

# Detection of Local Temperature Change on HTS Cables via Time-Frequency Domain Reflectometry

**Su Sik Bang<sup>1</sup>, Geon Seok Lee<sup>1</sup>, Gu-Young Kwon<sup>1</sup>, Yeong Ho Lee<sup>1</sup>,  
Gyeong Hwan Ji<sup>1</sup>, Songho Sohn<sup>2</sup>, Kijun Park<sup>2</sup> and Yong-June Shin<sup>1</sup>**

<sup>1</sup> School of Electrical and Electronic Engineering, Yonsei University, Seoul, 03722, Korea

<sup>2</sup> Korea Electric Power Corporation Research Institute, Daejeon, 34056, Korea

E-mail: [yongjune@yonsei.ac.kr](mailto:yongjune@yonsei.ac.kr)

**Abstract.** High temperature superconducting (HTS) cables are drawing attention as transmission and distribution cables in future grid, and related researches on HTS cables have been conducted actively. As HTS cables have come to the demonstration stage, failures of cooling systems inducing quench phenomenon of the HTS cables have become significant. Several diagnosis of the HTS cables have been developed but there are still some limitations of the experimental setup. In this paper, a non-destructive diagnostic technique for the detection of the local temperature change point is proposed. Also, a simulation model of HTS cables with a local temperature change point is suggested to verify the proposed diagnosis. The performance of the diagnosis is checked by comparative analysis between the proposed simulation results and experiment results of a real-world HTS cable. It is expected that the suggested simulation model and diagnosis will contribute to the commercialization of HTS cables in the power grid.

## 1. Introduction

High temperature superconducting (HTS) cables, which are expected as transmission and distribution cables in future power grid, are capable of high density power transmission with low loss and small dimension compared to conventional cables. Therefore, research of HTS cables and verification test are actively under-way to utilize the HTS cables to the power grid [1-3]. Especially, the reliability of cooling systems are significant to HTS systems because a failure of the system leads to quench phenomenon which can seriously impact on stability of the power grid. In order to prevent extreme accidents caused by the quench, diagnosis and protection techniques for HTS cables have been developed [4, 5]; however, it is difficult to reflect various types of defects in verification test of the techniques.

Modeling and simulations of HTS cables have been conducted in several ways to research in power grid [6-8]. Yet, the conventional simulations are not suitable for electrical signals with the high frequency range. In order to research the diagnostic technologies by simulation, the model of HTS cables should consider the frequency characteristic of the cables [9]. In addition, it is necessary to reflect thermal characteristic of HTS cables in the simulation model.

In this paper, a novel simulation model of a local temperature change on HTS cables is proposed to simulate various types of quench situation. The simulation model reflects thermal and frequency characteristics of HTS cables which influence accuracy of the simulation. Also, a non-destructive diagnostics applying time-frequency domain reflectometry (TFDR) [10] is proposed to detect a local temperature change point. TFDR simulation using the proposed model is explained in Section 3. In



Section 4, TFDR is applied to an experimental setup with a real-world HTS cable and the results are analyzed. Finally, conclusion is presented in Section 5.

## 2. Time-frequency domain reflectometry

An incident signal of TFDR is the Gaussian enveloped chirp signal which is designed on both time and frequency domain while incident signals of time domain reflectometry (TDR) and frequency domain reflectometry (FDR) are designed only on time or frequency domain. The Gaussian enveloped chirp signal is represented as:

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

where  $\alpha$  is a coefficient determining the time duration,  $\beta$  determines the sweep rate of frequency,  $t_0$  is center time and  $\omega_0$  is center frequency [10]. The propagation characteristic of a signal depends on structures of a cable and frequency range of the signal. Therefore, an optimal incident signal of TFDR can be designed by customizing the parameters of the Gaussian envelope chirp signal which consider characteristics of the target cable. The incident signal propagating on the cable is reflected at impedance discontinuities which have potential for defects. Thus, it is possible to detect the defects by measuring and analyzing the reflected signal.

In order to analyze a time signal  $s(t)$  on time-frequency domain, TFDR considers the Wigner-Ville distribution (WVD) represented by:

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

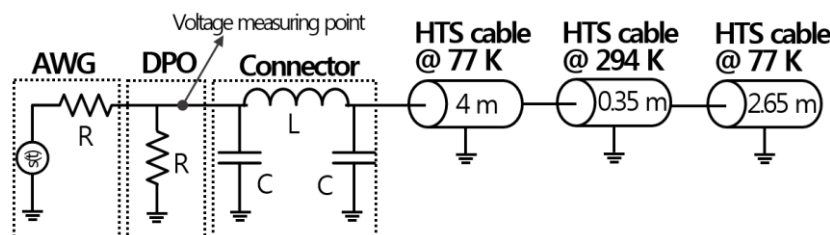
Denote the WVD of the incident signal and the reflected signal as  $W_s(t, \omega)$  and  $W_r(t, \omega)$  respectively. Then a time-frequency cross-correlation function  $C_{sr}(t)$  is evaluated as follows:

$$C_{sr}(t) = \frac{\iint_{T_s} W_s(t', \omega) W_r(t' - t, \omega) d\omega dt'}{\iint_{T_s} W_s(t', \omega) d\omega dt' \iint_{T_s} W_r(t' - t, \omega) d\omega dt'} \quad (3)$$

where  $T_s$  is the time duration of the incident signal. Values of the time-frequency cross-correlation function are bounded between 0 and 1 because the function is normalized by each energy of WVDs of the incident and reflected signals [10]. The results of the function represent the similarity between the incident signal and the reflected signal. Therefore, TFDR detects the faults through the evaluation of the time-frequency cross-correlation function results.

## 3. Simulation

In this paper, a simulation model of a HTS cable which considers the dielectric loss tangent and high frequency range is used to apply reflectometries on HTS cables suffering a local temperature change. The electrical impedances of HTS cables under ambient and superconductive condition are different. The parameters of the simulation model, permittivity, permeability, and dielectric loss tangent are obtained by analysis of scattering parameter (S-parameter) under ambient and superconductive conditions [9]. Figure 1 shows the reflectometry simulation model for a local temperature change on a



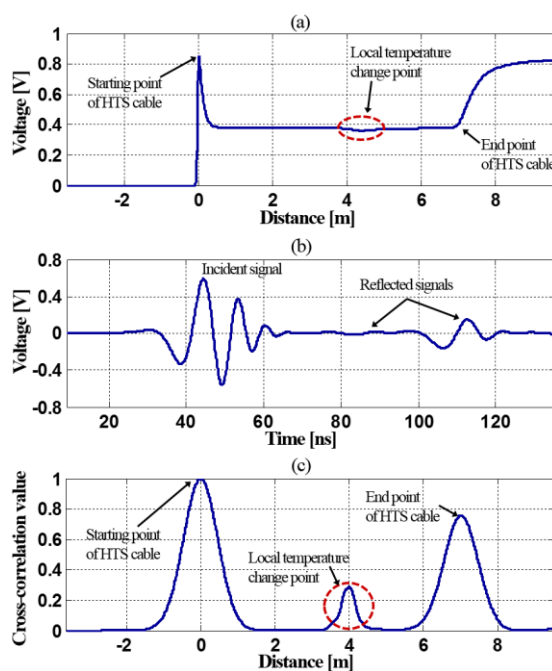
**Figure 1.** Reflectometry simulation model for a local temperature change on a HTS cable

**Table 1.** Parameters in reflectometry simulation model

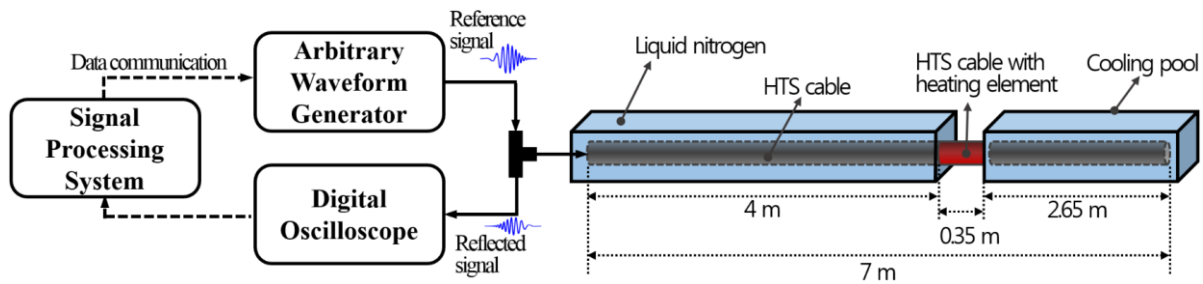
Parameter	Value	Unit
Inductance L in connector	43.6	nH
Capacitance C in connector	6.4	pF
Resistance R in AWG and DPO	50	ohm
Radius of inner conductor of HTS cable	10	mm
Inner radius of outer conductor of HTS cable	18	mm
Outer radius of outer conductor of HTS cable	19	mm
Conductivity of conductor of HTS cable	$6.3 \times 10^7$	S/m
Relative permeability of dielectric of HTS cable	0.69	-
Relative permittivity of dielectric of HTS cable	at 294 K	2.7
	at 77 K	2.664
Dielectric loss tangent of HTS cable	at 294 K	0.07
	at 77 K	0.0424

HTS cable. The HTS cable with 7 m of the total length is under superconductive condition without a local region from 4 m to 4.35 m. The length of the local region is determined by 5% of the total length of the HTS cable. In order to conduct accurate simulations of a local temperature change, the parameters of HTS cables as internal temperature are required. However, it is hard to obtain the accurate parameters on internal temperatures excluding room temperature and liquid nitrogen temperature because of limits in control and measurement for internal temperature without damage to the cable. Therefore, temperature of 294 K, which is room temperature, as a local temperature change is set in the simulation. In addition, the simulation model reflects the influences of the arbitrary waveform generator (AWG), digital phosphor oscilloscope (DPO), and connector to obtain the simulation results similar to actual experimental results. Each of the parameters referred by [9] in Figure 1 is shown in the Table 1.

In order to compare the performance of TFDR for detection of the local temperature change point, additionally TDR is conducted in this paper. Step signal and Gaussian enveloped chirp signal with center frequency of 90 MHz, bandwidth of 160 MHz and time duration of 30 ns are used as the incident signals of TDR and TFDR respectively. The plus and minus of the incident signal are applied to conductor and shield layer of the HTS cables respectively. The incident signal of TFDR is designed by considering



**Figure 2.** The simulation results; (a) TDR, (b) TFDR measured signal, (c) The values of time-frequency cross-correlation of TFDR

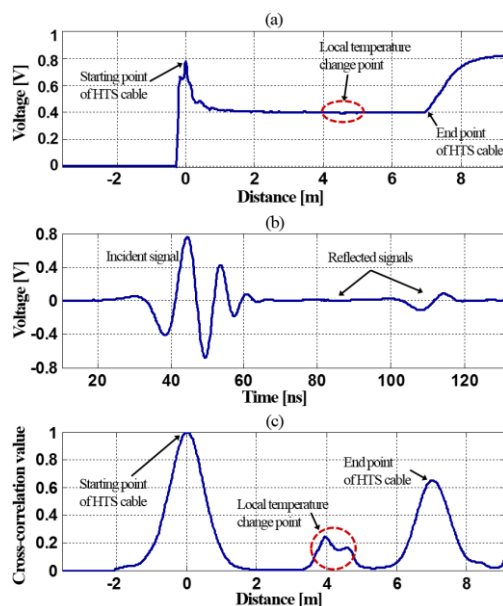


**Figure 3.** Experimental setup for reflectometries applying to real-world HTS cables with a local temperature change point.

structures of the HTS cable and the uncertainty principle [5]. The results of the TDR and TFDR simulations are represented in Figure 2. Figure 2(a) and (b) are the measured signals at DPO in Figure 1 using the step signal and the Gaussian envelope chirp signal respectively as incident signal. Also, the result of time-frequency cross-correlation calculated by (2) and (3) is shown in Figure 2(c). Both TDR and TFDR clearly detect the end point of HTS cable because of a large impedance discontinuity. However, although the local temperature change point can be classified finely in TDR result as represented in Figure 2(a), exact location of the local point is clearly distinguished only by the result of the time-frequency cross-correlation as shown in Figure 2(c). The distance value of peak included in red dotted line in Figure 2(c) perfectly matches the position of the local temperature change, 4 m without error, in the simulation model. In TDR result, it will be difficult to detect the local temperature change point if a noise is added in the measured TDR data. The noise analysis in TDR and TFDR will be discussed in the next section.

#### 4. Applying to real-world HTS cable

In order to verify simulation results of TDR and TFDR for detection of a local temperature change on HTS cables, TDR and TFDR apply to a real-world HTS cable as shown in Figure 3. A 7 m single-phase 22.9 kV/50 MVA HTS cable (1G) is used. The HTS cable is cooled with liquid nitrogen in cooling pools without a local region from 4 m to 4.35 m to conduct the experiment under same condition of the simulation in Section 3. The heating element is also installed on the HTS cable sheath of the local region separated with the cooling pools to maintain the temperature of the local region.



**Figure 4.** The experiment results; (a) TDR, (b) TFDR measured signal, (c) The values of time-frequency cross-correlation of TFDR

The incident signals used in the simulation is applied to the setup of real-world HTS cable. The experiment results are represented in Figure 4. The end point of the HTS cable is both detected by TDR and TFDR, but only the time-frequency cross-correlation of TFDR as shown in Figure 4(c) can display the local temperature change point similarly to the simulation result as shown in Figure 2.

The reason of the peak at starting point of HTS cable as shown in Figure 2(a) and Figure 4(a) is the connection accessories between the devices and the HTS cable. Reflectometry accessories and devices generate noise signals in the experiment. Therefore, the peak shape in the TDR experiment result as shown in Figure 4(a) is noisy unlike the TDR simulation result as represented in Figure 2(a). In addition, in measured results of TDR and TFDR as shown in Figure 4(a) and (b), it is hard to distinguish the local temperature change point from the noise. On the other hand, as shown in Figure 4(c), the result of time-frequency cross-correlation calculated by (2) and (3) using the data of Figure 4(b) clearly detects the local temperature change point. The distance value of peak included in red dotted line in Figure 4(c) is 3.934 m which corresponds to 1.65% of error rate of detection accuracy.

The time-frequency cross-correlation value of the end point of HTS cable in the experiment is smaller than that in the simulation because of the noise and attenuation from the connection accessories. Also, the shape of the graph at the local temperature change point in Figure 4(c) is distorted. It is possible to produce two peaks at the local temperature change because the reflected signal generated by the temperature change is distorted by the noise. However, this paper verifies that TFDR can detect the local temperature change point where TDR cannot distinguish from the noise in the real-world HTS cable.

## 5. Conclusion

In this paper, a non-destructive diagnostic technology, TFDR, is introduced for detection of local temperature change points on HTS cables. A simulation model of HTS cable with a local temperature change is proposed and the simulation considers the characteristics of electrical wave propagation and the effects of devices, AWG, DPO and connector. TFDR for detection of local temperature change points on HTS cables is examined by the simulation results. In addition, the performance of TFDR is verified using experimental setup of a real-world HTS cable which is similar to the simulation. The resolution and compatibility of TFDR for distinction of the local temperature change region is confirmed by comparative analysis with TDR. In this paper, the room temperature is considered as a local temperature change. If a lower the temperature change occurs, a lower reflected signal is generated. In theory, a low magnitude of reflected signal has not an effect on the performance of the proposed technique because the time-frequency cross-correlation function is normalized by each energy of WVDs of the incident and reflected signals as represented in equation (3). However, in order to apply for a low temperature changes on real-world HTS cable systems, other techniques such as noise filtering and compensation filter will be required to measure the low magnitude of reflected signal because of severe noise and distortion of reflected signal in the field. By utilizing the proposed simulation model, numerous kinds of failure as well as local temperature change on HTS cables, which is hard to emulate in real-world test-bed, are able to be simulated. It is expected that the analysis of the simulation results will improve the proposed diagnostics and the proposed technique will contribute to prevent accidents by quench in HTS cables in future power grid.

## Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT & Future Planning, #NRF-2017R1A2A1A05001022. Also, this research was supported by Korea Electric Power Corporation Research Institute.

## References

- [1] Sohn S H, Hwang S D, Lim J H, Yim S W, Hyun O B, Kim H R, Yatsuka K, Isojima S, Watanabe M, Ryoo H S, Yang H S and Kim D L 2007 *Physica C* **463-5** 1146-49
- [2] Sohn S H, Lim J H, Yang B M, Lee S K, Jang H M, Kim Y H, Yang H S, Kim D L, Kim H R, Yim S W, Won Y J and Hwang S D 2010 *Physica C* **470** 1567-71

- [3] Lim J H, Sohn S H, Yang H S, Hwang S D, Kim D L, Ryoo H S and Choi H O 2010 *Physica C* **470** 1597-600
- [4] Lee G S, Kwon G -Y, Chang S J, Lee C -K, Bang S S, Lee Y H, Park J B and Shin Y -J 2015 *Proc. Int. Conf. on Insulated Power Cables (Versilles, France)* C 7-4
- [5] Lee G S, Kwon G -Y, Bang S S, Lee Y H, Chang S J, Sohn S H, Park K and Shin Y -J 2016 *IEEE Trans. Appl. Supercond.* **26** 5401005
- [6] Kim J G, Kim A -R, Kim D, Park M, Yu I -K, Cho J, Sim K -D, Kim S, Lee J K and Won Y -J 2010 *IEEE Trans. Appl. Supercond.* **20** 1284-87
- [7] Del-Rosario-Calaf G, Lloberas-Valls J, Sumper A, Granados X and Villafafila-Robles R 2013 *IEEE Trans. Appl. Supercond.* **23** 5401204
- [8] Li J, Zhao Z, Shu B, Han X, Ma X, Bian B, Liang Z, Li J and Jiang W 2014 *IEEE Trans. Appl. Supercond.* **24** 4803205
- [9] Bang S S, Lee G S, Kwon G Y, Lee Y H, Chang S J, Lee C -K, Sohn S H, Park K and Shin Y -J 2016 *Physica C* **530** 142-6
- [10] Shin Y -J, Powers E -J, Choe T -S, Hong C -Y, Song E -S, Yook J -G and Park J B 2005 *IEEE Trans. Instrum. Meas.* **54** 2493-500