A Simplified Practical Relation of Tap-Changer Control Mode Upon HVDC Valve Power Loss and its Engineering Application

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SUMMARY

The tap-changer of a converter transfomer has two control modes: voltage control mode and angle control one. The HVDC valve power loss is derived here in these two modes, and their relation and the influence between one another have been found. The study results show that the voltage control mode makes the HVDC loss get larger than the angle control one does in the same transmission capacity. The analysis also confirmed that the voltage control mode of converter transformer tap changer is with high stability in relative large bus voltage fluctuation condition. One simplified relation formula between HVDC operation parameters and valve power loss is also presented here in different tap-changer control modes. This paper presents a powerful theory support for long-term stable operation of both HVDC valve and its cooling system, with large bus voltage fluctuation on primary side of HVDC converter transformer.

KEYWORDS

HVDC Station; Valve Power Loss; Tap Changer Control; Simplified Loss Formula

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INTRODUCTION

A converter transformer is one of most important equipment in HVDC station, while a tap-changer is a crucial part of the converter transformer for long-term safe operating period. Mechanical switching life time is a key index to examine the tap-changer performance, so to avoid the frequent motion of the tap-changer is very important in practice. There are often two control methods for tap-changer, such as constant firing angle control method and constant voltage control method.

In most cases, the tap-changer of a converter transformer usually operates in constant firing angle control mode. However, a constant voltage control of the tap-changer is preferred when its frequent motion happens due to dc voltage fluctuation at high-voltage dc busbar. The Gui-Guang HVDC project herein is taken as an example.

Constant firing angle control was ever set for two DC poles at the rectifier station of Anshun. The control method of the tap-changer at DC pole 2 was changed into constant voltage, because there was frequent motion of tap-changer due to big voltage fluctuations upon high voltage DC bus at DC pole 2. So a constant firing angle control is set to the tap-changer at Pole 1, and a constant voltage control is set to the tap-changer at Pole 2. After long-term on-site operation and data analysis, it shows that the temperature of cooling water for pole 2 valve room is higher than one for pole 1 valve room.

The paper has analyzed and concluded the change rule between the operating temperature of valve hall equipment and the inner circulating water temperature of valve cooling system under the different tap-changer position and control mode conditions, also setting up the mathematical model among them through taking into consideration various factors on power loss.

At the same time, on the basis of the established mathematical model, it has been confirmed further whether the valve hall equipment and the valve cooling system are in safe operation at long-term constant voltage control mode of tap-changer at Pole 2.

Moreover, the simplified formula between the operation data and valve power loss in different tap control mode is derived here directly, which is very convenient for the engineering design and do operation safety confirmation.

HVDC Project Parameters and Operating Modes

The Guizhou-Guangdong DC Transmission Project is designed as the bipolar 12-pulse HVDC transmission with a total rated power capacity of 3000 MW (500 kV, 3000 A), measured on the DC side of the rectifier.

It should be noted that in this project the dc voltage control is utilized as primary control method for the normal closed loop control mode at the inverter instead of extinction angle control, which can be often found in other DC schemes. Table 1 shows the nominal bipolar operation parameters.

Table 1. Nominal bipolar operation parameters.

Item	Variable	Unit	Rectifier	Inverter
DC power	Pdn	MW	3000	2847
DC current	Idn	A	3000	3000
DC voltage	Udn	kV	500	474.5
Firing angle	alfa	deg	15	---
Extinction angle	gamma	deg	---	17
Overlap	u	deg	21.3	19.5
Transformer impedance	uk	pu	0.16	0.152
Rel. inductive. voltage drop	dxn	pu	0.08	0.076
Rel. resistive voltage drop	drn	pu	0.003	0.003
Total. rel. voltage drop	dxtot	pu	0.083	0.073
No-load voltage	Udion	kV	283.5	268.6
Transformer rating (6-pulse)	Sn	MVA	889.6	843.8
Transformer secondary. voltage	Usecn	kV	209.7	198.9
Transformer primary voltage	Uac	kV	525	525
Converter reactive power	Qdc	MVAr	1537	1498

With extinction angle control, the extinction angle of the converter is controlled to a nominal minimum value typically in the range of 17°. The tap changer control at the inverter then controls the

inverter DC terminal voltage such that the rectifier DC terminal voltage is maintained within a band around the nominal dc voltage of 1 p.u., the dc voltage variation during operation depends on several parameters such as the tap changer positions. Table 2 shows the converter transformer tap changer parameters.

Table 2. Converter transformer tap parameters.

Item	Parameter	Parameter
Station	Anshun	Zhaoqing
Unom [kV]	525	525
Umax [kV]	551.25	551.25
Umin [kV]	498.75	485.625
Usecn [kV]	209.7	198.9
Maxi. steady state voltage, valve side [kV]	215.6	206.1
Nominal Ratio	525/209.67	525/198.56
Range:	- 5% to + 20%	- 7.5% to + 20%
No of steps:	- 4 steps/ +16 steps	-6 steps/ +16 steps
	(total 21 steps)	(total 23 steps)
Step size:	1.25 %	1.25%

Using DC voltage control method, the inverter controls the DC voltage of the inverter terminals such that the rectifier DC voltage is maintained at a constant value of 1.0 p.u.. In this mode of control, the tap changer is either controlled to maintain extinction angle within a defined range or to maintain the Udio(valve AC voltage) at a constant value.

The thyristor valves and associated equipment have been designed and rated to meet the performance. Each valve consists of 78 thyristor levels (three redundant) and 12 non-linear valve reactors connected in series. The valve sections consist of 13 thyristor levels and two valve reactors connected in series and one grading capacitor. The cooling system shall be a single closed loop system. Heat transfer to ambient will be provided by evaporative coolers. Each system of one single pole works independent from other cooling and air conditioning system. Table 3 shows the cooling system parameters.

Table 3. Cooling system parameters.

Item	Anshun Station	Zhaoqing Station
Cooling capacity	5100kW	5100kW
Max Water inlet temperature	49.2C°	49.2C°
Min Water inlet temperature	5C°	5C°
Min deionized water flow	4110 l/min	4110 l/min
Max deionized water flow	4280 l/min	4280 l/min
Pressure drop across on Thyristor tower	3.5 bar	3.5 bar
Max deionized water pressure	0.5 MPa	0.5 MPa
Water conductivity	0.2-0.5μs/cm	0.2-0.5μs/cm

Relation between Tap Changer Control Mode and Valve Power Loss

The paper first considers the relation between valve power loss and water coolant temperature and water coolant flow rate at the rated condition. There is not a better method to do direct measure loss because of the complexity of the operating waveform of the converter valve.

The international standard of IEC61803 is taken as engineering design criteria to calculate the converter valve loss so as to design the valve cooling system. The thyristor valve loss includes on-state losses, diffusion loss, other on-state losses of a single valve, and resistive damping loss, turn-off loss, and anode-reactor loss. The largest part of them is both on-state loss and damping loss. The commonly used method is to calculate the loss of each component of thyristor valve, and finally to do the sum of the losses of the converter valve.

A large amount of on-site measured data and design data ensure correct results. In given direct current conditions, constant firing angle control mode will ask for good positioning of tap changer in the case of setting firing angle 15 degree. The operation data in constant firing angle control mode is listed in table 4 after selecting the nearest tap position to approach this ratio value.

Table 4. Operation data in constant firing angle control mode

Direct current (A)	Firing angle (deg)	Overlap angle (deg)	DC power (MW)	DC voltage (KV)	No-load voltage (KV)	Tap position
3000	14.85	21.76	1500	500	282.62	2
2400	15.84	18.14	1200	500	279.14	3
1800	14.41	15.53	900	500	272.48	5
1200	15.68	10.94	600	500	269.30	6
600	14.67	6.55	300	500	263.22	8

In given bus voltage of 537kV, the tap position is calculated to be two in order to keep the Udi0 value constant under the constant voltage control mode,. The operation data calculated in constant voltage tap control mode is shown in table 5.

Table 5. Operation data in constant voltage control mode

Direct current (A)	Firing angle (deg)	Overlap angle (deg)	DC power (MW)	DC voltage (KV)	No-load voltage (KV)	Tap position
3000	14.85	21.76	1500	500	282.62	2
2400	18.16	16.85	1200	500	282.62	2
1800	20.97	12.37	900	500	282.62	2
1200	23.45	8.14	600	500	282.62	2
600	25.71	4.04	300	500	282.62	2

It is known that there is more significant difference between two control modes of tap changer upon valve loss under small transmitted power condition. Then some measured data on site near minimum delivered power had been collected for further comparison and verification.

As for loss calculation in working conditions, it is concluded that the pole 2 valve loss is usually more than pole1 valve one at the same transmitted power, in result of the pole 2 water cooling water temperature relatively higher, as illustrated in figure 1. In the case of the same transmission power, especially near the minimum power, loss in the constant voltage control mode is significantly bigger than one in the given angle control mode. The closer the transmission power is to the rated power, the closer the valve loss is to the same in these two cases. The figure 2 demonstrates such conclusion.

Table 6. The measured data of Pole 1.

Time	Measured firing angle of Pole 1	Measured dc power of Pole 1	Measured dc voltage of Pole 1	Measured dc current of Pole 1
12:50 on Feb. 6	14°	250MW	499kV	503A
17:45 on Feb. 6	15°	300MW	499kV	503A
12:23 on Feb. 7	15°	250MW	499kV	502A
17:52 on Feb. 7	15°	300MW	499kV	503A

Table 7. The measured data of Pole 2.

Time	Measured firing angle of Pole 2	Measured dc power of Pole 2	Measured dc voltage of Pole 2	Measured dc current of Pole 2
12:50 on Feb. 6	29°	250MW	-497kV	502A

17:45 on Feb. 6	29°	250MW	-497kV	502A
12:23 on Feb. 7	28°	250MW	-497kV	501A
17:52 on Feb. 7	28°	300MW	-497kV	604A

Table 8. The measured positions of tap changer.

Time	Position of tap changer at transformer 1 of Pole 1	Position of tap changer at transformer 2 of Pole 1	Position of tap changer at transformer 1 of Pole 2	Position of tap changer at transformer 2 of Pole 2	Measured AC bus voltage
12:50 on Feb. 6	9	9	2	2	537kV
17:45 on Feb. 6	8	8	2	2	537kV
12:23 on Feb. 7	9	9	2	2	537kV\539kV
17:52 on Feb. 7	8	8	2	2	535kV\537kV

Table 9. The temperature of water coolant of valve cooling system and the corresponding power loss.

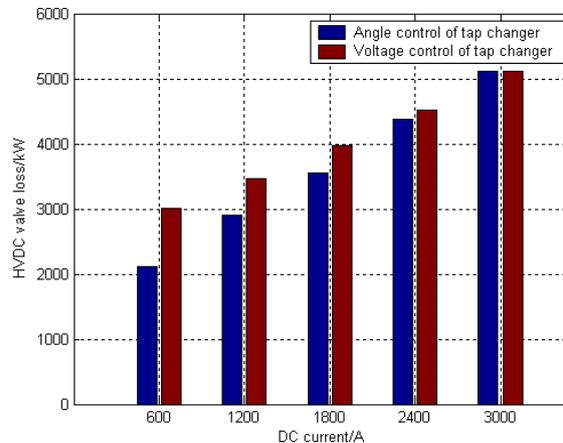| Time	Water coolant temperature of cooling system of Pole 1		Water coolant temperature of cooling system of Pole 2		Valve power loss of Pole 1	Valve power loss of Pole 2
-	Inlet/C°	Outlet/C°	Inlet/C°	Outlet/C°	kW	kW
12:50 on Feb. 6	20.2	21.5	24.9	28.2	1953.0	3176.0
17:45 on Feb. 6	23.8	25.5	29.6	32.8	2026.0	3272.0
12:23 on Feb. 7	23.5	25.0	31.1	34.0	2008.0	3107.0
17:52 on Feb. 7	25.0	26.5	32.6	35.9	2137.0	3195.0

Figure 1. Valve loss versus direct current in different tap changer control mode.

Simplified Power Loss Formula

There are many parameters mentioned in IEC61083 which is not easy for operators to understand their meaning and extract them from many specialized materials as to get direct relation between operating status and valve power loss. Herein, a simplified relation is presented which takes into the input variables of the important operating parameters of HVDC transmission project while the physical parameters of equipment are not required. Thereby operators are able to get real-time valve power loss from monitored data on HMI screen by means of such simplified relation.

It is applied with the fitting high-order variable and single variable as a practical approach and with valve operation characteristic and power loss calculation base on IEC61083. Two formulas with high accuracy as compared with IEC61083-base results have been achieved in two tap changer control modes.

The valve power loss is calculated in the follow formula 1 in constant firing angle mode, and illustrated in the tables from 10 to 12.

$$P_{loss} = U_L^2 \left\{ \frac{61}{7399} \alpha + \alpha^2 \left(\frac{1009}{2524} \cdot 10^{-9} U_{dc}^2 - \frac{9}{89077} \right) \right\}$$

$$+ U_L^2 \left\{ \alpha^2 \left(-\frac{133}{856} \cdot 10^{-4} \frac{U_{dc}}{\alpha} \right) + \alpha^4 \left(\frac{1727}{1913} \cdot 10^{-8} + \frac{575}{678} \cdot 10^{-18} U_{dc}^4 \right) \right\}$$

$$+ U_{dc} \left(\frac{2007}{106} - \frac{312}{21275} U_{dc} - \frac{87706}{19 \cdot U_{dc}} \right)$$

$$+ I_{dc} \left(\frac{563}{560} + \frac{825}{256} \cdot 10^{-8} U_L I_{dc} + \frac{1291}{1217} \cdot 10^{-9} U_L^2 I_{dc} \right)$$

(1)

where, P_{LOSS} is the valve power loss per 12 pulse, kW ; U_L is the phase-phase voltage RMS of converter transformer on valve side, kV ; α it's the firing angle, degree; U_{dc} is the direct voltage across valve, kV ; I_{dc} direct current, A。

Table 10. Bipolar operation mode，100% DC voltage, Rdc = 8.5Ω, Uac=525/525kV.

Firing angle	Direct voltage	Direct current	Valves Loss /kW	
(deg)	(kV)	(A)	IEC61083	Formula
39.7	356.5	421	3263	3265
27.9	408.4	551	2641	2629
20	432.5	694	2330	2339
15.3	500	900	2519	2533
17.3	500	1350	3179	3177
16	500	2400	4394	4390
15.1	500	2550	4538	4527
14.3	499.3	3156	5294	5294
13.6	498.6	3312	5468	5471

Table 11. Monopolar ground mode，100% DC voltage, Rdc = 13.76Ω, Uac=525/525kV.

Firing angle	Direct voltage	Direct current	Valves Loss /kW	
(deg)	(kV)	(A)	IEC61083	Formula
39.7	356.5	421	3263	3265
27.9	408.4	551	2641	2629
20	432.5	694	2330	2339
16.3	500	750	2403	2425
15.3	500	900	2519	2533
17.3	500	1350	3179	3177
16.2	500	1950	3840	3834
14.1	500	3150	5278	5275
13.1	500	3300	5434	5430

Table 12. Monopolar metallic return mode，100% DC voltage, Rdc = 22.7Ω, Uac=525/525kV.

Firing angle	Direct voltage	Direct current	Valves Loss /kW	
(deg)	(kV)	(A)	IEC61083	Formula
39.7	356.5	421	3263	3265
27.9	408.4	551	2641	2629
20	432.5	694	2330	2339
16.3	500	750	2403	2425
15.3	500	900	2519	2533
17.3	500	1350	3179	3177
16.8	500	2700	4826	4843
14.1	500	3150	5278	5275

13.1	500	3300	5434	5430

The same method is applied so that the valve power loss is calculated in the follow formula 2 in constant voltage control mode, and illustrated in the tables from 13 to 15.

$$P_{LOSS} = U_{dc}^2 \left\{ \frac{2362}{177 \cdot U_{dc}} - \frac{95}{4272} + \frac{1894}{995} \cdot 10^{-5} \frac{U_L^2}{U_{dc}} \alpha \right\}$$
$$+ U_{dc}^2 \left\{ \alpha^2 \left(\frac{982}{837} \cdot 10^{-19} U_L^2 U_{dc}^2 \alpha^2 - \frac{1265}{249} \cdot 10^{-10} U_L^2 \right) \right\}$$
$$+ U_L^2 \left(\frac{5}{36946} \alpha^2 - \frac{241}{28942} \alpha - \frac{1751}{276} \alpha^4 \right)$$
$$+ I_{dc}^2 \left(\frac{993}{1135 \cdot I_{dc}} + \frac{2693}{1378} \cdot 10^{-8} U_L + \frac{908}{493} \cdot 10^{-9} U_L^2 \right)$$
$$- \frac{10482}{41}$$

(2)

where, P_{LOSS} : valve loss per 12 pulse, kW ; U_L :phase-phase voltage RMS of converter transformer on valve side, kV ; α :firing angle, degree ; U_{dc} :direct voltage across valve, kV ; I_{dc} :direct current, A。

Table 13. Bipolar operation mode，100% Direct voltage, Rdc = 8.5Ω, Uac=525/525kV.

Firing angle (deg)	Direct voltage (kV)	Direct current (A)	Valves Loss /kW IEC61083	Formula
26.97	500	300	2824	2829
25.91	500	600	3034	3035
24.82	500	900	3256	3255
23.08	500	1350	3611	3609
22.47	500	1500	3736	3734
21.22	500	1800	3993	3992
19.88	500	2100	4262	4262
18.45	500	2400	4541	4543
16.91	500	2700	4831	4833
14.54	499.3	3156	5303	5307
13.83	498.6	3312	5477	5486

Table 14. Monopolar ground mode，100% DC voltage, Rdc = 13.76Ω, Uac=525/525kV.

Firing angle (deg)	Direct voltage (kV)	Direct current (A)	Valves Loss /kW IEC61083	Formula
26.97	500	300	2824	2829
25.91	500	600	3034	3035
24.82	500	900	3256	3255
24.25	500	1050	3372	3370
21.86	500	1650	3863	3862
20.56	500	1950	4126	4126
19.18	500	2250	4400	4401
17.7	500	2550	4685	4687
16.08	500	2850	4980	4981
14.29	500	3150	5286	5282
13.31	500	3300	5442	5434

Table 15. Monopolar metallic return mode，100% DC voltage, Rdc = 22.7Ω, Uac=525/525kV.

Firing	Direct voltage	Direct	Valves Loss

angle (deg)	(kV)	current (A)	/kW IEC61083	Formula
26.97	500	300	2824	2829
25.91	500	600	3034	3035
24.82	500	900	3256	3255
24.25	500	1050	3372	3370
23.08	500	1350	3611	3609
21.86	500	1650	3863	3862
21.22	500	1800	3993	3992
19.18	500	2250	4400	4401
17.7	500	2550	4685	4687
15.21	500	3000	5132	5131
14.29	500	3150	5286	5282
13.31	500	3300	5442	5434

Conclusions

It is concluded that the temperature of valve water coolant in the case of tap-changer operating in constant voltage mode, particularly near the minimum transmission power, is much higher than the case in constant firing angle mode.

The reason behind such phenomena is got by taking into consideration the mathematical relation of tap-changer control mode and HVDC valve power loss.

There is only no more than 0.2 per cent as mean error between IEC61803-based valve power loss and simplified-formula presented in the paper. These results show that the presented formula of valve loss based on operation data, can agree well with the IEC61083-based calculated power loss. With IEC 61083 Standard by using the parameters of relative primary equipment to calculate the valve power loss, these parameters of primary equipment usually are numerous and not available, which make on-site operator difficult to understand and to use properly. The presented formula gives the user a easy way to get the data on operating interface in the control room to generate the valve power loss rapidly.

The formula is convenient for on-site operator to perform effectively analysis and visual inspection on the valve operation safety in different tap changer control mode. This way has been utilized in Anshun HVDC station by the operators to predict the valve power loss where the correctness and precision are demonstrated with real operation data.

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