Electromagnetic Transient Simulation for Study on Commutation Failures in HVDC Systems

Xia Chengjun, Xu Yang, Shan Yuanda

Abstract--In order to improve reliability of HVDC transmission system, commutation failures in HVDC systems are studied. Electromagnetic transient simulation model of Longquan-Zhengping HVDC system has been established and simulation results are compared using different AC system equivalent method. Analysis about affection of three phase fault and single phase fault on inverter commutation failure suggests that phase shift other than voltage dip has also large affection on commutation failure under certain circumstances.

Keywords: HVDC, Electromagnetic Transient Simulation, Commutation Failure

I. INTRODUCTION

High Voltage DC transmission technology is commonly used for long distance bulk power transmission and asynchronously connecting two AC power grids. With the implementation of West-East Electricity Transmission Project and Nationwide Power Interconnection Project, with the construction of large scale hydropower stations and pithead thermal power plants in western areas, HVDC technology will have a wide application prospect in China.

The running experiences of existing HVDC transmission systems suggest that we shall pay special attention to reliability of HVDC transmission systems: (1) Statistic data about main long distance high capacitance HVDC projects in the world illustrates that average HVDC mono-pole blocking is 9.08 times per year, and average HVDC bi-pole blocking is 0.64 time per year, commutation failure is 43.3 per year. The running experience of Gezhouba-Shanghai, Tianshengqiao-Guangzhou HVDC systems suggests that fault rating of HVDC in China is even higher than the statistic data. (2)With the increasing of HVDC link's transfer capacity (such as 3000MW), the affection of HVDC faults (such as commutation failure, mono-pole blocking, bi-pole blocking) will have greater affection to both sending terminal and receiving terminal. For sending terminal fast generator dropping can be utilized, while for receiving terminal, some load must be cut to maintain power system's security in severe case. If HVDC bi-pole blocking occurs and stops running, the receiving terminal lose a bulk power supply and maybe lose stability especially when it runs under heavy load and little spare power supply, which has some similar points with the blackout of Italy in 2003. (3)Interactions of multiple HVDC links terminating in a same AC system (Multi-infeed HVDC system) may cause several HVDC systems bi-pole blocking and stop running at the same time, which threatens stability of power system severely.

As previous work shows that when HVDC system faults such as mono-polar blocking, bipolar blocking occur, the receiving terminal Jiangsu Provincial power grid will not lose transient and dynamic stability, and the voltage of main 500kV buses is in the permitted range. The focus is whether faults of AC system will cause HVDC system continuous commutation failure, leading to HVDC stop running.

In this paper the electro-magnetic transient model including the control and protection of Longquan-Zhengping HVDC transmission system is established. Parameters of the main circuit use the practical project parameters. Longquan Station runs as rectifier station at constant current (CC) mode, and Zhengping Station runs as inverter station at constant extinguish angle (CEA) mode. Two different equivalent methods of AC network are applied and affection of AC system faults (three phase short circuit and single phase short circuit to ground) to HVDC system is studied.

II. OVERVIEW OF LONGQUAN - ZHENGPING HVDC PROJECT

Totally there will be three HVDC links from Three Gorges Area to East China. First one, Gezhouba-Nanqiao HVDC link has been running since 1989. Second one Longquan-Zhengping HVDC link is commissioned in 2003. The Third one, Three Gorges to Shanghai is under construction and planned to run in 2007.

The Longquan-Zhengping HVDC link starts at Longquan Converter Station in Yichang City, Hubei Province, and terminates in the east at Zhengping Converter Station in the city of Changzhou, Jiangsu Province. The distance of transmission is around 890km. The typical operation parameters of the DC system are: (1) The transmission power $P_d = 3000MW$. (2) The minimum transmission power $P_{d\_\min} = 300MW$ (both for bipolar and monopolar). The overload capacity is 10%. (3) The rated DC voltage is $V_d = \pm 500kV$, $V_{d\_\min} = \pm 350kV$. (4) The firing angle $\alpha = 15°$, the extinguish angle $\gamma = 17°$. (5) The normal continuous operation voltage ranges of Longquan and Zhengping Converter Station AC buses are 500-550kV and

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490-525kV respectively. The most frequent operation ranges of AC bus voltages of Longquan and Zhengping Converter Station are 530-540kV and 500-510kV respectively.

Some parts of the project relating simulation model will be illustrated as follows.

A. Thyristor Valves

Because single phase two winding converter transformers are used in the project, double valve scheme is designed.

Thyristors built from $\Phi 125mm$ crystal are used in the project. The rated current and voltage are 3kA and 7.2kV. There are 90 thyristors in a valve at Longquan and 84 thyristors in a valve at Zhengping. New elements, such as dry type damping capacitors and film DC resistors are used.

B. Converter Transformers

Converter transformers of Longquan and Zhengping converter station are single phase two winding configuration. Rated parameters are as follows:

(1) Longquan Converter Transformers: Rated voltage (phase to earth, rms) of Line Winding is $525/\sqrt{3}$ kV, that of valve windings is $210.4/\sqrt{3}$ for Y winding and 210.4 for Δ winding. The rated power is $S_{N2w} = 297.5MVA$. Transformer reactance is 16%.

(2) Zhengping Converter Transformers: Rated voltage (phase to earth, rms) of Line Winding is $500/\sqrt{3}$ kV, that of valve windings is $200.4/\sqrt{3}$ for Y winding and 200.4 for Δ winding. The rated power is $S_{N2w} = 283.7MVA$. Transformer reactance is 16%.

C. Reactive Compensation

Both sending and receiving AC systems are strong and only switch-able capacitor banks on the converter station AC buses are used as compensation equipment (also as AC filters). At Longquan, 8 switch-able sub-banks (2*118+6*140Mvar) with capacity of 1076 Mvar are designed and at Zhengping, 9 switch-able sub-banks (4*190+5*220) with capacity of 1860 Mvar are installed. At Longquan, 4*50 Mvar low voltage capacitors are installed on the tertiary of 500/220 autotransformer to absorb reactive power surplus at light load.

D. AC Filtering

At Longquan Station, all 8 reactive power compensation capacitor sub-banks are designed as three types of AC filters. 3 are designed as double tuned filters tuned at 11^{th} and 13^{th} harmonic. 3 are designed as double tuned filters tuned at 12^{th} and 24^{th} harmonic. The other 2 are designed as C-type filters tuned at 3^{rd} harmonic. At Zhengping Station, 5 from 9 capacitor banks are designed as double tuned filters tuned at 12^{th} and 24^{th} harmonic and the rest 4 banks are used as parallel capacitor banks.

E. DC Filtering

At each terminal pole, two filter arms are installed. Both are designed as double tuned filters, one tuned at 12^{th} and 24^{th} harmonic and the other tuned at 12^{th} and 36^{th} harmonic.

F. Smoothing Reactor

Oil insulated smoothing reactors with reactance of 270mH are used for this project. All bushings are of composite type.

G. HVDC Transmission Line

The HVDC transmission line is composed of 4*ACSR720. Two ground wires are built through the whole distance of the line for lightening protection, in which one is OPGW.

III. EQUIVALENT AC SYSTEM

Two different methods representing inverter AC system, one is based on short circuit current and the other is based on Ward equivalent method, are employed in our simulation owing to the following considerations:

(1) It is difficult to include a large scale AC system in electromagnetic transient simulation, so we must equate the AC system.

(2) We believe that key issue about multi-infeed HVDC system is to investigate how and what the ac system interacts with HVDC system. Our present research work is the basis to resolve multi-infeed HVDC system problem.

(3) Part of the ac system is represented in detail and others are equivalent, the accuracy and the feasibility of our research can be balanced.

A. Based on Short Circuit Current

According to the minimum short-circuit capacity and current considered at designing stage: the minimum short-circuit capacity and current of Longquan Station are 11185MVA and 12.3kA respectively; the minimum short-circuit capacity and current of Zhengping Station are 20698MVA and 23.9kA respectively. AC system impedance can be calculated by the formula $X_s = \frac{U^2}{S}$. Thus the AC system impedance of Longquan converter station is $X_{rs} = \frac{U^2}{S} = \frac{525^2}{11185} = 24.64\Omega$, and the system impedance of Zhengping is $X_{rs} = \frac{U^2}{S} = \frac{500^2}{20698} = 12.08\Omega$.

Then the ac system can be composed of the system impedance and infinite AC source as Fig.1 shows.

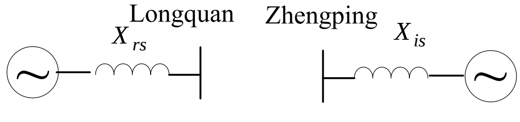

Fig. 1. AC System of Longquan and Zhengping Converter Station

Since our purpose is to study commutation failure at Zhengping converter station, in the following contents of this paper, AC system of Longquan remains the same as Fig.1. AC system of Zhengping will have a more detailed representation.

B. Based on Ward Equivalent Method

For a certain running configuration of Jiangsu electric power system in 2006, equivalent ac system based on Ward equivalent method has been finished. That is to equate the ac system to 500kV Wunan and Yini bus as Fig.2 shows. The 500kV ac lines of Zhengping to Wunan and Zhengping to Yini remain the same as they actually are. The parameters of ac system are obtained from transient stability program PSASP. The 500kV Zhengping to Wunan lines are 4*LGJ-720 with length 6km. The Zhengping to Yini lines are 6*LGJ-240 with length 42km.

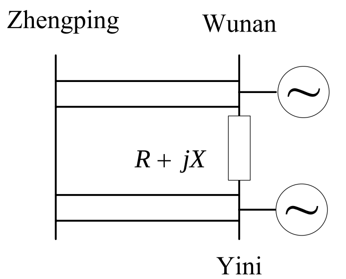

Fig. 2. AC System of Zhengping Converter Station

IV. SIMULATION MODEL

System Configuration of Longquan-Zhengping monopolar HVDC link can be shown as Fig.3. It is a 12 pulses HVDC system. Parameters of main circuits can be obtained from the actual system. Converter controllers of the CIGRE bench model are modified a little and applied in our simulation.

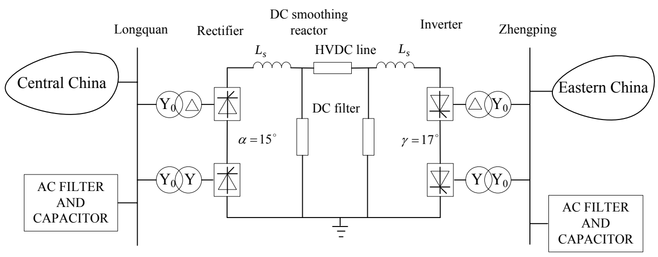

Fig. 3. Monopolar of Longquan-Zhengping HVDC Link

Simulation tests were performed to induce commutation failures during single-phase ground faults and three phase ground faults on the Eastern China side. For ac system represented by Fig.1, the fault is applied at the inverter bus (Zhengping). For ac system represented by Fig.2, the fault is applied at 500kV Wunan bus and 500kV Yini bus respectively.

A fault resistance is connected at the fault location. By adjusting the fault resistance, voltage dips with different remaining voltages are applied at the inverter bus. The fault starts at time instant 0.4s and continues for 0.1s.

V. COMMUTATION FAILURE ANALYSIS

A. Infinite AC System

Commutation failures in HVDC transmission systems are illustrated in [1]. Symmetrical three-phase conditions, (1) give the maximum inverter voltage reduction which will not, in theory, cause commutation failure or, as a corollary, it gives the minimum voltage reduction required to produce the onset of commutation failures for a balanced three-phase ground fault in the ac system, without consideration of any possible fundamental wave distortions or phase angle shifts.

$$\Delta V = 1 - \frac{I_d'}{I_d} \frac{X_{cpu}}{X_{cpu} + \cos\gamma_0 - \cos\gamma} \tag{1}$$

Unsymmetrical three-phase conditions, the onset or probability of commutation failures depends on both the voltage reduction magnitude and the zero-crossing phase shift as expressed by (2).

$$\Delta V = 1 - \frac{I_d'}{I_d} \frac{X_{cpu}}{X_{cpu} + \cos(\gamma_0 + \phi) - \cos\gamma} \tag{2}$$

Before the simulation, let's estimate the voltage reduction leading to commutation failure for Zhengping inverter, just assuming the Zhengping side ac system is infinite.

For the Longquan-Zhengping HVDC project, which is a large, bulk power, long overhead line system, $X_{cpu} = 16\%$, $\gamma = 17°$, $\alpha \cong 142.78°$. Considering a constant dc current and an impractical limit-case of $\gamma_0 = 0°$ (perfect ideal valves):

$\Delta V = 1 - 0.16/(0.16 + 1 - \cos 17°) \cong 21.5\%$

That is, a voltage reduction of 20% would be required to produce a commutation failure. If a more realistic valve turn-0ff of $\gamma_0 = 8°$ is assumed, the voltage reduction would have to be:

$\Delta V = 1 - 0.16/(0.16 + \cos 8° - \cos 17°) \cong 17.5\%$

If a dc current increase of 5% occurred due to the reduced ac voltage, then the voltage reduction required to produce commutation failure would only have to be:

$\Delta V = 1 - 1.05 * 0.16/(0.16 + \cos 8° - \cos 17°) \cong 13.4\%$

The corresponding ΔV for a 10% current increase would be:

$\Delta V = 1 - 1.1 * 0.16/(0.16 + \cos 8° - \cos 17°) \cong 9.3\%$

B. Equivalent System Based on Short Circuit Current

Under this condition, simulation results of three phase faults and single phase fault with various fault resistance are shown in TABLE I. From curve of γ, if $\gamma \le 8°$ is found, then commutation failure occurs. If during all the simulation time, $\gamma \succ 8°$, then there's no commutation failures.

TABLE I
SINGLE PHASE FAULTS & THREE PHASE FAULTS

	Three Phase Fault		Single Phase Fault	
Rf(Ω)	V(p.u.)	Commu	V(p.u.)	Commu
0	0.00	FAIL	0.00	FAIL
10	0.55	FAIL	0.60	FAIL
20	0.72	FAIL	0.77	FAIL
30	0.82	FAIL	0.84	FAIL
40	0.86	FAIL	0.88	FAIL

50	0.88	FAIL	0.91	FAIL
60	0.90	FAIL	0.92	FAIL
70	0.91	FAIL	0.94	OK
80	0.91	FAIL	0.94	OK
90	0.92	OK	0.95	FAIL
100	0.94	OK	0.96	OK

It also found from TABLE I that simulation result is abnormal when the case is Rf=90Ω for single phase faults. Thus the simulation curves for single phase faults and three phase faults Rf=90Ω are given in Fig.4 and Fig.5 respectively. It can be seen that in single phase fault case, commutation failure occurs as soon as fault clears, which is different from ordinary case.

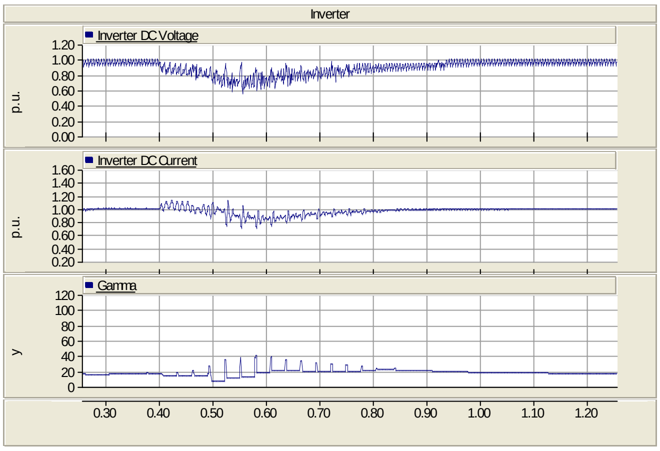

Fig. 4. Single Phase Fault, Rf=90Ω

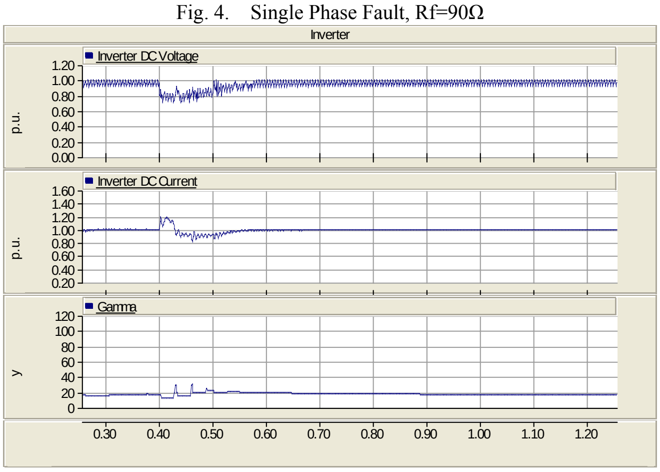

Fig. 5. Three Phase Fault, Rf=90Ω

C. *Equivalent AC System by Ward*

When AC system is given by Ward equivalent method, two fault locations are considered to study the affection of remote ac system faults. Simulation results are shown as TABLE II and TABLE III respectively.

From the simulation results we can deduce that since Wunan ac system is strong, it can prevent much more ac disturbances. However as Yini ac system is relatively weak, ac disturbances will cause HVDC system commutation failure of much more probability. Because in 2007 the Yixing Pumped Storage Plant will connect to Yini substation, we shall pay special attention to the running mode and mode-changing of pumped storage plant.

TABLE II
SINGLE PHASE FAULTS & THREE PHASE FAULTS WITH FAULT LOCATION AT 500KV YINI BUS

	Three Phase Fault		Single Phase Fault	
Rf(Ω)	V(p.u.)	Commu	V(p.u.)	Commu
0	0.40	FAIL	0.43	FAIL
10	0.73	FAIL	0.75	FAIL
20	0.84	FAIL	0.85	FAIL
30	0.89	OK	0.90	OK
40	0.91	OK	0.92	OK
50	0.92	OK	0.93	OK
60	0.93	OK	0.93	FAIL
70	0.94	OK	0.94	FAIL
80	0.94	OK	0.94	OK
90	0.95	OK	0.95	OK
100	0.95	OK	0.95	OK

TABLE III
SINGLE PHASE FAULTS & THREE PHASE FAULTS WITH FAULT LOCATION AT 500KV WUNAN BUS

	Three Phase Fault		Single Phase Fault	
Rf(Ω)	V(p.u.)	Commu	V(p.u.)	Commu
0	0.0	FAIL	0	FAIL
10	0.77	FAIL	0.75	FAIL
20	0.89	FAIL	0.78	FAIL
30	0.91	OK	0.92	OK
40	0.93	OK	0.93	OK
50	0.93	OK	0.94	OK
60	0.94	OK	0.95	OK
70	0.95	OK	0.95	OK
80	0.95	OK	0.95	OK
90	0.95	OK	0.96	OK
100	0.95	OK	0.96	OK

VI. CONCLUSIONS

Electromagnetic transient simulation model for Longquan-Zhengping HVDC transmission project has been established. Simulation results on HVDC commutation failures under three phase faults and single phase faults are analyzed. In the simulation, various methods to represent ac system are compared. It indicates that under certain conditions, unsymmetrical three phase faults (phase shift) other than voltage dips do have large affection on HVDC commutation process. It may lead to seemly abnormal results which shall be researched deeply in next step.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

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IX. BIOGRAPHIES

Xia Chengjun was born in Huanggang city, Hubei Province, P. R. China, on January 7, 1974. He graduated from Xi'an Jiaotong University in 1995 and received B.S. degree of electrical engineering. He received Ph.D. degree from Huazhong University of Science & Technology in 2003, also in electrical engineering. His employment experience included the Wuhan Steel Electric Power company, Jiangsu Provincial Electric Power Grid Company. Currently he is a post-doctor of Jiangsu Provincial Electric Power Research Institute. His major interest is stability analysis and control of electric power system, HVDC, FACTS, and power system simulation.

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