The Development of the $\pm 80\text{kV}$ 60MW HVDC System in Korea

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Abstract – HVDC transmission systems can be configured in many ways to take into account cost, flexibility and operational requirements. [1] For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance of each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be warranted, due to other benefits of direct current links. HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between the source and the load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows the transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing the exchange of power between incompatible networks. This paper proposed to establish Korean HVDC technology through a cooperative agreement between KEPCO and LSIS in 2010. During the first stage (2012), a design of the $\pm 80\text{kV}$ 60MW HVDC bipole system was created by both KEPCO and LSIS. The HVDC system was constructed and an operation test was completed in December 2012. During the second stage, the pole#2 system was fully replaced with components that LSIS had recently developed. LSIS also successfully completed the operation test. (2014.3)

Keywords: Current Source Converter (CSC) HVDC, Jeju HVDC pilot project, HVDC converter transformer, HVDC thyristor valve, HVDC valve base electronics, HVDC valve cooling system, HVDC control and protection

1. Introduction

As of 2012, due to more than 50 years of experience in the operation of line-commutated CSC HVDC transmission, the transport of bulk power by direct current is commonly accepted to be a mature and well-understood technology such as the Wolgograd-Donbass interconnection or the SACOI link between the island of Sardinia, the island of Corsica, and the Italian mainland. [2] It presents HVDC system that converts AC to DC at one converter station, which is then transmitted to a second converter station, converted back to AC, and fed into another electrical network. LSIS successfully first produced the current source converter (CSC) HVDC project in Korea. Our project is based on the establishment of Korean HVDC technology by KEPCO and LSIS. During the first stage (2012), KEPCO and LSIS completed the design of the $\pm 80\text{kV}$ 60MW HVDC bipole system. They also constructed the HVDC system and finished the operation test in December 2012. During the second stage, the pole#2 system was fully replaced with components that LSIS had developed. LSIS also successfully completed an operation test. (2014.3)

2. Basic Design for the Jeju HVDC Pilot Project

The Jeju HVDC Pilot Project stations are typically a CSC system that is composed of a thyristor valve, converter transformer, and control and protection. The HVDC Pilot's power line connection diagram between stations is link with the Jeju Power System that it should consider the sub synchronous resonance (SSR) analysis since the SSR interaction impacts the turbine shaft oscillation that can damage the shaft of a generator. [3]

The multi-mass model is utilized to demonstrate the dynamic oscillation characteristic for a generator turbine. The SSR analysis is based on the difference between electrical torque and mechanical torque of generator with considering the dynamic characteristic. This difference can be a main factor of fatigue on turbine system. Therefore, the SSR stability is analyzed based on the convergence of the oscillation of this difference. The convergence is evaluated by prony analysis which provides the information on the damping ratio. The Eq. (1) explains the prony analysis. It contains the information on the magnitude, damping ratio, frequency, and phase angle of a waveform.

$$f(t) = \sum_{i=1}^N A_i e^{\sigma_i t} \cos(2\pi f_i t + \phi_i) \quad (1)$$

Fig. 1 shows the stable case of sub synchronous

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Fig. 1. A stable case of the sub synchronous oscillation

Fig. 2. The Jeju HVDC pilot project location (Hallim C/S, Geumak C/S)

Fig. 3. The Jeju HVDC pilot project power transmission line

oscillation causing from a system disturbance. In the stable case, the waveform of the difference between electrical torque and mechanical torque of generator converges. Therefore, the prony analysis result of this case has no positive value on damping ratio.

Fig. 2 shows the HVDC systems in Jeju island. The HVDC #1, #2 which are commercial PJT was constructed by KEPCO. The ± 80 kV 60MW HVDC system design which is pilot PJT was done by LSIS.

The power flow is from Geumak C/S to Hallim C/S by HVDC. Also, the power flow of the reverse direction is acceptable. [Fig. 3] The system rating of DC voltage is ± 80 kV, and the DC rating is 60MW. [Table 1&2] The rectifier system is Geumak C/S. The inverter side is Hallim C/S.

The DC transmission line is 5.2km. The length of the cable is 500 meter and the overhead line is 4.8km. This DC line is located with the AC 154KV line at the same tower.

Table 1. The Jeju HVDC pilot project AC system specification

AC system data	Geumak	Hallim
Nominal system voltage	154 kVrms	154 kVrms
Nominal operating voltage	156 kVrms	156 kVrms
Minimum operating voltage, steady-state	139 kVrms	139 kVrms
Maximum operating voltage, steady-state	164 kVrms	164 kVrms
Maximum short circuit current, symmetrical 3 phase	1191.76 MVA	1166.47 MVA
Minimum short circuit level (SCL) at AC contingency considered as the minimum AC System SCL	950.42 MVA	926.28 MVA
Rated frequency	60 Hz	60 Hz
Frequency variation range	60 $\pm$ 0.2 Hz	60 $\pm$ 0.2 Hz

Table 2. The Jeju HVDC pilot project DC system specification

DC system data		
Direct power - bipole	Maximum (at 100% load)	60 MW
	Minimum (at 10% load)	6 MW
Direct current	Measurement error	± 0.6 %
	Nominal DC current (at 100% Load)	375 A
	Minimum DC current (at 10% Load)	0.375 A
Direct voltage	Measurement error	± 0.6 %
	Nominal (at 100% load)	± 80 kV

The upper side of the tower includes AC three phase lines. Lower sider is dc line. But there are no interference between ac and dc.

3. Main Components of the Jeju HVDC Pilot Project

The Jeju HVDC Pilot Project stations are typically current source converter (CSC) systems, which are composed of a thyristor valve, converter transformer, smoothing reactor, AC filter, and control and protection. [Fig. 4] This chapter introduces the thyristor valve, converter transformer, valve base electronics (VBE), control and protection, valve cooling system composed of the ± 80 kV 60MW HVDC system.

3.1 HVDC thyristor valve

Thyristor is the most critical component in the valve. Through the on/off operation of the thyristor valve, it can transform the AC to DC. Five or more thyristor levels in a valve section should be tested for adequate representation in case the valve section is composed of twelve or more levels in series. [4]

The used thyristor is electrical triggered thyristor (ETT) 6.5kV and 600A rating. Thyristor valves employ high power thyristors, together with associated gating, damping and grading circuits, arranged in 6 or 12 pulse converter groups. Fig. 5 is the structure of the thyristor valve. [5] The

Table 3. The Jeju HVDC pilot project valve specification

Item	Value
Number of pulses	12
Converter bridge per pole	1 x 12 pulse
Total number of levels per valve	20
Redundant levels per valve	1
Rated AC voltage	33.5 kVrms
Rated DC voltage	80 kV
No load voltage	91 kV
MCAV	52.77 kVpk
Rated DC current	378 A
Continuous max current (1.05 p.u.)	396 A
2 hour overload current (1.13 p.u.)	426 A
10 seconds overload current (1.2 p.u.)	460 A
Rectifier control angle at nominal	19.3°
Inverter control angle at nominal	22°
Short circuit current	5.7 kA _{pk}
SIPL	90.5 kVpk
SIWL	104.13 kVpk
LIPL	92.09 kVpk
LIWL	112 kVpk

Table 4. The Jeju HVDC pilot project converter transformer specification

Item	Specification				
Number of phases	3 Phases				
Rated voltage	154/33.5 - 33.5 kV				
Rated frequency	60 Hz				
Rated power	36/18 - 18 MVA				
Type of cooling	ONAN/ONAF (56%/100%)				
Insulation level	LI	SI	AC	DC	PR
- HV line terminal	650	-	275	-	-
- HV neutral	325	-	140	-	-
- LV I (Delta)	240	220	100	130	95
- LV II (Star)	145	135	55	70	45
Vector group	YNy0d11				
Temperature rise	Top oil		Average winding		
	50°C		55°C		
Weight	Total		Shipment		
	89,700 kg		47,400 kg		
Application standards	IEC 60076/61378

Fig. 4. Main components layout of the Jeju HVDC pilot project

Fig. 5. The Jeju HVDC pilot project valve configuration

Fig. 6. The Jeju HVDC pilot project converter transformer

thyristor valve hall is contained in three quadri valves (valve $\times$ 4). One of the three valves is replaced by LSIS's valve. Table 3 shows specifications of the thrister valve designed by LSIS.

3.2 HVDC converter transformer

The HVDC converter transformer provides the connections between the AC system and the valve. The role of the transformer is to provide stable voltage to the valve side, which is nearly independently of the AC side. [6] Therefore, the converter transformer is a very important component in the HVDC system. Fig. 6 is the structure of the HVDC converter transformer made by LSIS.

LSIS designed Table 4 which is the HVDC converter transformer specifications in the $\pm 80\text{kV}$ 60MW HVDC system. [7]

3.3 The HVDC valve base electronics system

The valve base electronics (VBE) system is the electrical optical firing interface between the control and protection (C&P) system and the valve gate units. In addition, the VBE provides valve monitoring and protection for each

Table 5. The Jeju HVDC pilot project VBE configuration

Item		Value
FSG (Firing Signal Generation)	FSG	2
	OEIV (optic to electrical interface VD)	2
	EO (electrical to optic)	48
VSC (Valve Status Diagnosis)	DIDO (digital input digital output)	2
	VDI (valve diagnosis Interface)	12
	VCU (valve communication unit)	1
	OED (optic to electrical interface & display)	36

Table 6. Functions of HMI, C&P, field level

Item		Detail Functions
HMI	System Operation and Control	OWS (Operation WorkStation)
		EWS (Engineering WorkStation)
		TFR (Transient Fault Recorder)
		DB (Database Server)
		RCI (Remote Communication I/F)
C&P	Control and Protection Action	SCS (Station Control Station)
		PCS (Pole Control Station)
		PPS (Pole Protection Station)
		MIS (Measurement Interface)
Field I/O	Field Device Signal	Field Device I/O
		Measurement I/O

Fig. 7. The Jeju HVDC pilot project valve base electronics

Fig. 8. Structure of the Jeju HVDC pilot project control and protection platform

thyristor valve. [Fig. 7] Table 5 is the VBE configuration made by LSIS.

Table 7. The Jeju HVDC pilot project control function

Control Function	Detail Functions
Master Control/ AC Yard Control (4EA)	Power limits
	Master power control
	Power/frequency control
	Reactive power control
Pole Control (5EA)	Blocking control
	Pole power control
	Overload control
	Current order coordinator
	Current balancing
Phase Control (10EA)	Phase limit
	Oscillator
	Ring counter
	Loop control
	AC measurement
	Alpha balancing
	Gamma balancing
	VDCL
	Aux. loop control
	Tap changer control

Fig. 9. Structure of the Jeju HVDC pilot project redundancy control and protection system

3.4 HVDC control and protection system

The core components of an HVDC control and protection system are human-machine interaction (HMI), hardware platform and algorithm. [Fig. 8] They execute actions to control and protect all equipment, including the thyristor valve, converter transformer and filter, used in the HVDC system. [8]

The control and protection system is designed as a hierarchical structure and consists of an operation level of HMI, control level of the control and protection controller and a field level. [Table 6]

Using the control function, operators can control the transmission power level and change the direction of the power flow. In addition, the system is protected by protection functions when some fault occurs in an AC or DC part. [Fig. 9]

The control and protection were the main three parts. The one is a SCADA system. The second is the HVDC control system. [Table 7] The final system is a protection part. The pole#2 control and protection system of the pilot

is replaced by the LSIS system that developed the LSIS HVDC control and protection system. The HMI is used to monitor and control the HVDC system. The main HMI of the system is the system configuration, alarm, event and all overview display. [Fig. 10] The operating engineer can edit and monitor the control and protection algorithm logic by using the open process automation system (OPAS) engineering tool which is made by LSIS and integrated control logic processor based on software model using the programming languages. [8] Fig. 10 is the LSIS HVDC HMI display.

In order to achieve high reliability, control and protection pieces of equipment are electrically isolated from each other and are duplicated to ensure full redundancy of the system. The control and protection system has three control levels and each level operates with its own functions. [Fig. 11]

Fig. 10. The Jeju HVDC pilot project HMI display

Fig. 11. The Jeju HVDC pilot project pole protection configuration

The structure of the pole protection cubicle is the same as the control cubicle. In addition, the protection area is divided into three areas and each area has various protection functions. [Table 8]

The measurement interface system (MIS) directly transduces the signals from the current transformer (CT) and the potential transformer (PT) to the controller. Field I/O sends and receives the signals from field devices through fieldbus communication. [Fig. 12]

3.5 HVDC valve cooling system

The valve cooling system (VCS) is the equipment for dissipating heat from the valve towers. The VCS maintains the operation temperature of the valve while the power is transmitted. [Fig. 13] Table 9 is specifications of the valve cooling system designed by LSIS.

Table 8. The Jeju HVDC Pilot Project Protection Function

Protection Area	Protection Functions
DC Pole Protection (14EA)	Asymmetry protection
	Pole differential
	Abnormal firing
	AC $\rightarrow$ DC differential
	DC $\rightarrow$ AC differential
	AC overcurrent
	AC overvoltage (Line Side)
	AC overvoltage (valve side)
	AC under voltage
	Tap limits
	DC undercurrent
	Open line test
	DC overvoltage
	DC overcurrent
DC Neutral Protection (2EA)	Common neutral area
DC Line Protection (3EA)	Neutral bus overvoltage
	DC line faults
	Cable longitudinal
	Cable overcurrent

Table 9. The Jeju HVDC pilot project VCS specification

Parameter	Specification
Valve Tower	44.0 kW
Pole	132.0 kW
The Valve Pressure Difference	0.12 MPa
Rated Coolant Flow	29 m ³ /h
Conductivity of Coolant	$\leq 0.5 \mu\text{S/cm}$
Power	AC : $2 \times 380 \text{ VAC} \pm 10\%$
Rated Power	27 kW

Fig. 12. The Jeju HVDC pilot project MIS and field I/O cubicle

Fig. 13. The Jeju HVDC pilot project VCS

Fig. 14. The Jeju HVDC pilot project reference made by LSIS

Fig. 15. The Jeju HVDC pilot project test results of monopole operation

4. The Jeju HVDC Pilot Project Operation

On October 2013, the main components of the Jeju HVDC Pilot Project pole#2 were replaced with LSIS products (C.TR, Valve, C&P). [Fig. 14]

LSIS's current source converter HVDC system was first developed in Korea. [9]

In addition, LSIS successfully conducted and completed the operation test that involved a 30MW full load operation of pole#2. [Fig. 15]

Fig. 16 shows AC voltage, AC current, DC voltage, DC current about monopole test.

Fig. 16. The Jeju HVDC pilot project test waveform of monopole operation

5. Conclusion

This paper introduced the development of the $\pm 80\text{kV}$ 60MW HVDC system on Jeju Island. The design of the Jeju HVDC pilot project made by LSIS took into account the diverse operating requirements of Korea.

For the future works, LSIS will offer advanced the current source converter (CSC) HVDC solutions and voltage source converter (VSC) HVDC solutions for the increasing demand for electric power in load centers, and a growing interest to use renewable energy resources usually generated far away from load centers calls for bulk power transmission. It is important to conduct other HVDC projects.

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