Verification on Valve Losses of LCC HVDC Converter Station in Korea

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Abstract—**This paper deals about valve losses review of HVDC converter stations in Korea. Technique of calculating losses is one of important verification process to evaluate systems performance, so customers have right to get accurate imformation of losses in precedure of bid. It is very important to verify documents which are submitted by maker, however it is not easy for utility company to verify maker's documents because of getting limited imformation from makers.**

Losses of a converter station can be easily estimated from calculation of two main equipments, valve and transformer, because proportion of two equipments accounts for more than 80% of the total values in the HVDC converter station. In this paper, authors firstly analyzed calculating process of valve losses and verified if the calculated results are accorded with the reports provided from maker in accordance with the IEC standards, IEEE standard, EPRI Handbook in case of Jeju No.2 converter station in Korea. After that, it was verified whether the results were satisfactory compared to KEPCO's specification.

Keywords- HVDC, power losses, LCC, valve, converter station, and specification

I. INTRODUCTION

Like the investment in major electrical plants and systems for power generation and transmission facilities, the power losses of the HVDC converter station must be measured accurately. In other words, the calculation for generators, transformers, reactors, etc. is part of the budget calculation, and the losses components normally generated at the HVDC converter station do not appear in the AC system, but have a significant impact on the overall losses from voltage control devices such as synchronous compensators, stationary reactive power compensators, AC/DC harmonic filter, converter transformer, thyristor valve, and smoothing reactor [1][2].

The losses of a single component and the total losses of a converter station are respectively calculated under the conditions of ambient temperature, rated current, etc., and the contractor guarantees that the equivalent total losses is guaranteed. This is obtained by adding no-load and load loss. In the KEPCO specification, the load losses is the nominal current, AC voltage, and frequency when the temperature is 20 °C, and is defined as the losses of the firing angle from the no-load loss. For harmonic losses calculation of AC system, all harmonic currents other than fundamental frequency are assumed to be open circuit [3].

KEPCO specifies that the all load losses of each converter should be less than 0.8% of the rated power, and that the total load losses of both converter stations should be less than 1.6% of the rated power. It is also stated that the all no-load losses of each converter should be less than 0.1% of the rated power, and the total value of converter station should be less than 0.2% of the rated power.

In this paper, authors firstly apprehended losses of each device in a typical LCC HVDC converter station and summarized the losses calculation method of valve. And then valves, which is the main factors, was mainly calculated at each load rate by referring to [3][4][5]. After that, the results of calculated values was verified to be satisfied with KEPCO's specification.

II. CONFIGURATION AT A TYPICAL CONVERTER

HVDC converter station has different devices such as valves, converter transformers, AC filters, and smoothing reactors that can cause losses compared with AC substations [4]. The mechanism will vary from plant to plant and in general, the total losses is not determined by factory testing or field testing alone. When operating at rated conditions, they typically range from 0.5% to 1% of the rating power of each converter.

Table I shows the composition ratio of the losses of general facilities. Due to the complexity of the entire converter station, the nonlinear voltage and current waveforms in operation, various methods are used to estimate the total converter losses [5].

TABLE I. Losses configuration at an HVDC station

Item	Typical losses at nominal operating conditions [%]	Losses according to rated power [%]		KEPCO Spec.
		0.5%	*1.0%*	
Converter transformers	39-53	0.20~0.27	0.39~0.53	0.31~0.42
Thyristor valves	32-35	0.16~0.18	0.32~0.35	0.26~0.28
AC filters	7-12	0.04~0.06	0.07~0.12	0.06~0.10
Smoothing reactor	4-6	0.02~0.03	0.04~0.06	0.03~0.05
DC filters	1-2	0.01	0.01~0.02	0.01~0.02
other losses	3-7	0.02~0.04	0.03~0.07	0.02~0.06
Total	100	0.5	1.0	0.8

Table I shows classified values according to the converted value to compare with the KEPCO's specification. As shown in Table I, converter transformers account for 39-53% and thyristor valves do 32-53% of the total losses. When the rated power is converted to 0.5% and 1.0%, the thyristor valve is 0.16 to 0.18% at 0.5% and 0.32 to 0.35% at 1.0%. KEPCO's specification states that the total losses at one converter station should be within 0.8%. Based on this criterion, the losses of the thyristor valve can be calculated as 0.26 to 0.28%. These values will be used as the basis for verification in this paper.

Losses calculation of converter station is performed under the following general operating conditions, which are AC bus voltage and frequency for nominal converter transformer, nominal equipment error, nominal measurement error, ambient temperature 20°C, and transformer's tap for specific operating conditions [4][5].

On-site measurement of power circuit losses at the converter station is not suitable as a method of achieving high efficiency due to the relatively low accuracy of the measurement device compared to the small difference between high input and output. Moreover, losses is guaranteed at certain AC systems and ambient temperature conditions, making it very difficult to re-measure in practice. Therefore, the date for calculation was allowed to use factory test results [5].

III. VALVE LOSSES CALCULATION AT TYPICAL HVDC CONVERTER STATION

A. Typical Thyristor Valve Losses

When the valve is blocked, no-load operation losses was occurred and is different from the possible losses mechanism in normal operation. A simple three-phase circuit diagram of an HVDC 12-pulse converter is shown in Fig. 1. This figure means the conduction sequence of the thyristor in the valve

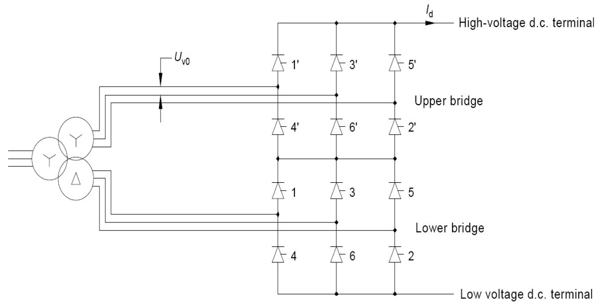

Figure 1. Three-phase schematic diagram of the HVDC 12-pulse converter

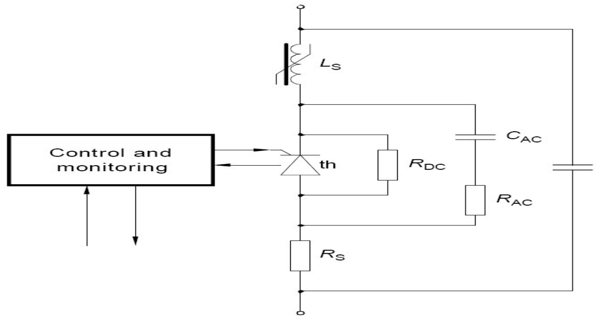

Figure 2. Simplified equivalent model of a typical thyristor valve12-pulse converter

In Fig. 2, thyristor(th) together constitutes the influence of two thyristors in series with the valve. The $R_{th,}$ C_{th} damping circuits are used for overvoltage suppression and voltage sharing. R_{DC} is grading resistance and other resistive elements, which can cause losses when the valve blocks the voltage. This also includes the thyristor leakage current effect. C_s is stray capacitance and surge sharing capacitor. L_S is a saturation reactor that limits di/dt to a safe level and improves the distribution against steep voltage rising. R_s is resistance of the current-carrying element of the valve, such as winding resistance, contact resistance, and busbar. The power losses of the valve arrester was ignored [7].

Fig. 3 shows the current and voltage waveforms when valve 1 operates as a rectifier and inverter. The firing time of the upper bridge is delayed 30 ° with respect to the valve of the lower bridge for phase movement. For each valve, the length of the conduction section is 130 ° ($2\pi/3 + \mu$). At rectification, it is assumed that the valve current changes linearly, but in practice the valve current follows a portion of the sinusoidal wave. This simplification has only negligible effects on the resulting losses effects and is mainly simplified to trapezoidal waveforms for calculations. The voltage blocked by the valve shows the notch due to the current between the individual valves [3][7].

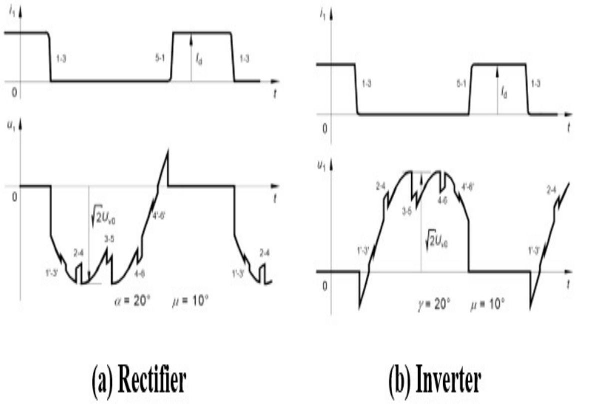

Figure 3. Current and voltage waveforms of 12-pulse converter valve operation

B. Valve Loss Calculation Process [3][4][5]

1) Thyristor conduction losses per valve

This losses can be calculated with the multiplication of the ideal on-state voltage and the conduction current i(t) in Fig. 4 and 5. P_{v1a} is well assumed to be smoothing of the DC bridge current. If the sum of the square roots of the DC-side harmonic currents exceeds 5% of the DC component, the equation P_{v1b} should be used instead.

$$P_{V1a} = \frac{N_t I_d}{3}\left[U_o + R_O I_d\left(\frac{2\pi-\mu}{2\pi}\right)\right] \quad (1)$$

$$P_{V1b} = \frac{N_t I_d U_O}{3} + \frac{N_t I_d}{3}\left[I_d^2 + \sum_{n=12}^{48} I_n^2\right]\left(\frac{2\pi-\mu}{2\pi}\right) \quad (2)$$

Where :

- N_t : Number of thyristors connected in series to the valve
- U_o : Current dependent component of on-state voltage of average thyristor[V]
- R_o : Gradient Resistance of the On-State Characteristics of an Average Thyristor[Ω]
- I_d : DC current[A]
- I_n : Calculated RMS of nth Harmonic Current in Bridged DC Connections[A]

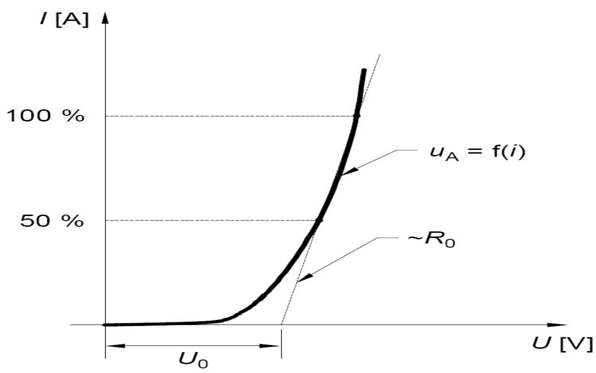

Figure 4. Thyristor-on-state characteristic curve

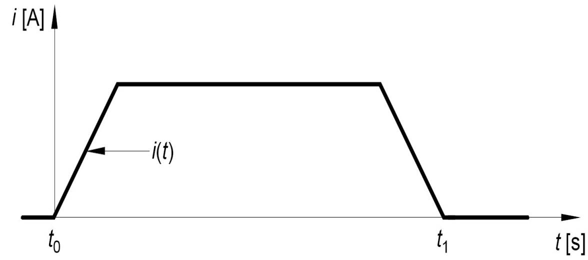

Figure 5. Thyristor conduction current curve

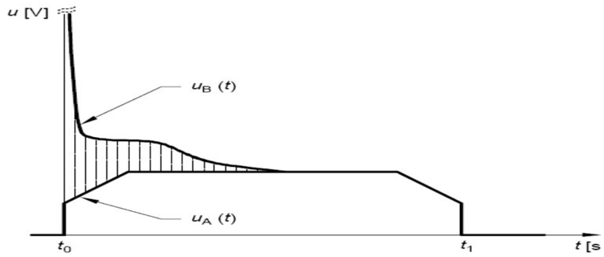

Figure 6. Voltage drop curve of ideal thyristor and actual thyristor

2) Thyristor Spreading Losses per Valve

This is an additional losses of the thyristor that occurs in the delay from the turn on of the thyristor to the conduction of the entire silicon. This losses can be calculated by the multipilication of voltage and current where the thyristor voltage exceeds the ideal thyristor on-state drop. In Fig. 6, it is hatched.

$$P_{V2} = N_t \times f \times \int_0^{T1}[u_B(t) - U_A(t)] \times i(t)dt \quad (3)$$

Where, T_1 means length of conduction section[sec], U_B is determined by the instantaneous on-state voltage. The instantaneous on-state voltage is determined for the appropriate junction temperature, measured as the trapezoidal current in terms of current overlap and magnitude. $U_A(t)$ is determined by calculated instantaneous on-state voltage of the average thyristor at the same junction temperature for the same current pulse, the voltage with the conduction area fully established through single conduction. i(t) means the instantaneous current in the thyristor.

3) Other conduction losses per valve

The other factor of the valve is the losses of conduction in the main circuit of the valve.

$$P_{V3} = \frac{R_O \cdot I_d^2}{3}\left(\frac{2\pi-\mu}{2\pi}\right) \quad (4)$$

Where, R_s menas the DC resistance between the valve's terminals except for the thyristor. The value of R_s is determined by direct measurement of a representative valve section covering all parts of the valve's main circuit.

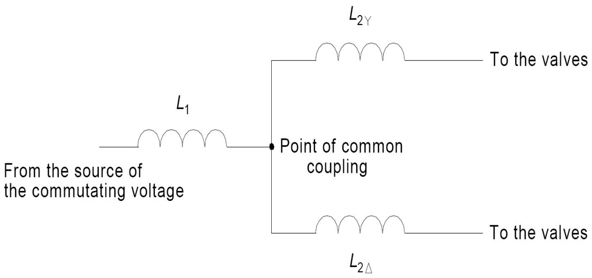

Figure 7. Distribution of rectified inductance between L_1 and L_2

4) DC volage related losses per valve

This is the losses in the parallel resistance of the valve resulting from the voltage present between the valve terminals in the non-conducting section. This is caused by losses in thyristor off-state and reverse leakage.

$$P_{V4} = \frac{U_{Vo}^2}{2\pi R_{DC}}\left\{\frac{4\pi}{3} + \frac{\sqrt{3}}{4}[\cos(2\alpha) + \cos(2\alpha + 2\mu)]\right\} + \frac{6m^2-12m-7}{8}[\sin(2\alpha) - \sin(2\alpha + 2\mu) + 2\mu] \quad (5)$$

Where, R_{dc} menas effective off-state DC resistance of all valves obtained by current measurement in valve terminal-terminal DC voltage type test. m is $L_1/(L_1+L_2)$, L1 menas the inductance between the common coupling point between the Y and Δ winding and the rectified voltage source, and L_2 means the inductance between the valve and the common coupling point between the Y and Δ winding, which should include the saturation inductance of the valve saturation reactor in Fig. 7.

5) Damping losses per valve :resistance dependent

This losses is determined by the voltage present between the valve terminals during the non-conducting period and by the value of the resistive element of the circuit coupled with AC through a series capacitor.

$$P_{V5} = 2\pi f U_{Vo}^2 C_{AC}^2 R_{AC}\left[\frac{4\pi}{3} - \frac{\sqrt{3}}{2} + \frac{3\sqrt{3}m^2}{8} + (6m^2 - 12m - 7)\frac{\mu}{4} + \left(\frac{7}{8} + \frac{9m}{4} - \frac{39m^2}{32}\right)sin2\alpha + \left(\frac{7}{8} + \frac{3m}{4} + \frac{3m^2}{32}\right)\sin(2\alpha + 2\mu) - \left(\frac{\sqrt{3}m}{16} + \frac{3\sqrt{3}m^2}{8}\right)cos2\alpha + \frac{\sqrt{3}m}{16}cos(2\alpha + 2\mu)\right] \quad (6)$$

Where, C_{ac} is effective value between terminals of valve damping capacitance, and R_{ac} is effective value between terminals of damping resistor connected in series.

6) Damping losses per valve : change in capacitor energy term

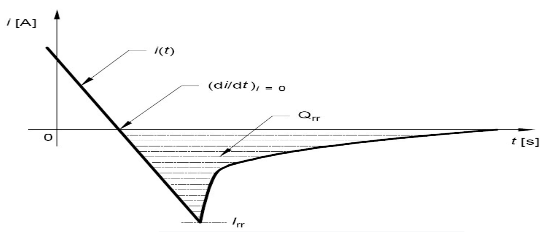

Figure 8. Thyristor current at reverse recovery

This losses is arised from the change of stored energy in the valve capacitance as a result of the unit change ΔU in the voltage blocked by the valve. Each unit change produces energy losses equal to (7), which is derived from the sum of the energy lost due to the twelve voltage jumps occurring during one cycle blocking voltage multiplied by the system frequency.

$$P_{V6} = \frac{U_{Vo}^2 \times f \times C_{HF} \times (7+6m^2)}{4}[sin^2\alpha + sin^2(\alpha + \mu)] \quad (7)$$

Where, the sum of the effective capacitances between the terminals of all the capacitive equalization circuits in the valve and the total effective stray capacitances between the valve neighbors and the valve terminals generated from externally connected equipment or externally connected equipment.

7) Turn-ff losses per valve

This loss is caused by the damping resistance and the thyristor due to the reverse current flowing through the thyristor at turn-off in Fig. 8.

$$P_{V7} = Q_{rr} \times f \times \sqrt{2} \times U_{Vo} \times sin\left(\alpha + \mu + 2\pi \times f \times \sqrt{\frac{Q_{rr}}{(di/dt)_{i=0}}}\right) \quad (8)$$

Where, Q_{rr} means Average value of thyristor charge, U_o menas Effective value voltage between lines for valve winding, and $(di/dt)_{i=0}$ means Measured commutating di / dt at zero current.

8) Reactor losses per valve

Reactor losses include three loss components: eddy current loss, winding resistance loss, and hysteresis loss of the magnetic core.

$$P_{V8} = n_L \times M \times k \times f \quad (9)$$

Where, N_L means Number of reactor cores in the valve, and M means Mass of individual reactor cores, and k is Property losses.

9) Total valve losses

The total losses of the valve is the sum of the eight losses calculated above.

$$P_{VT} = \sum_{i=1}^{i=8} P_{vi_L} \quad (10)$$

10) No load operation losses per valve

The no-load operation loss per valve is the sum of the losses generated by the current induced by the voltage blocked by the valve through the valve resistance. It consists of two terms: the first is the losses in a resistor connected in parallel with the blocking thyristor, and the second is the losses in the capacitively coupled resistor.

$$P_{VSB} = \frac{U_{Vo}^2}{3}\left(\frac{1}{R_{DC}} + \frac{R_{AC}}{Z_{AC}^2}\right) \quad (11)$$

Where, Z_{AC} is derived from $\sqrt{R_{AC}^2 + \left(\frac{1}{2\pi f C_{AC}}\right)^2}$ equation.

IV. VALVE LOSSES CALCULATION AT TYPICAL HVDC CONVERTER STATION

The losses of Table II were calculated based on from (1) to (9). The valve losses were calculated using the firing angle, maximum rectified voltage, frequency, and direct current of the project reports which were submitted by manufacturer. Some parameters like stray capacitance were assumed by [3][8]. Several parameters, the values of U_a and U_b, used in P_{V2} calculations were not found, so the values were taken from other projects, however the results were not significantly different from the manufacturer's report.

Each on-load losses was calculated according to the operating load ratio, and the parameters used in the calculation are depicted in Table II. Some parameters like line DC current(I_d) and superposition angle(μ) change depending on the load rate. The different point with other projects is that the firing angle has fixed value at 13 degrees. Fig. 9 shows increasement of losses depending on load rate.

TABLE II. Different valve's losses according to load rate

Load rate	10%	20%	40%	60%	80%	100%
PV1	1.25	2.55	5.30	8.24	11.36	14.66
PV2	1.8	1.8	1.8	1.8	1.8	1.8
PV3	0.003	0.014	0.056	0.13	0.23	0.36
PV4	5.19	5.12	4.97	4.83	4.68	4.53
PV5	3.32	3.28	3.20	3.13	3.05	2.98
PV6	12.4	15.46	21.17	26.28	30.98	35.31
PV7	0.99	1.16	1.43	1.64	1.80	1.95
PV8	0.43	0.43	0.43	0.43	0.43	0.43
PV(total)	22.97	27.45	36.05	44.22	52.12	59.85

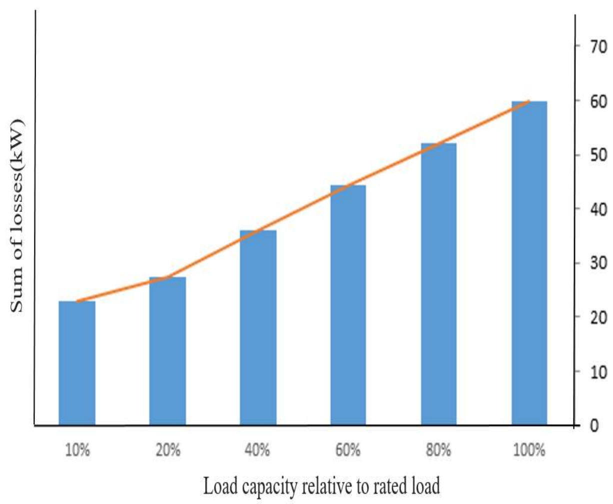

Figure 9. Progress losses graph with load rate

TABLE III. Parameter value used in the calculation

Load rate	25%	50%	75%	100%
U_o(kV)	149.9			
R_o(Ω)	0.4×10^3			
N_t	36			
I_o (A)	80	200	599	800
α(°)	13			
μ(°)	8.70	14.44	18.90	22.64
Rs(Ω)	0.00167			
f(Hz)	60			
Ca_{c1}(μF)	0.5			
Ra_{c1}(Ω)	55			
Ca_{c2}(μF)	0.5			
Ra_{c2}(Ω)	144			
C_s(μF)	0.0057			
R_{dc}(MΩ)	94			
m(H)	0.667			
C_H(μF)	1.006			
Q_{rr}(μC)	625			
di/dt	2.3×10^6			
N_L	6			
M(kg)	6			
k(jouls/kg)	0.2			
V_t(V)	1.27			
V_{avg}(V)	2.4			

V. LOSSES VERIFICATION WITH KEPCO SPECIFICATION

Table IV shows the results of the values specified in the No.2 HVDC report and the actual calculated values. From P_{v1} to p_{v8} represent each on-load losses, and PV is the total on-load losses. The total no-load losses is the sum of no-load DC and no-load damping losses.

TABLE IV. Losses comparison value at each converter station

Load	25%		50%		75%		100%	
Valve losses	Rep	cal.	Rep	cal.	Rep	cal.	Rep	cal.
PV1	2.81	3.23	5.86	6.75	9.43	10.57	13.21	14.68
PV2	0.45	1.80	0.54	1.80	0.61	1.80	0.68	1.80
PV3	0.02	0.02	0.08	0.09	0.17	0.20	0.29	0.36
PV4	3.67	5.08	3.57	4.71	3.48	4.71	3.38	4.53
PV5	1.46	3.27	1.44	3.07	1.42	3.07	1.39	2.98
PV6	7.65	16.95	10.78	29.85	13.76	29.85	16.62	35.31
PV7	3.20	1.24	4.72	1.77	6.14	1.77	7.49	1.95
PV8	1.11	0.43	1.13	0.43	1.13	0.43	1.13	0.43
PV (total load)	20.37	29.66	28.20	40.19	36.11	50.18	44.16	59.85
No-load DC	1.55	2.21	1.55	2.21	1.55	2.21	1.55	2.21
No-load Damping	0.64	1.47	0.64	1.47	0.64	1.47	0.64	1.47
P_{VSB} (Total no load)	2.19	3.68	2.19	3.68	2.19	3.68	2.19	3.68

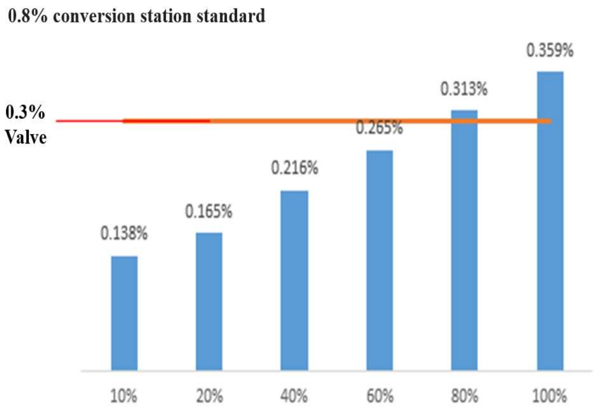

Figure 10. Graph of valve losses and KEPCO specification

TABLE V. **Valve Loss Specification vs. Calculation**

LOAD STATE	KEPCO SPEC. (MW)		VALUE(MW)	
On load losses	KEPCO (32%)	KEPCO (35%)	Calculation	Report
	1.02	1.12	1.44	1.06
No load losses	0.128	0.140	0.088	0.053

According to [3][4][5], the standard of valve losses is below about 0.3% per converter station. The value is slightly larger than standard value at 80% and 100% load as shown in the corresponding graph in Figure 10. This is estimated to be error from using of unknown parameters like mutual reactance(m) for the calculation. However, it is judged that the value is not far from the reference value.

Table V represents comparison of the losses defined in the KEPCO specification with the valve losses calculation value at each converter station in Jeju No.2 HVDC system. The KEPCO specification stipulates that the load losses at a converter station should be less than 0.8% of its rated power. Among them, the load loses of the valve is about 32 ~ 35% at the HVDC converter station, and this vaule can be converted into 1.02MW at 32% and 1.12MW at 35% of total losses when calculated based on the rated 400MW. Based on the monopole, the load losses calculation is 0.06 MW. The total reflectance of the valve in bipole scheme is 1.44 MW. The losses value suggested by the manufacturer is 1.06MW, which is similar with KEPCO's specification.

No-load losses is specified within 0.1% per conversion station in the KEPCO specificaton, so the valve losses must be within 128 kW (32%) for a rated 400 MW. In Table V, the calculated value is 3.68kW, which is 88kW in case of bipole configuration, and the no-load losses value of manufacturer's report is 2.19kW, which is within the KEPCO specification.

VI. CONCLUSION

It is very important to verify the performance, price, etc. of the manufacturer's HVDC converter system. Among them, losses is used as an important factor in evaluating the system. In this paper, it was verified whether the losses value provided from maker is well calculated according to standards in case of valve equipments, which is a important facility in the conveter station. Although calculations were made based on various standards, some important parameter values for the calculation were found to be marginal, such as using estimates. The valve losses calculated in Jeju No.2 HVDC system was a little different from the report provided by the manufacturer, however the error was small enough to be ignored. Therefore, it can be estimated that it satisfies KEPCO's specification.

REFERENCES

[1] G.Peter and A. Saha, “Power Losses Assessments of LCC-based HVDC Converter Stations Using Datasheet Parameters and IEC 61803 STD,” 2018.
[2] H. Lips, "Loss determination of HVDC thyristor valves," IEEE transactions on power delivery, vol. 3, pp. 358-362, 1988.
[3] IEC 61850, “Determination of power losses in high-voltage direct curret(HVDC) converter station, pp.7-30, 1999.
[4] EPRI HVDC HADNBOOK, “System efficiency”, pp.427-434, 1994.
[5] IEEE std 1158-1991, “IEEE Recommended practice for Dete Determination of Power Losses in High-Voltage Direct-Current(HVDC) Converter Stations, “ pp. 7-19, 1991.
[6] A.Gole and A.Canelhas, “HVDC connecting to the future”, pp. 305-307, 2010.
[7] N. B. Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," Electric power systems research, vol. 76, pp. 916-927, 2006.
[8] M. Arunachalam, R. Babu, B. Bose, and D. Dutta, "Evaluation of losses in thyristor valve for SVC application," in Power Electronics, Drives and Energy Systems for Industrial Growth, Proceedings of the 1996 International Conference, pp. 399-402, 1996.

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