Analysis and Limiting Measures of Interphase Switching Surges on 1000kV Compact Transmission Lines

Wang Xiaotong, Ban Liangeng, Lin Jiming, Xiang Zutao

***Abstract*-- The interphase switching surges of 1000kV compact transmission lines with inverse triangle arrangement are analyzed and compared with conventional transmission lines using EMTP. It's found that interphase switching surges on compact transmission lines with the length of 360km and compensation degree of 89% could be close to 2.9p.u. even if the closing resistors of circuit breakers are applied, which are slightly higher than that of conventional transmission ones. In view of the fact that the phase distances of compact lines are significantly less than that of conventional ones, the level of interphase switching surges should be further decreased. Several measures are taken into account, such as reducing rated voltage of metal oxide arresters, installing metal oxide arresters at the middle of transmission lines, using four-star connection metal oxide arresters and so on. The results show that using four-star connection metal oxide arresters is a kind of comparatively effective measure to restrict interphase switching surges.**

***Keywords*: EMTP, 1000kV, compact transmission line, interphase switching surge, four-star connection metal oxide arresters.**

I. Introduction

THE compact transmission line technique is commonly applied to optimize the structure and arrangement of phase conductors through reducing inter-phase distance and increasing the number of bundle conductors and equivalent radius of phase conductors. As a result, not only the surge impedance is decreased, but also the natural transmission power is increased and the line corridor is compressed evidently [1-4].

China has a big population and lack of tillable field, economization on land is very important. Further reduction of the transmission line corridor and enhancing the surge impedance loading of transmission lines in a given corridor are urgently expected. The first pilot 220kV 23.6km An-Lang compact transmission line in China was put into operation in 1994. The first pilot 500kV 82.5 km Chang-Fang compact transmission line in China was put into operation in 1999. Up to now, thousands of compact transmission lines have been put into operation or are being built in China [5-10].

The first UHV Pilot Project (from Jindongnan to Jingmen) in China was put into operation in 2009. To further increase the natural transmission power of UHV transmission lines, save the line corridor, and improve the whole benefit of power network, compact transmission lines are intended to be adopted in 1000kV AC transmission system. The interphase switching surges on the 1000kV compact transmission lines are analyzed and the limiting measures are compared in this paper.

II. Electrical Parameters of Compact Transmission Lines and the Scheme of HV Shunt Reactors

The equilateral inverse triangle arrangement in tower window is used for three phase conductors of 1000kV compact transmission lines, as shown in Fig.1. The conductor configurations for triangle arrangement and level arrangement of 1000kV conventional transmission lines (which are called 'conventional 1' and 'conventional 2' for short respectively in this paper) are shown in Fig.2, where the abscissa represents the distance between conductor or ground wire and midline of line tower (right side is positive and left side is negative), the ordinate represents average height of conductor or ground wire, and the unit is in meter.

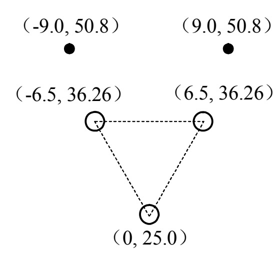
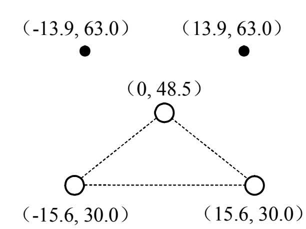


Fig. 1. Schematic diagram of conductor configurations of 1000kV compact transmission lines for inverse triangle arrangement



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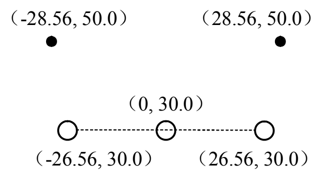
a）Triangle Arrangement (Conventional 1)



b）Level Arrangement (Conventional 2)

Fig. 2. Schematic diagram of conductor configurations of 1000kV conventional transmission lines

The sequence parameters of 1000kV compact transmission lines are list in Table I, where the earth resistivity is 1000Ω·m. As comparison, the results of conventional lines under triangle and level arrangement are also given. 12×LGJ-400/35 and 8×LGJ-500/35 aluminum conductors steel-reinforced are taken for compact and conventional transmission lines respectively. Moreover, the types of ground lines are JLB20A-170(grounded at one point for each insulated segment) and OPGW-170(grounded at several points for each continuous segment).

TABLE I

SEQUENCE PARAMETERS FOR 1000KV TRANSMISSION LINES

Line Type	Sequence parameters	Resistance (Ω/km)	Reactance (Ω/km)	Capacitance (μF/km)
Compact	Zero Sequence	0.2386	0.9162	0.00823
	Positive Sequence	0.0065	0.1899	0.01879
Conventional 1	Zero Sequence	0.2196	0.8971	0.00865
	Positive Sequence	0.0078	0.259	0.01398
Conventional 2	Zero Sequence	0.2146	0.8782	0.00946
	Positive Sequence	0.0081	0.2736	0.01351

The natural power (voltage is considered as 1050kV) and charging power (voltage is considered as 1100kV) are shown in Table II.

TABLE II

NATURAL POWER AND CHARGING POWER FOR 1000KV TRANSMISSION LINES

Line Type	Positive Sequence Surge Impedance（Ω）	Natural Power（MW）	Charging Power per 100km（Mvar）
Compact	179.4	6146.3	714.2
Conventional 1	242.9	4539.7	531.3
Conventional 2	253.9	4342.7	513.7

Since the charging power of compact transmission lines is larger than that of conventional lines at same length, larger compensating capacity of HV shunt reactors is needed. If compensating degree of transmission line is 80%-90%, the schemes of HV shunt reactors for both compact and conventional transmission lines with the overall length of 360km are shown respectively in Table III.

TABLE III

THE SCHEMES OF HV SHUNT REACTORS OF 1000KV TRANSMISSION LINES

Line Type	Length（km）	Charging Power（Ω）	Capacity of HV Shunt Reactors（Mvar）		Compensating Degree（%）
			Sending End	Receiving End	
Compact	360	2571.1	1200	1080	88.7
Conventional 1	240	1275.1	960	720	88.8
Conventional 2	120	616.4			

III. SWITCHING OVERVOLTAGES OF COMPACT TRANSMISSION LINES

According to the reference [11], the maximal phase to ground statistical switching overvoltages along the 1000kV transmission lines should be under 1.7p.u., and in the substation, not only this voltages should be under 1.6p.u., but also the maximal phase to phase statistical switching overvoltages should be under 2.9p.u.. Here, the statistical switching overvoltage refers to the switching overvoltage with its probability of emergence no more than 2%, and 1p.u. = 1100kV $\sqrt{2}/\sqrt{3}$.

A 1000kV transmission system in China is analyzed in this paper, as shown in Fig.3, where the receiving end is a switching station.

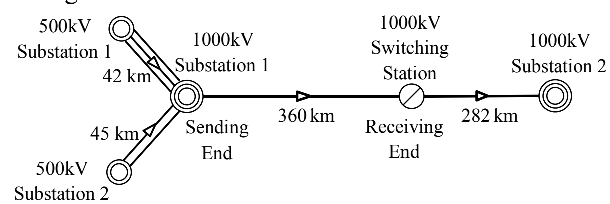


Fig. 3. Schematic diagram of a certain 1000 kV transmission system

The phase to ground and phase to phase statistical switching overvoltages (where the maximal values are taken from two cases: closing de-energized lines and single-phase re-closing) for compact and conventional transmission lines are shown in Table IV and V respectively. Only the maximal values under two operation modes are listed. In this research, 100 times of random closing for the line breakers are simulated and the maximal overvoltage among three phases is used for statistics each time; the dispersion of closing times for three phase line breakers does not exceed 5ms; 400-600Ω for the closing resistance of the line breakers are considered and its action time 8-11ms; the rated voltages of metal oxide arresters（MOA）is 828kV. In addition, the J.MARTI line model is applied in order to simulate frequency-dependent characteristics of transmission lines more precisely in this paper.

TABLE IV

STATISTICAL SWITCHING SURGES FOR COMPACT TRANSMISSION LINES

Switching Location	Closing Resistance (Ω)	Phase to Ground Statistical Overvoltages（p.u.）			Phase to Phase Statistical Overvoltages（p.u.）		
		Switch-ing Side	Along the Line	End of the Line	Switch-ing Side	Along the Line	End of the Line
Sending End	—	1.61	2.01	1.63	3.03	3.27	3.17
	400	1.32	1.44	1.43	2.29	2.44	2.40
	500	1.38	1.50	1.48	2.39	2.56	2.54
	600	1.43	1.55	1.52	2.46	2.67	2.65
Receiving End	—	1.61	1.79	1.61	3.04	3.18	3.12
	400	1.51	1.65	1.58	2.60	2.88	2.86

Switching Location	Closing Resistance (Ω)	Phase to Ground Switch-ing Side	Phase to Ground Along the Line	Phase to Ground End of the Line	Phase to Phase Switch-ing Side	Phase to Phase Along the Line	Phase to Phase End of the Line
	500	1.51	1.66	1.58	2.60	2.88	2.86
	600	1.52	**1.67**	1.58	2.61	**2.88**	2.86

TABLE V

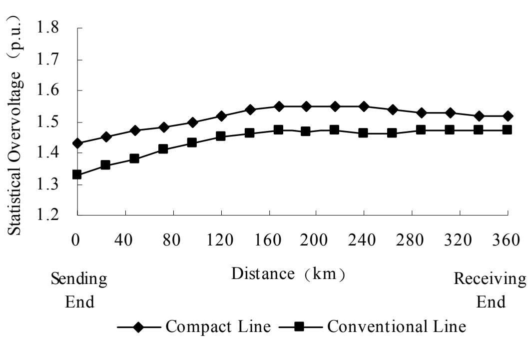
STATISTICAL SWITCHING SURGES FOR CONVENTIONAL TRANSMISSION LINES

Switching Location	Closing Resistance (Ω)	Phase to Ground Statistical Overvoltages (p.u.)			Phase to Phase Statistical Overvoltages (p.u.)		
		Switch-ing Side	Along the Line	End of the Line	Switch-ing Side	Along the Line	End of the Line
Sending End	—	1.58	1.96	1.62	2.92	3.30	3.16
	400	1.27	1.37	1.36	2.18	2.49	2.48
	500	1.30	1.43	1.42	2.21	2.54	2.54
	600	1.33	1.47	1.47	2.26	2.57	2.57
Receiving End	—	1.60	1.82	1.61	2.96	3.22	3.14
	400	1.50	1.66	1.56	2.56	2.75	2.75
	500	1.50	1.66	1.57	2.56	2.77	2.76
	600	1.50	**1.68**	1.58	2.56	**2.79**	2.77

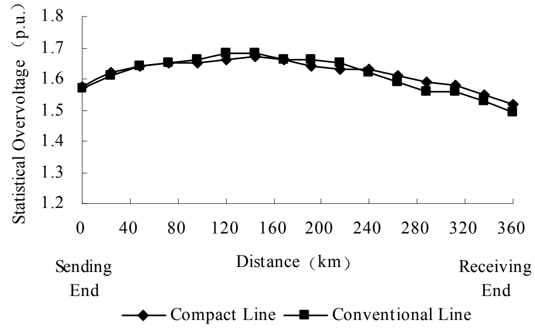
The results show that the maximal phase to ground and phase to phase statistical switching overvoltages would exceed the allowable values if the closing resistors of the line breakers were not installed. Therefore, it's necessary to install the closing resistors on the line breakers.

The maximal phase to ground switching overvoltage is generally present in the middle of the line; however, the maximal phase to phase switching overvoltage is usually present at the end of the line or its vicinity. Because of the difference of electrical parameters between the compact lines and the conventional lines, the process of reflection and refraction are more complex when the electromagnetic wave is propagated to the juncture of compact and conventional line which may result in high switching overvoltages in some situations. The phase to phase switching overvoltages for compact lines in the above cases can reach 2.88p.u. even if the closing resistors of circuit breakers are applied.

The voltage profile along the line of statistical switching overvoltages with 600Ω closing resistance of the line breakers installed for compact and conventional transmission lines are shown in fig.4-5.

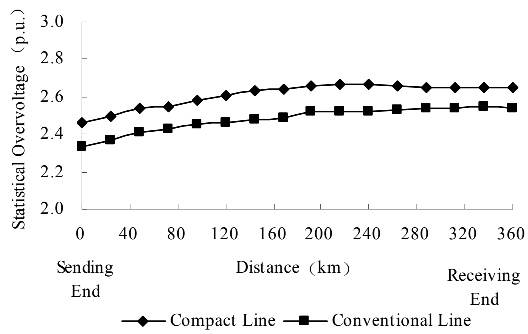


a）Switching at the sending end

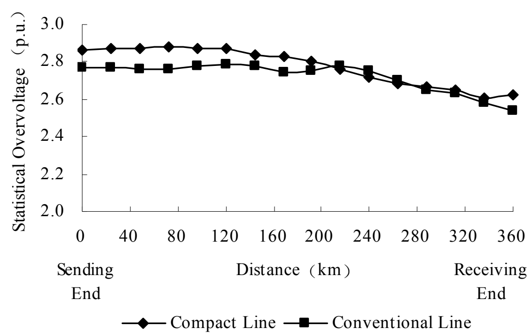


b）Switching at the receiving end

Fig. 4. Voltage profile along the line of phase to ground statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers



a）Switching at the sending end



b）Switching at the receiving end

Fig. 5. Voltage profile along the line of phase to phase statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers

If the receiving end is a substation instead of switching substation, phase to ground and phase to phase switching surges for different values of equivalent impedance for 600Ω closing resistance of the line breakers are shown in Table VI. The results show that the interphase switching surges of compact lines reduced if the receiving end is a substation instead of switching substation. If the system equivalent impedance is not more than 100Ω, the interphase switching surges is not more than 2.72p.u..

TABLE VI

STATISTICAL SWITCHING SURGES FOR COMPACT TRANSMISSION LINES IF THE RECEIVING END IS A SUBSTATION

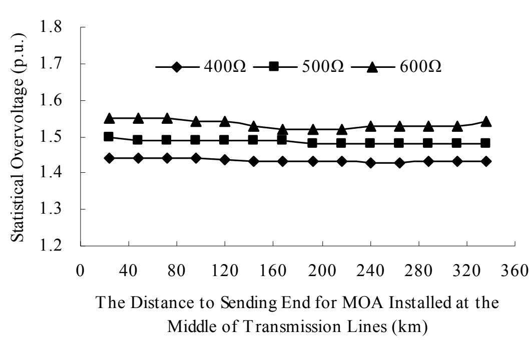
Equivalent Impedance (Ω)	Phase to Ground Statistical Overvoltages (p.u.)			Phase to Phase Statistical Overvoltages (p.u.)		
	Switching Side	Along the Line	End of The Line	Switching Side	Along the Line	End of the Line
50	1.42	1.57	1.55	2.44	2.61	2.61
100	1.46	1.60	1.56	2.49	2.72	2.72
150	1.47	1.62	1.56	2.51	2.77	2.77
200	1.48	1.62	1.57	2.54	2.80	2.80
250	1.48	1.63	1.57	2.57	2.81	2.81
300	1.48	1.63	1.57	2.57	2.82	2.82

IV. FURTHER MEASURES TO RESTRICT SWITCHING SURGES OF 1000KV COMPACT TRANSMISSION LINES

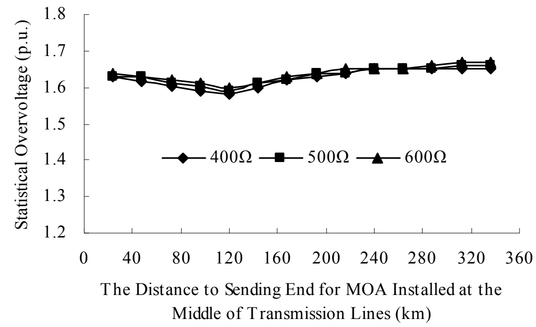
Based on the above calculation results, even if 400-600Ω closing resistors are used on the line breakers, the phase to phase statistical switching overvoltages of compact transmission lines can reach 2.88p.u. in case of switching at the receiving end. It is related to the situation where the receiving end is a switching substation. In view of the inter-phase distances of compact line significantly less than that of conventional line, it's essential to restrict the phase to phase statistical switching overvoltages of compact transmission lines. Three kinds of measures are considered in this paper:

A. Metal oxide arresters in the middle of lines

When the metal oxide arresters (rated voltage is 828kV) in the middle of lines are installed at different places, the maximal phase to ground and phase to phase statistical switching overvoltages along the lines are shown in Fig.6-7. The results show that installing metal oxide arresters in the middle of lines can restrict phase to ground switching surges to some extent. However, there is little effect to phase to phase switching surges.

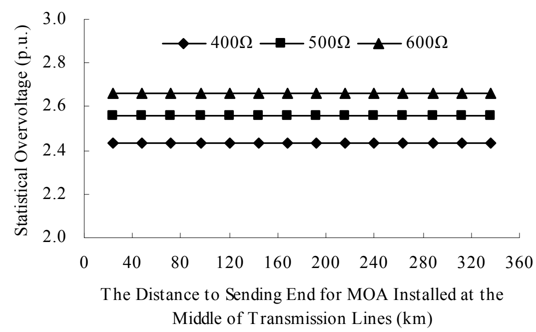


a) Switching at the sending end

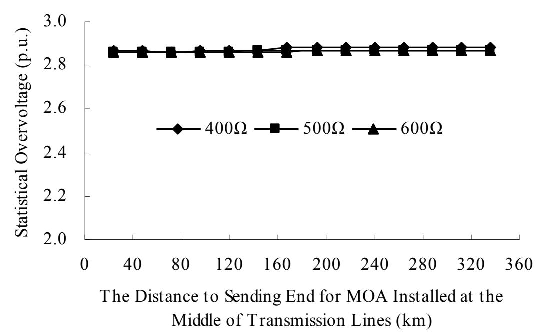


b) Switching at the receiving end

Fig. 6. Maximal phase to ground statistical overvoltages when metal oxide arresters installed at the middle of transmission lines



a) Switching at the sending end



b) Switching at the receiving end

Fig. 7. Maximal phase to phase statistical overvoltages when metal oxide arresters installed at the middle of transmission lines

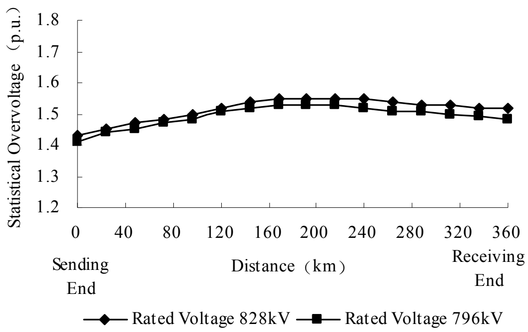
B. Reducing the rated voltage of metal oxide arresters

The phase to ground and phase to phase switching surges if the rated voltage of metal oxide arresters is reduced from 828kV to 796kV are shown in Table VII. The results show that there is no obvious effect on the interphase switching surges to reduce the rated voltage of metal oxide arresters. The voltage profile along the line of statistical switching overvoltages with 600Ω closing resistance of the line breakers installed for rated voltage 828kV and 796kV are shown in fig.8-9.

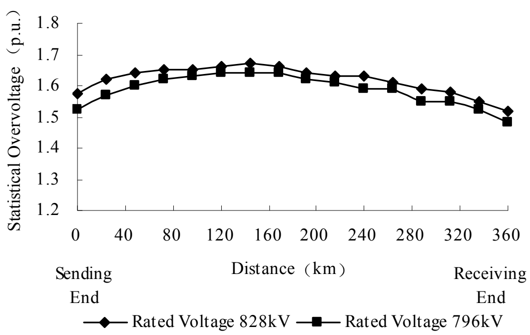
TABLE VII

STATISTICAL SWITCHING SURGES FOR COMPACT TRANSMISSION LINES IF THE RATED VOLTAGE OF MOA IS REDUCED

Switching Location	Closing Resistance (Ω)	Phase to Ground Statistical Overvoltages (p.u.)			Phase to Phase Statistical Overvoltages (p.u.)		
		Switch-ing Side	Along the Line	End of the Line	Switch-ing Side	Along the Line	End of the Line
Sending End	400	1.32	1.43	1.41	2.29	2.43	2.40
	500	1.37	1.48	1.45	2.38	2.55	2.53
	600	1.41	1.53	1.48	2.46	2.66	2.64
Receiving End	400	1.48	1.63	1.52	2.57	2.85	2.83
	500	1.48	1.64	1.52	2.57	2.85	2.83
	600	1.48	1.64	1.52	2.58	2.85	2.83

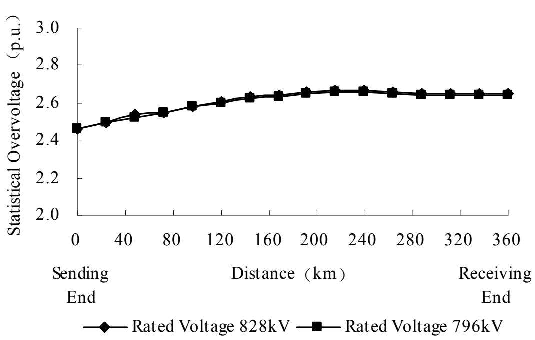


a）Switching at the sending end

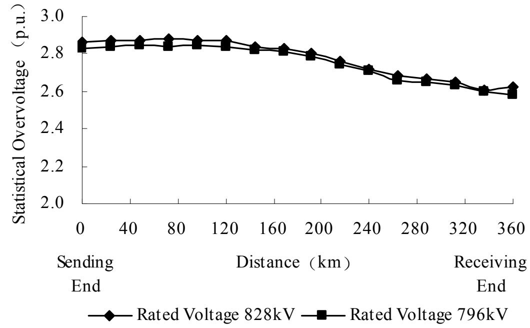


b）Switching at the receiving end

Fig. 8. Voltage profile along the line of phase to ground statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers



a）Switching at the sending end



b）Switching at the receiving end

Fig. 9. Voltage profile along the line of phase to phase statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers

C. Four-star connection metal oxide arresters

The principle schematic diagram of four-star connection metal oxide arresters [12] is shown in Fig.10, where the upper three phase metal oxide arresters are called upper elements, while the lower one is called lower element (while generally used phase to ground connection method is called three-star connection metal oxide arresters). In this paper, the rated voltage of upper element is 696kV, while the rated voltage of lower element is 132kV. The allowable energy loss for metal oxide arresters with rated voltage of 828kV is 40MJ. If the same characteristic of ZnO resistor is adopted, the allowable energy loss for upper element metal oxide arresters is 33.6MJ, while the allowable energy loss for lower element metal oxide arresters is 6.4MJ. Accordingly, phase to ground and phase to phase switching surges are shown in Table VIII. The energy losses of metal oxide arresters during closing de-energized lines for 1000kV compact lines are shown in Table IX.

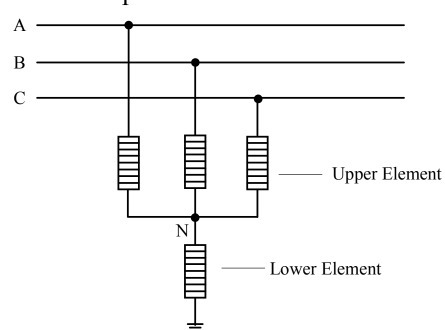


Fig. 10. Principle schematic diagram of four-star connection metal oxide arresters

TABLE VIII

STATISTICAL SWITCHING SURGES FOR COMPACT TRANSMISSION LINES USING FOUR-STAR CONNECTION METAL OXIDE ARRESTERS

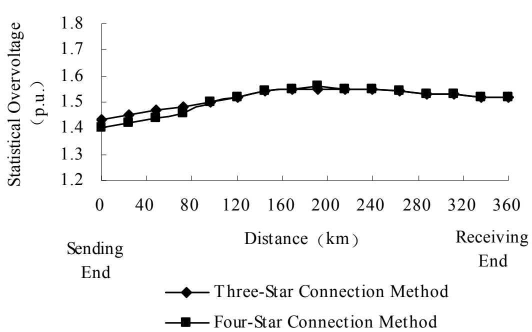
Switching Location	Closing Resistance (Ω)	Phase to Ground Statistical Overvoltages （p.u.）			Phase to Phase Statistical Overvoltages （p.u.）		
		Switch-ing Side	Along the Line	End of the Line	Switch-ing Side	Along the Line	End of the Line
Sending End	400	1.32	1.44	1.43	2.28	2.42	2.38
	500	1.36	1.50	1.47	2.37	2.53	2.48
	600	1.40	1.56	1.52	2.43	2.60	2.55
Receiving End	400	1.50	1.65	1.57	2.54	2.73	2.64
	500	1.50	1.66	1.58	2.53	2.74	2.63
	600	1.51	1.67	1.58	2.53	2.74	2.64

TABLE IX

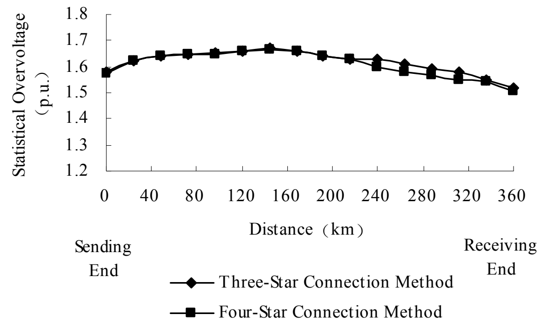
ENERGY LOSSES OF METAL OXIDE ARRESTERS DURING CLOSING DE-ENERGIZED LINES FOR COMPACT LINES

Connection Method of Metal Oxide Arresters		Closing Resistance (Ω)	Energy Losses（kJ）	
			Switching at the Sending End	Switching at the Receiving End
Three-Star Connection Method		400	115.7	1219.5
		500	342.1	1245.7
		600	624.6	1280.0
Four-Star Connection Method	Upper Element	400	189.8	1380.9
		500	445.2	1462.0
		600	740.0	1553.8
	Lower Element	400	23.3	253.4
		500	62.5	255.9
		600	107.6	260.3

The results show that phase to phase switching surge can be decreased to 2.74p.u. on condition that four-star connection metal oxide arresters are used. The maximal energy loss of upper element MOA is 1.6MJ (while the maximal energy loss for three-star connection MOA is 1.3MJ), the maximal energy loss of lower element MOA is 0.3MJ. Therefore, there are fairish margin for the allowable value.

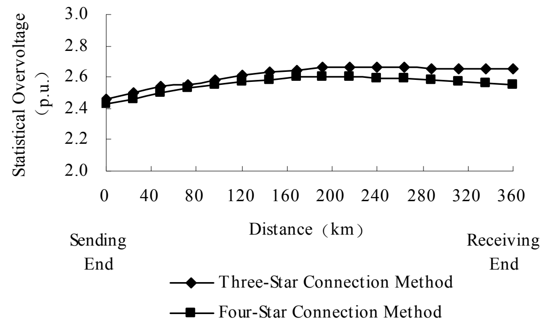


a）Switching at the sending end

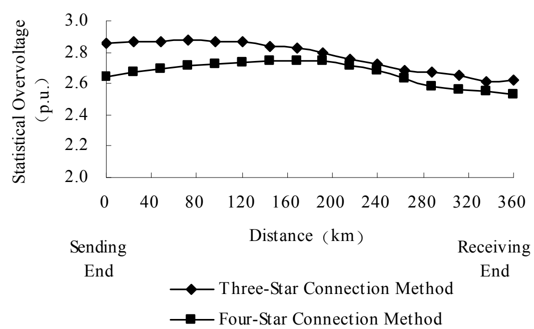


b）Switching at the receiving end

Fig. 11. Voltage profile along the line of phase to ground statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers



a）Switching at the sending end



b）Switching at the receiving end

Fig. 12. Voltage profile along the line of phase to phase statistical overvoltages on the condition that switching at the receiving end for 600Ω closing resistance of the line breakers

D. Comparison of above restrictive measures

The maximal phase to ground and phase to phase switching surges with different measures are listed in Table X. It can be seen that phase to phase switching surges are comparatively low on the condition that four-star connection metal oxide arresters are installed.

TABLE X

STATISTICAL SWITCHING SURGES FOR COMPACT TRANSMISSION LINES USING FOUR-STAR CONNECTION METAL OXIDE ARRESTERS

Restrictive Measures	Closing Resistance (Ω)	Phase to Ground Statistical Overvoltages （p.u.）	Phase to Phase Statistical Overvoltages （p.u.）
Three-Star Connection Metal Oxide Arresters	400	1.65	2.88
	500	1.66	2.88
	600	1.67	2.88
Metal Oxide Arresters in the Middle of Lines（the distance is 144km）	400	1.60	2.87
	500	1.61	2.87
	600	1.61	2.87
Reducing the Rated Voltage of Metal Oxide Arresters	400	1.63	2.85
	500	1.64	2.85
	600	1.64	2.85
Four-Star Connection Metal Oxide Arresters	400	1.65	2.73
	500	1.66	2.74
	600	1.67	2.74

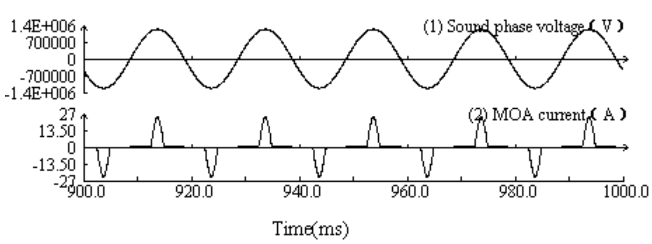
V. OPERATING CONDITION OF FOUR-STAR CONNECTION METAL OXIDE ARRESTERS DURING LOAD REJECTION WITH SINGLE-PHASE FAULT

Voltages and currents of metal oxide arrester for 1000kV compact transmission lines during load rejection with single-phase fault are shown in Table XI. Accordingly, the correlative waveforms are shown in Fig.10. Assume that the during time of single-phase fault is 5s, the energy losses of upper and lower element metal oxide arresters are 22.5MJ and 5.0MJ respectively, which are in the margin of the allowable values. As a matter of fact, during time of single-phase fault is not more than 0.5s. Therefore, the metal oxide arresters energy losses are much lower than the above values.

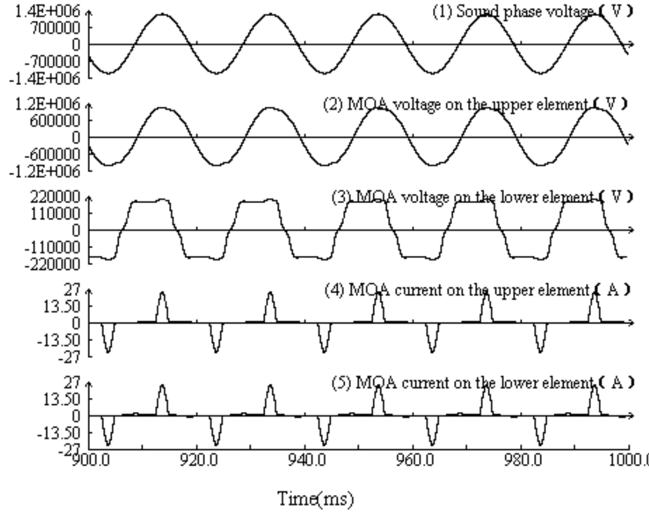
TABLE XI

VOLTAGES AND CURRENTS OF METAL OXIDE ARRESTERS DURING LOAD REJECTION WITH SINGLE-PHASE FAULT

Connection Method of Metal Oxide Arresters		Voltages（kV, peak value）	Currents（A, peak value）	Sound Phase Voltages（kV，peak value）
Three-Star Connection Method		1227.1	24.0	1227.1
Four-Star Connection Method	Upper Element	1031.5	24.1	1227.1
	Lower Element	195.6	24.0	



a) Three star connection method



b) Four star connection method

Fig. 10. Voltages and currents of metal oxide arrester for load rejection with single-phase fault

VI. CONCLUSIONS

It's found that interphase switching surges on compact transmission lines with the length of 360km and compensation degree of 89% could be close to 2.9p.u. even if the closing resistors of circuit breakers are applied. In view of the fact that the phase distances of compact lines are significantly less than that of conventional ones, the level of interphase switching surges should be further decreased. Several measures are taken into account, the results show that:

1）The phase to ground switching surges can be restrict to some extent to install MOA in the middle of lines. However, there is little effect on the interphase switching surges in this paper.

2）There is no obvious effect on the phase to ground and interphase switching surges to reduce the rated voltage of MOA in this paper.

3）The interphase switching surges can be lower than 2.8p.u. on the condition that four-star connection metal oxide arresters are installed. However, there is little effect on the phase to ground switching surges in this paper.

4）The energy losses of upper and lower element metal oxide arresters during load rejection with single-phase fault are all in the margin of the allowable values on the condition that four-star connection metal oxide arresters are installed.

In conclusion, using four-star connection metal oxide arresters is a kind of comparatively effective measure to restrict interphase switching surges.

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