlet temperature of the HTS cable from 69 K to 77 K via cryogenic refrigeration system. Fig. 6 shows the monitoring results of the time-frequency cross-correlation change rate with the increase of temperature. The data using up-chirp and down-chirp signals are collected every minute and the results show that the time-frequency cross-correlation of both up-chirp signal and down-chirp signal decrease to 90 % and 92.5 %, respectively with little fluctuation.

Owing to the limited space, we did not include results with the decrease of temperature, but the results show that the time-frequency cross-correlation of both up-chirp signal and down-chirp signal increase. Thus, we can conclude that the change rate is inversely proportional to the the sign of temperature change. In second and third rows of Table I, the time-frequency cross-correlation values are summarized. At normal operation temperature, from 69 K to 77 K, a small amount of the IF value is decreasing with the increase of the temperature, but there is a significant change at abnormally high temperature, 300 K. The results of the time-frequency cross-correlation show that the insulation property has influence on the value of the time-frequency cross-correlation [5]. The insulation temperature affects the insulation characteristics of HTS cable and the impedance discontinuity points. In the next subsection, the results of IF estimation which is also affected by the insulation temperature will be discussed.

C. IF Analysis and Comparison with Time-frequency Cross-correlation Result

The forth and fifth rows of Table I summarize the results of IF estimation when using up-chirp and down-chirp signals. The slopes of the reference signal's IF which are used as an initial estimate are ± 6.61 THz/s. Because, as illustrated in Fig. 2, the high frequency component has fast velocity and high

TABLE I
IF ESTIMATION AND TIME-FREQUENCY CROSS-CORRELATION RESULTS

Temperature [K]	ref.	69.8	76.6	300
Correlation Value (Up-chirp)	1	0.69	0.64	0.33
Correlation Value (Down-chirp)	1	0.77	0.76	0.51
Slope of IF (Up-chirp) [THz/s]	6.61	11.7	11.9	∞
Slope of IF (Down-chirp) [THz/s]	-6.61	-5.50	-5.47	-4.06

attenuation, the IF slopes of reflected signals at the joint box are increasing; the absolute value of positive slope increases to infinity and that of negative slope decreases to 4.06 THz/s. Similarly with the time-frequency cross-correlation, results of IF have no significant change at normal operation cooling temperature, but there are significant changes at the room temperature. For up-chirp signal at the room temperature, the signal which is propagated and reflected at the joint box is significantly distorted to estimate IF. Because, at the room temperature, the insulation property is worsen after being filled with nitrogen gas, it has a lower relative permittivity. The change of the insulation property which is affected by temperature can be monitored by the variation in both time-frequency cross-correlation and the slope of IF.

IV. CONCLUSION

In this paper, a diagnostic technique to monitor of insulation failure and malfunction of cryogenic refrigeration system for HTS cable is proposed. To monitor the HTS cable system, TFDR and IF estimation methods via XWVD are used. This proposed technique is applied to the HTS cable with the specification of 22.9 kV, 50 MVA, and 410 m lengths at the 154 kV Icheon substation of the KEPCO power grid. The results of monitoring show that the proposed technique allows us to detect the change of insulation characteristics of HTS cable systems as temperature changes.

This proposed technique allow us to check the status of cryogenic operation for real-world HTS power systems in real-time manner. In future work, during the cooling time, from 300 K to 76 K, which is not covered in this paper, TFDR will be applied to HTS cable systems to monitor and assess the condition of HTS cable systems. For the commercialization of the long-distance and massive electric HTS cable systems, diagnostic technique is essential. It is expected that time-frequency analysis of the HTS cable with temperature changes will propose the technical solutions to check the status of stable operation for grid-connected HTS cable systems in real-time manner.

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