Impact of Smart HTS Transmission Cable to Protection Systems of the Power Grid in South Korea

Eun Young Ko, Seung Ryul Lee, Sangsoo Seo, and Jeonwook Cho

***Abstract*—In South Korea, Korea Electrotechnology Research Institute (KERI) has developed a 154 kV smart High Temperature Superconducting (HTS) cable system with fault current limiting function since May 2017. This project is funded by the Ministry of Trade, Industry, and Energy of Republic of Korea. It is very important to design the protective relay system for a successful application of the smart HTS cable system to a practical power grid. In general, the smart HTS cable can have a negative impact on the protective coordination in power transmission system because of the variable impedance of the cable. This paper reviews some protection problems which can be caused by the application of the 154 kV smart HTS cable to power transmission systems in Korea and proposes a protection scheme for a test power system. And then we conduct a basic study to find solutions for the problems using an electromagnetic transient program, PSCAD/EMTDC.**

***Index Terms*—Current differential relay, distance relay, HTS, protection coordination, PSCAD.**

I. Introduction

With the development of science and technology and population growth, it is expected that the expansion of the power system and the high density of the load will accelerate worldwide.

The High Temperature Superconductivity (HTS) cables, using superconductors with high critical temperature, and the superconducting fault current limiter have been spotlighted to respond to the changing power system characteristics. The HTS cable minimizes the power loss and makes it easy to transmit the large-capacity power.

And with this trend, researches on the HTS cable and the current limiter are being actively studied around the world.

Studies on the HTS cable in U.S. include AEP project with the demonstration in substation [1], [2], Albany project with the HTS cable parallel operation in part of section [1], [3], Hydra project with the demonstration of connection between substations [4], [5], LIPA project [1], [6] and ComEd project [7], [8]. In addition, there are Yokohama project in Japan [9] and Ampacity project in German [10]. The HTS cable with current limiting in the ComEd project is the same as "the smart HTS cable" in this paper.

Studies on the SFCL include in U.S. AVANTI project [11] and Applied Materials, Inc. project [12]. And in Europe there are boxburg project in Germany which is the first case of applying SFCL to power plant [13], A2A/RSE project in Italy and ECCOFLOW project in Slovakia and Spain [14].

Studies on HTS power devices have been carried out in Korea as well.

The Jeju project in Korea is the first demonstration of applying DC 80 kV and AC 154 kV HTS cable to the real system. In 2011, this project was started to connect and operate DC 80 kV/250 MW, 500 m and AC 154 kV/600 MVA, 1 km superconducting power cables for transmission at the Hanlim C/S-Geumak C/S section in Jeju Island. The Jeju project was completed in 2016, and Korea Electrotechnology Research Institute (KERI) studied the impact of HTS cable on the power system in this project [15].

In 2001∼2003, As part of the 21st century frontier business of Ministry of Education, Science and Technology, 22.9 kV/50 MVA, 30 m 3-phase HTS cable was developed in the Green superconducting Electric power Network in the Icheon substation (GENI) project managed by KERI. This project acquired long-term operating performance over 10,000 hours utilizing the developed technology of the HTS cable. GENI project installed 22.9 kV/50 MVA, 410 m HTS cable for power distribution at Icheon substation in 2010 and operated the real power system from August 2011 [16].

Based on studies of the HTS cable demonstration, this paper suggests the smart HTS cable to solve the system problems more efficiently than the HTS cable. It is a functional superconducting cable combined with the HTS cable and the fault current limiter, and it can satisfy both of the large capacity power transmission and the fault current limiting. The fault current limiting HTS cable is called the smart HTS cable in this study.

Therefore as a part of a study on the application of smart HTS cable at the real power system, this paper examined the impact of the smart HTS cable in the protection coordination system by modeling the simple test system which is applying the smart HTS cable and making the fault for each line location.

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II. Characteristics of the Smart HTS Cable

The smart HTS cable, designed to generate a current limit impedance on the existing HTS cable structure, is a hybrid type smart electric power equipment that can perform both large capacity power transmission of HTS and fault current limiting. The smart HTS cable provides the necessary current limit impedance required by the power system as generating the constant current limit impedance per unit length and regulating the installation length on the basis the intermediate connection box. And it greatly improves the flexibility of the power system operating because the bus connection operation is possible instead of the power system plan accompanying the system stability degradation as like bus disconnection or line opening.

In South Korea, KERI is conducting a development project of the smart HTS cable and this project aims to develop smart HTS cable with the function of fault current limit making the fault current of 154 kV transmission system to lower than the rated capacity of 154 kV circuit breaker.

III. Impact of Smart HTS Cable to Protective Coordination on 154 kV Transmission Line in South Korea

A. Protection Scheme of 154 kV Transmission Line in South Korea

In South Korea, as the protection scheme of transmission line, the differential current relay is used for main protection and the distance relay is used for back up protection. Some of 154 kV lines use the directional overcurrent or the overcurrent relay system.

The current differential relay decides the line fault of inside or outside by comparing the current magnitude and direction on the both ends of line. The distance relay decides the fault location by calculating the impedance from the distance relay to fault point [17].

B. Impact of Smart HTS Cable on Protection System

If a fault occurs in the power system with the smart HTS cable, the smart HTS cable will be quenched. In this case, the current differential relay has a low impact on detecting the fault of relay even if the line impedance is changed because the current differential relay compares the vector value of the current on both ends of the line. But as distance relay setting considers the quench resistance of the smart HTS cable, the relay has a negative impact on detecting and determining a the fault of line. Therefore the impedance change of the quenched smart HTS cable should be considered in case of distance relay setting.

IV. Design of Smart HTS Cable Protection System

A. Transmission Protection Scheme in Outline With Smart HTS Cable

This paper suggests to protect a smart HTS cable by current differential relay as a main protection and distance relay as backup protection according to the general 154 kV transmission protection scheme in South Korea. And the thermal protection is suggested which is one of the smart HTS cable protection scheme. This is necessary to separate the smart HTS cable from the system for minimum time and frequency by calculating the energy margin.

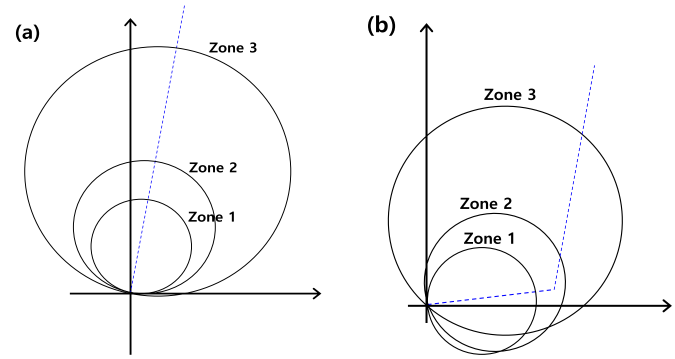

Fig. 1. (a) The case of Mho type characteristic: Application characteristic of only existing line impedance (b) The case of Mho type characteristic: Application characteristic of HTS cable impedance with existing line.

B. Relay Setting on Protection System With Smart HTS Cable

The characteristic of distance relay used the quadrilateral type component.

The smart HTS cable and general lines are completely different in the line characteristics depended on a line impedance. In the case of applying the mho type, the relay setting is difficult and complex because it is restrictive to setting the zone area of relay considered the characteristics of two different lines as shown in Fig. 1. Without the smart HTS cable, it is possible to apply the mho type to the characteristic of relay.

If the quadrilateral component is applied as the characteristic of relay, it has a disadvantage in term of the fault resistance protection. The fault resistance excesses the base value of the fault resistance that the relay can check because of the quench resistance of superconducting cable caused by a fault, and finally the system can not determine the fault. However it can be compensated by calculating the fault resistance considering the quench resistance when the relay is set.

In addition, when set the relay setting it is appropriate to use the line impedance angle of next line (existing line) as the line impedance angle of relay setting for satisfying both impedance characteristics of the smart HTS cable and next line as shown in Fig. 2.

C. Necessity of Smart HTS Cable Protection

In the worst case such as a large fault current flows for a long time and exceeds a thermal limit of the smart HTS cable, the smart HTS cable may be necessary to be disconnected from the system. The existing line does not have a big problem even when a large current (50 kA, 100 cycle) flows thus it does not have to be disconnected from the system.

However the smart HTS cable which is slightly different depending on design value is influenced by a large current, so it is

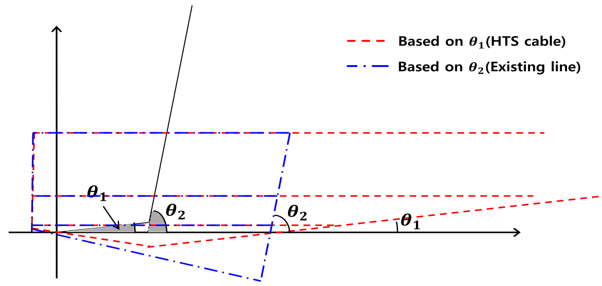

Fig. 2. The quadrilateral characteristic of relay based on line impedance angle: line impedance angle of both HTS cable and existing line.

necessary to disconnecting operation for smart HTS cable. And a problem with lines other than the smart HTS cable may cause the smart HTS cable to be disconnected from the system.

It is possible to operate without disconnecting operation from the system on case by case, of course, since all of fault current are not close to 50 kA and all of generated fault heat energy are not large. Thus the smart HTS cable could be disconnected (opened) from the system and operated, but it is important to minimize that the frequency and time of disconnection (open) for the reliability and stability of the system.

D. *Suggestion of Applying Thermal Protection*

As a remedy for the above, there is the thermal protection which is protecting smart HTS cable itself and aiming to minimize disconnecting the smart HTS cable from the system. The thermal protection previously predicts the generated energy resulted from a fault and protects the system as well as the smart HTS cable. For those reasons this paper suggests to apply the thermal protection to power system.

Examples of applying thermal protection for protecting the HTS cable are the LIPA project in New York, U.S. and Icheon project of GENI in South Korea. These projects used the way to calculate the energy margin of the HTS cable for each fault cases and apply the algorithm with on-off the HTS cable.

Based on these examples for application of the thermal protection, the algorithm of calculating the energy by a fault current and a duration time taking a fault to eliminate on the line is required. Therefore this paper proposed the basic concept algorithm of system operation to minimize line disconnection from system for protection of the smart HTS cable and the system as shown in Fig. 3.

The energy margin calculation process of thermal protection is shown in Fig. 3. When a single phase current is more than 4 kA, the timer starts and the fault current and the fault duration time are measured. If the measured fault current is greater than the standard current, the line state is lockout for a set time depending on the fault current size. And if the measured fault current is smaller than the standard current, the energy margin is calculated with the measured fault current and duration time. If the calculated energy is greater than the standard energy, the line state is lockout until the energy decreased enough.

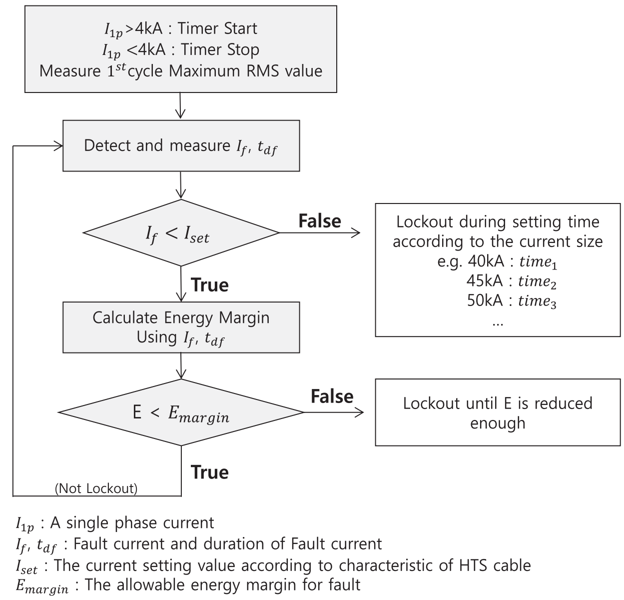

Fig. 3. The basic thermal protection algorithm of smart HTS cable.

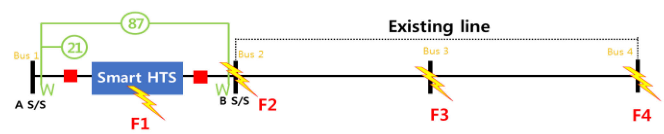

Fig. 4. Fault locations in the test system model: F1-F4.

V. Examination for Protection System Simulation

A. *Composition of Test System and Setting of Relay*

With reference to the preceded studies, the 154 kV test system applying the smart HTS cable was simply comprised using PSCAD/EMTDC which is an electromagnetic transient simulation program. The smart HTS cable and existing lines consist of pi circuit model. The modeling of smart HTS cable used in this paper is the addition of the current limiting function [16] to the modeling of the HTS cable [15]. The length of smart HTS cable is the same as the length of existing line per section between buses and it was assumed 7 km.

The smart HTS cable was protected by the current differential relay as a main protection and the distance relay as a back-up protection as shown in Fig. 4. In Fig. 4, ⑧⑦ means the current differential relay and ㉑ means the distance relay.

Only the current differential relay and the distance relay were applied in this simulation among suggested protection scheme contents so as to apply a general protection relay. Because the standard value is necessary based on the spec of designed cable to calculating the energy margin needed in thermal protection. But since the smart HTS cable and the thermal protection system are still in development, it is impossible to apply the thermal protection scheme which is required a detailed characteristic of the smart HTS cable.

TABLE I
THE RESULTS OF SIMULATION OF EACH CASE

Relay type	Fault type	Fault location F1	F2	F3	F4
87 Current differential relay	Single line to ground	Operate	-	-	-
	Three-phase short circuit	Operate	-	-	-
21 Distance relay	Single line to ground	Operate (Zone 1)	Operate (Zone 2)	Operate (Zone 3)	-
	Three-phase short circuit	Operate (Zone 1)	Operate (Zone 2)	Operate (Zone 3)	-

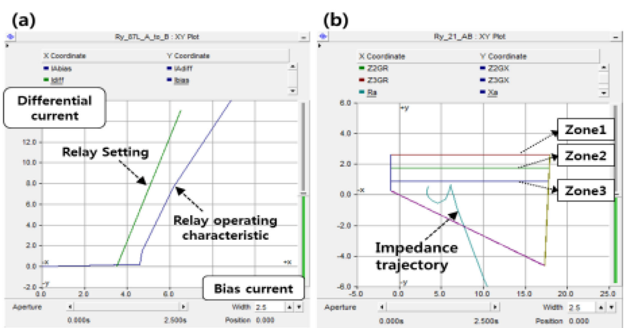

Fig. 5. In case of single line to ground fault, the operation characteristic graph of relay when the fault occurred at F1: (a) current differential relay (b) distance relay.

As described above, the line impedance angle of existing line was applied as a line impedance angle on the distance relay setting and the characteristic of distance relay used the quadrilateral characteristic.

In this simulation a single line to ground fault and a short circuit fault would occurred from F1 to F4. The location of F1 is the middle of smart HTS cable and other fault locations are on each bus.

B. Results of Simulation

This paper supposed the single line ground fault and three-phase short circuit fault by location of line, then set the protection relay considering smart HTS cable and reviewed the operation of the relay.

The results of simulation are as shown in Table I. In Table I, when the internal fault of smart HTS cable was occurred (F1), the current differential relay and the distance relay operated.

When the external fault of smart HTS cable was occurred (F2∼F4), the current differential relay did not operate because it works on internal fault by distinguishing internal fault and external fault. In cases of F2 and F3, the distance relay operated in zone2 and zone3 respectively and it did not operate on F4 which is none-protection area of the distance relay.

Fig. 5 and Fig. 6 which are examples of simulation results show the fault detection of both the current differential relay and the distance relay in a single line fault and three-phase short circuit fault respectively.

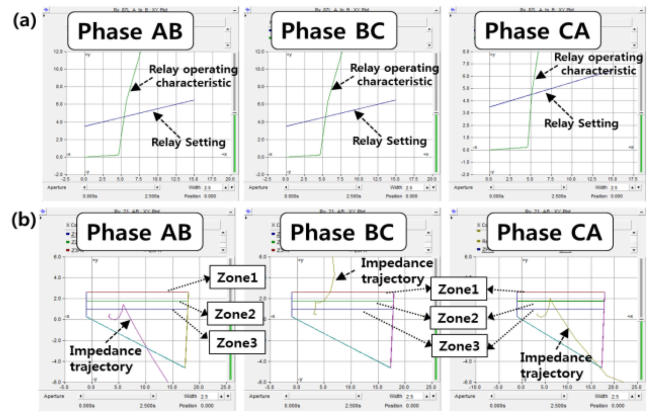

Fig. 6. In case of three-phase short circuit fault, the operation characteristic graph of relay when the fault occurred at F1.: (a) ∼ (c) current differential relay, (d) ∼ (f) distance relay.

As a result of the relay setting based on the impedance characteristics of existing line, relays worked normally for each fault location though the line characteristics of smart HTS cable differed from the existing line's. Therefore it would not be necessary to change the setting value of relays separately on the existing system.

VI. CONCLUSION

To minimize the disconnection operation of line on the real system that applying the smart HTS cable, this paper proposed the basic thermal protection concept and the algorithm. The thermal protection was not used in this simulation since it is still in development, but in future it is possible to apply on the real system if the smart HTS cable are designed. Since a protection system with the thermal protection will be needed so as to efficiently apply the smart HTS cable on the real system, the advanced researches of the thermal protection is necessary.

We modeled the test system applying the smart HTS cable and reviewed the relay operations after generating faults by type. As results of simulation which are setting the relays value suitably for the existing line without changing the setting value separately, the current differential relay and the distance relay normally detect the faults by location and normally work.

If the setting value of relay is considered with the characteristics of smart HTS cable, it is difficult to detect a fault properly which is considering the fault resistance and relays will overreach or underreach. Therefore it is necessary to set the relays with the characteristic of existing line to satisfy both characteristics of the smart HTS cable and the existing line.

This study contributed to solving the massive capacity, complexity and high density problems of power system by suggesting the smart HTS cable that can conduct to the both role of the HTS cable and the current limiter. Furthermore this paper suggested the basic concept and algorithm of the thermal protection to compensate the disadvantage of the smart HTS cable. If the smart HTS cable is designed, it will be able to simulate minutely that applying the smart HTS cable with thermal protection to the power system as a follow-up study.

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