Qualification and Demonstration of a 80 kV 500 MW HTS DC Cable for Applying into Real Grid

Byeongmo Yang, Jiwon Kang, Seungryul Lee, Changlyul Choi, and Younghyun Moon

Abstract— **Until now some countries including South Korea have made big progress and many efforts in the development of HTS (High Tc Superconducting) power equipment, especially a superconducting power cable system is the strongest candidate among them from the viewpoint of applying to real grid owing to high current capacity of it. Specially, in the future, high-current long-distance HTS DC cable will play an important role in the power transmission systems. Because HTS DC cable nearly has no loss with the comparison of HTS AC cable. In this paper, the authors suggest a new testing method for load cycle and suitable thermal cycles in order to meet the requirement of qualification in HTS DC cable to apply into real grid. The prototype for qualification was a 100 m/3.25 kA/80 kV HTS DC cable. Qualification based on HTS experiences, international standard activities of HTS AC cable, and standards on conventional HVDC cable has been carried out. It was performed like conventional HVDC cable during 6 months in KEPCO PT (Power Testing) Center. Thanks to successful qualification of it, the 500 MW/80 kV HTS HVDC cable system will have been operated and demonstrated in KEPCO real grid since October 2014, in order to evaluate practical requirements and confirm technical feasibility of it. This paper says the recommendation and results of qualification and demonstration in it.**

***Index Terms*—Qualification, Demonstration, HTS AC Cable, HTS DC Cable, AC loss, Load Cycle, Thermal Cycle**

I. Introduction

A superconducting power cable uses superconducting materials instead of the copper or aluminum conventionally used to carry electricity in overhead power lines and underground cables. Superconducting cables, carrying three to five times more power than conventional cables, can meet increasing power demands in urban areas via retrofit applications. These high capacity cables will allow grid companies to greatly enhance capacity, thereby giving the grid more flexibility and reliability. Over the past decade, several HTS cable designs have been developed and demonstrated [1]-[6]. The use of HTS technologies in power systems provides the following benefits: enhancement of the transmission capacity, lower losses, lowering of allotment areas, improvement of environmental conditions, and insurance of fire and explosion safety. HTS DC cables give additional advantages including increased capacity without increasing of fault current levels, flexible power regulation and lower power losses as compared with HTS AC cables. When transmitting DC power, superconductors have no electrical resistance and introduce no electrical losses of their own. Since there are a lot of obvious advantages of HTS DC cables, in many countries, e.g., in the USA, China, Japan, Russia etc. have begun works to construct these lines for various purposes [7]–[12].

Before applying a HTS DC cable to a real power system, qualification by severe and believable tests is needed. The most important advantage of a HTS DC cable inherent to nearly zero AC loss is its high current density together with high voltage like a conventional HVDC cable. However, until now there hasn't been any standard activity on HTS DC cable. It creates difficulties when it's tested with applying both voltage and current at the same time like conventional HVDC cable. Load cycle test injecting both direct voltage and current together is very hard due to needed the very high capacity of testing source. Moreover a current transformer having induction type like a conventional HVDC cable shouldn't be applied because of AC loss characteristics of HTS DC cable [13]-[14]

Another problem is the thermal cycles in the HTS cable considering its long life in order to verify its contracting and expansion stress due to the cooling-down and warm-up process. It's difficult to decide the number of cycles. Because it largely depend on installation environment and methods, specially whether it employ the movable or fixed terminals, the extensible bellows, the movable or fixed joints, and snake installing way etc.[15]-[16].

In this paper, the authors suggested a qualification methods successively performed based on HTS experience, conventional HVDC cable testing methods, and HTS AC cable standard activity and showed that the 500 m/80 kV/500 MW HTS DC cable system has install in KEPCO real grid [17]-[18]. It will have operated and demonstrated in real grid since October 2014, in order to evaluate practical requirements and confirm technical feasibility of it.

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II. Qualification of the Prototype HTS DC Cable

A. *Recommendation on Tests of HTS DC Cable*

TABLE I. Recommendations for Qualification on HTS DC Cable

Item	Recommendation	Reference [a]
Bending	25(d+D)+5%, 3times	Cigre TB 538
Vacuum leak	Less than 1.0×10^{-8} mbar-l/sec,	Cigre TB 538
Pressure	No Pressure down @1.25×Max P	Cigre TB 538
DC Ic	1.85U0, 24 H 16 Cycles	Cigre TB 538
Load Cycle	1.85U0, 48 H 3 Cycles	Electra 496
Polarity Reversal	1.45U0, 8 H 8 Cycles	Electra 496
Superimposed Switching Impulse	-Up2,0 @+U0, 10 times +Up2,0 @-U0 10 times	Electra 496
Superimposed Lightning Impulse	-Up1 @+U0, 10 times +Up1 @-U0 10 times	Electra 496
Subsequent DC Voltage	-1.85U0 during 2 H, no heating	Electra 496
Thermal Cycle	Warm up → Cool Down → DC Ic → 2 times Load Cycles @+1.85U0 during 4 Cycles	HTS Experience
Visual Inspection	No significant Damage	HTS Experience

B. *Requirements of Power System for HTS DC Cable*

In order to apply HTS DC cable into real grid, the requirements of power system was asked in Table II.

TABLE II. Requirements of Power System

Item	Unit	Requirement
Nominal Voltage	kV	DC 80
Power Capacity	MW	500
Rated Current	A	3.25
Cable Length	M	500
Ground	-	Sheath
BIL	kV	285
Short Circuit Current	kA/sec	2/1
Installation Condition	-	Duct/Tunnel
Cable	-	2 pole/2 cyrostat
No. of Termination	Ea	2
Pressure Range in Normal Term	bar.G	5-9
Pressure Range in Short Term	bar.G	3-14
Temperature Range in Normal Term	K	67-72
Instantaneous Max. Temperature in Fault	K	96

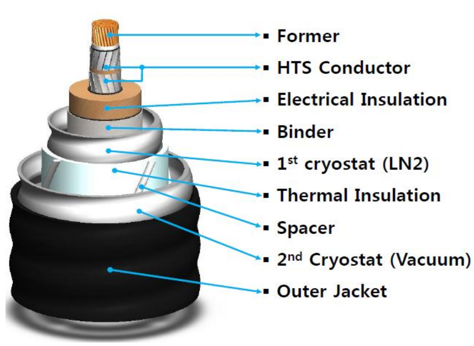

Fig. 1. Configuration of HTS DC cable, Courtesy of LSC

Following successful development of DC 80 kV HTS cable system, qualification of it had been performing at KEPCO PT (Power Testing) Center during 6 months, which was completed in Oct. 2013. This test field began in March, 2005 and was designed to promote joint research by incorporating several types of test equipment, construction of test operating facilities, and being an internationally certified authority [15].

C. *Fabrication of the Prototype 80 kV HTS DC Cable*

The length of the prototype is 100 m and followed below production process by LS cable in Fig 2.

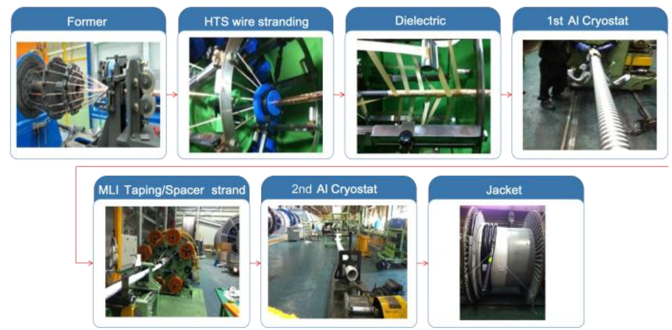

Fig. 2. Fabrication of HTS DC cable by manufacturer LSC

D. *Internal Tests of the Prototype 80 kV HTS DC Cable*

After the fabrication of the prototype 80 kV HTS DC cable, internal tests partly based on main components should be tested as follows:

- Ic measurement on cable
  - 2690 A@77 K
  - Bending test : when bent with diameter of 3700 mm, Ic degradation did not occur
- Fault & withstanding voltage test on cable
  - 2 kA/1 sec
  - Withstanding voltage : above 2.7 U0
  - Impulse Tests : above 425 kV
  - Heat loss : less than 3 W/m
- Terminations tests
  - DC withstanding voltage test(210 kV/24 H)
  - Polarity reversal test :116 kV/ 8 H, 4 times
  - Superimposed switching Impulse test
- Joint part tests
  - DC withstanding voltage test
  - Superimposed Impulse test

All above testing items is also based on Electra 219 like conventional HVDC cable tests and HTS Experience

E. *Qualification of a 100 m/80 kV/3.25 kA HTS DC Cable*

After the internal tests on main components, for example cable, termination, and joint, Qualification of 100m 3kA DC 80kV HTS cable have been carried out and it had been installed and tested successfully in order to meet qualification test requirements made by KEPCO Grid Company which based on HTS experiences and international standardization on both HTS cable and conventional DC cable [Table I]. It had been performed like conventional dc cable during 6 months in KEPCO PT center, which is the internationally certified Authority [19], since the end of 2012.

- Rating voltage : 80 kV, 250 MW
- Cable length : 100 m
- Testing location : KEPCO PT Center
- Testing period : 20 Dec. 2012 – 31 Oct. 2013

This test loop was composed of 2ea terminals, a mid-joint, and 101m cable in tunnel, duct, and on the ground surrounding

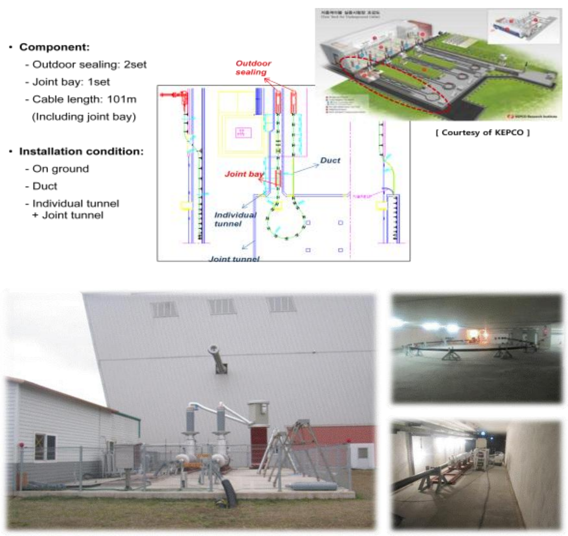

Fig .3. Installation of 100 m/3 kA/80 kV HTS DC cable at KEPCO PT Center

The bending test was carried out flexing the cable several times to a specified radius of curvature in both directions prior to electrical testing.

After the bending test, the prototype-100 m 3 kA 80 kV HTS DC cable had cool-down like Fig. 4.

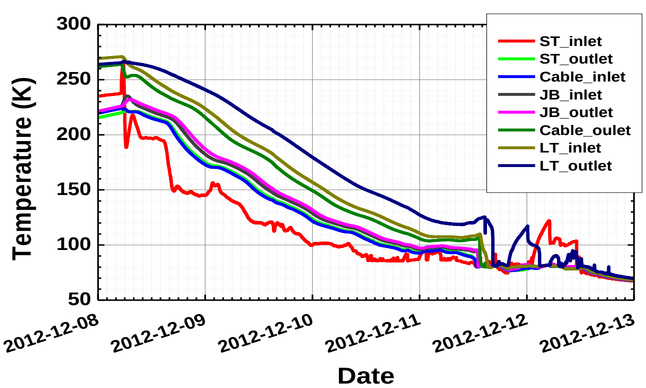

Fig .4. Cool-Down of 100m 3kA 80kV DC HTS cable in KEPCO PT Center

Pressure and leak test were performed to confirm the reliability of piping and vessel and leakage after completing cool down in 100m 80kV HTS DC cable. Leak test after vacuum evacuation was performed as follows.

- Background vacuum rate : under 1.0E-2Torr, Conducted at Vacuum area through the outer and inner wall
- The leak rate: under 1.0E-8mbar•ℓ/sec at all check point.

After finishing mechanical tests, all electrical tests showed Table I had successfully been performed. Especially high voltage DC current source suggested newly was stably operated during long time, 6 months in Fig. 5. It's necessary to use it as the testing equipment of HTS DC cable owing to AC loss.

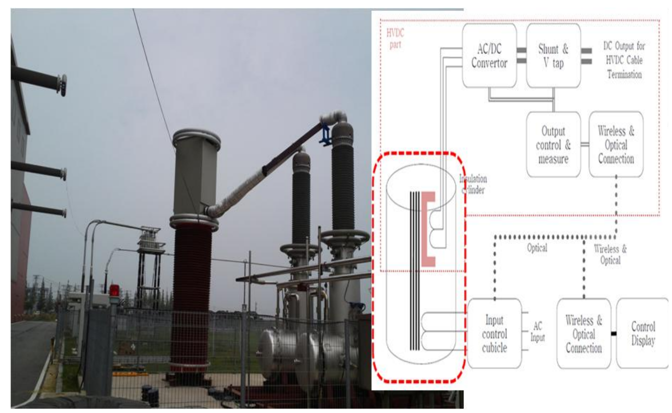

Fig .5. Development and Design of high voltage DC current source for Load

High voltage current source for testing DC HTS cable system is composed of high voltage part and low voltage part by means of high voltage insulation cylinder. High voltage part includes AC/DC converter, measuring equipment (shunt), and control & monitoring system. Low voltage part does AC input and control & monitoring system which uses LabVIEW and data acquisition system. In order to control high and low voltage part at the same time, wireless optical communication tool is used. Also it's necessary to be outdoor type owing to connection with DC HTS terminals directly in Fig. 5. It's designed by 150 kVdc 15 kA and enough to perform to 80 kV 3.25 kA DC HTS cable system. In Fig. 6, there was no problem to test full load cycle using a developed high voltage DC current.

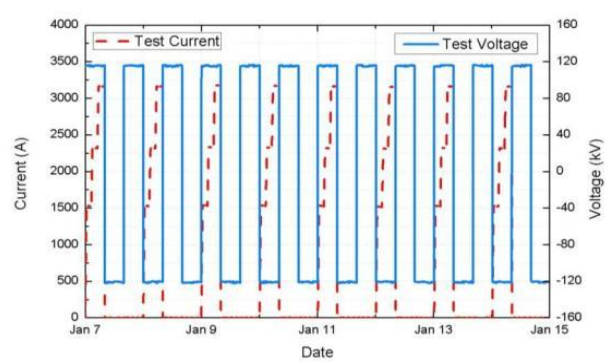

Fig .6. Load Cycle of 80 kV DC HTS Cable using high voltage DC current source

Just after superimposed impulse tests in Table I, as recommendation on thermal cycles, the prototype- a 100 m 80 kV DC HTS cable was tested for the 4th cool-down. In Fig. 7, every thermal cycle we measured the deviation of cable length when the cable had suffered from its contraction and expansion. We found that it reached the saturation points on 4^{th} cycle. We concluded that there was no degradation as DC Ic measurements of it in Fig. 8 [20].

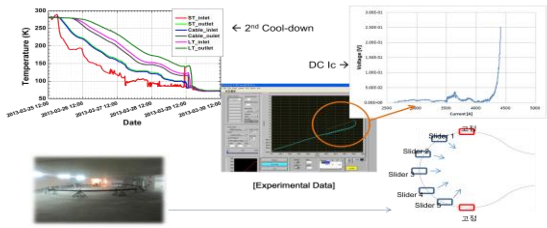

Fig .7. Deviation measurement of cable's contraction and expansion every thermal cycle considering cable's long life

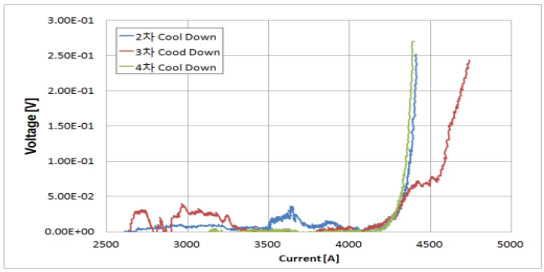

Fig .8. Ic measurement 4 times after coo-down every thermal cycle

Finally the integrity of the prototype-100m 80kV DC HTS cable system was successfully verified

III. Demonstration of 80 kV 500 MW HTS DC cable

80 kV 500 MW HTS DC cable has passed all qualification in March 2013, and is installing for applying into real grid by connecting between existing DC overhead line and DC-to-AC converter station. 80 kV 500 MW HTS DC cable will operate October 2014 with 500 m long Circuit, 2 fixed-type outdoor terminations and cryogenic system as depicted in Fig. 9.

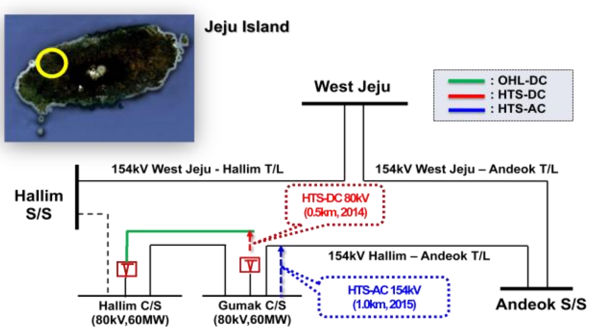

Fig .9. Demonstration Plan to apply DC and AC HTS cable system into KEPCO Real Grid

IV. Conclusion

In order to apply it into KEPCO real grid, the authors recommended qualification tests procedure for HTS DC cable system because of no standard of it. It's based on HTS experience, conventional HVDC cable testing methods, and HTS AC cable standard activities. In the recommended items, a high voltage DC current source was developed to overcome limitations in AC loss and the necessity and way of thermal cycle considering cable's long life was included.

Finally the prototype-a 100 m 3 kA 80 kV HTS DC cable was successfully qualified. The 80 kV 500 MW HTS DC cable will have been operated into KEPCO real grid since October 2014. The results of qualification show the reliability and integrity of it. The recommendation on qualification tests for HTS DC cable is expected to expand into other countries..

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