Research on High-voltage Reactor Compensation of UHV Lines

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Abstract

In order to ensure the safe operation, the shunt reactor was configured on UHV lines. So the effect factors of power frequency over voltage, characteristics and configuration mode of high voltage shunt reactor have been studied in this paper. Simulation results show that the power angle difference, zero positive sequence impedance ratios and the power of positive sequence impedance is closely related with the power frequency overvoltage. HV shunt reactor can only effectively suppressed power frequency overvoltage that load throw-off happened at the some end with shunt reactor. In order to protect the voltage along the line are located in the appropriate range, sectional compensation is needed when the line is longer than 550km. Principle of secondary arc current and open-phase operation resonance over voltage, and relationship with compensation degree is analyzed. The determination of HV shunt reactor compensation program is given.

Keyword: UHV lines; compensation degree of high voltage shunt reactor; the voltage distribution along the line; secondary arc current; not all phase resonance overvoltage

1. Introduction

UHV has character of long distance, huge capacity, low power consumption, and construction of UHV power has significant economic and social benefits. But UHV line's charging power is too high that producing power frequency overvoltage seriously affects the safety of line operation. Currently we are mainly using shunt reactors to limit this [1-4].

Shunt reactor's main purpose is to limit over-voltage. Meanwhile it also meets the needs of limiting secondary arc current, avoiding resonance over voltage. Currently analysis of UHV high resistance is still not specific enough, and did not give comprehensive compensation solution to the factors and high resistance to UHV characteristics.

To solve the above problems, this article analyzed various factors one by one, provide the range of high resistance safety working, and specific procedure of solution of HV shunt reactor, and provide a theoretical basis of controllable high resistance working value.

2. Calculation Conditions

Use ATP-EMTP simulation software build UHV model for simulation. Owl tower. Wire type is $8\times LGJ-630/35$ ACSR. Split spacing is 400mm.Ground wire is $LBGJ-150-20AC$ .Triangular arrangement of wires. Transmission line parameters can be derived EMTP program as shown in Tab.1.

Table 1:Electrical parameters of UHV lines

Positive sequence parameters			Zero sequence parameters		
Resistance	Reactance	Capacitance	Resistance	Reactance	Capacitance
Ω/km	mH/km	$\mu F/km$	mH/km	mH/km	$\mu F/km$
0.00805	0.84016	0.01378	0.15118	3.6150	0.00832

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3. Effect Factors of Frequency Over Voltage

Power frequency overvoltage circuit mainly caused by capacitive effect, load shedding and ground fault. The value has relation with many factors. According to the literature [5] , a single line power frequency overvoltage is mainly relates to the single-phase ground and three-phase load shedding over-voltage. After the researching people repeatedly calculated, compared, and learned from other countries experiences, the value of 1000kV system line-side power frequency overvoltage generally should not exceed 1.4p.u.

3.1 Power Angle Difference

When other parameter is same, different transmission power causes different power frequency overvoltage if malfunction load rejection occurred. Let's calculate the Single-phase ground and three-phase load shedding power frequency overvoltage under different angle difference, the results shown in Fig.1.

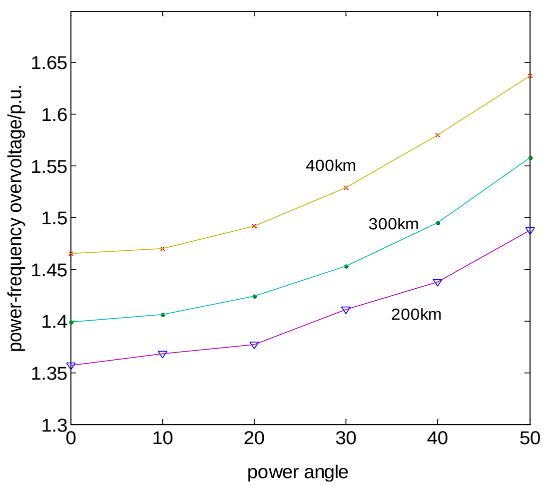


Figure 1: The influence of the power angle to power-frequency overvoltage

We can see, the longer of the line, the bigger of power angle difference value is. The bigger of power angle difference value, the bigger of power frequency overvoltage. Therefore to calculate the max power frequency overvoltage, we should take the max value of power angle difference value.

3.2 Zero Sequence Impedance Ratio

Using symmetrical components, we can obtain B, C two-phase voltage amplitude when single-phase ground fault occurs.

$$U_B = U_C = \sqrt{\left(\frac{1.5\frac{X_0}{X_1}}{2+\frac{X_0}{X_1}}\right)^2 + \frac{3}{4}} U_{A0} = KU_{A0} \quad (1)$$

$$K = \sqrt{\left(\frac{1.5\frac{X_0}{X_1}}{2+\frac{X_0}{X_1}}\right)^2 + \frac{3}{4}} \quad (2)$$

U_{A0} is A phase voltage when normal operation at fault point.

Relationship between K and $\frac{X_0}{X_1}$ as follows:

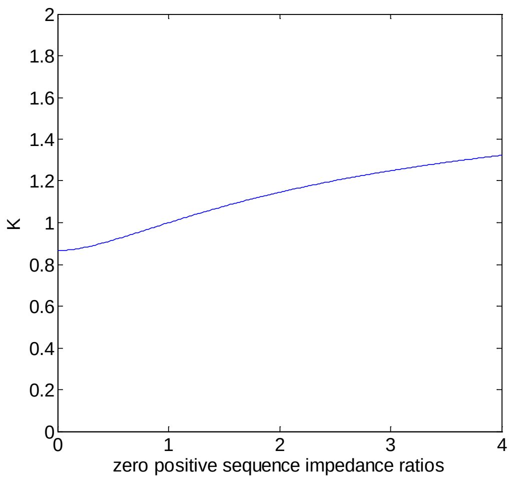


Figure 2: multiples of power-frequency overvoltage when Single-phase ground fault

We can see the bigger of the Zero sequence Impedance ratio, the bigger of the overvoltage value. Therefore, to calculate the max value of overvoltage we should take the max value of Zero sequence Impedance ratio.

3.3 Power Positive Sequence Impedance

Power frequency overvoltage is mainly caused by the line capacitance effect, load shedding and ground fault. The bigger of the power of positive sequence impedance, the higher of power frequency voltage caused by unloaded line capacity is. When the power angle difference is same, different power's positive sequence impedance caused different line output power and different load shedding voltage. Meanwhile, the change of power positive sequence caused the change of Zero sequence impedance ratio. Therefore we need to comprehensively analysis the power positive sequence effect on the overvoltage.

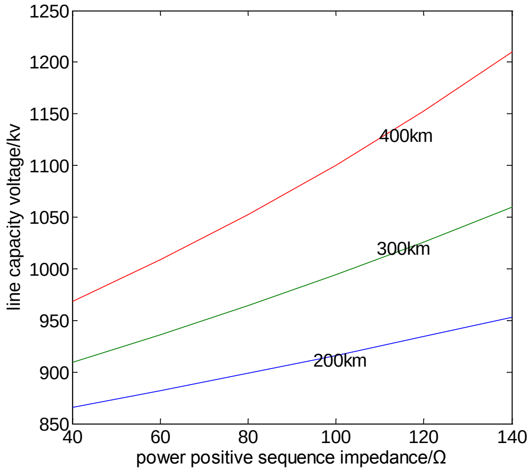


Figure 3: The influence of the power positive sequence impedance to line capacity voltage rise

We can see that the bigger of power positive sequence impendance is, the bigger of power frequency overvoltage caused by nonloaded line capacity effect is. And the longer of the line, the bigger of power frequency overvoltage is.

Given the same power angle difference, under different power positive sequence impedance, different line length caused different power frequency overvoltage. The Result is showing on Fig.4:

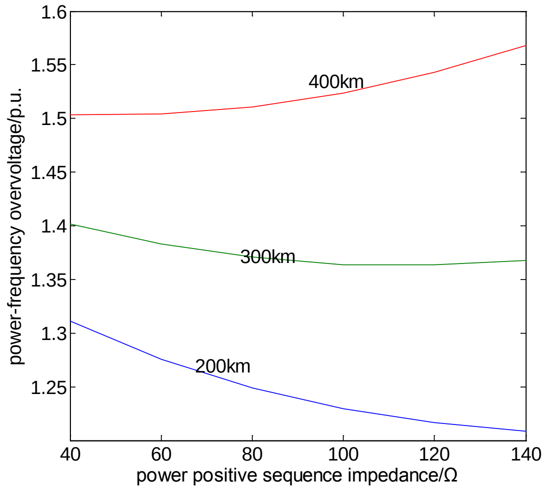


Figure 4: The influence of the power positive sequence impedance to power-frequency overvoltage

We can see from the Fig.3 and Fig.4, although the bigger of power positive sequence impedance, the overvoltage caused by capacity effect is. But the max power frequency value of 200km line is getting smaller along with the power positive impedance value getting bigger. But the max power frequency value of 400km line is getting bigger along with the power positive impedance value getting bigger. The reason is:

1).according to $P = \frac{EU}{X_{\Sigma}} \sin\delta$,when the power angle is same, if the power positive impedance value is up, the power of line output is down, therefore affect the load shedding voltage value.

2).when the power zero frequency impedance is same, if the power positive frequency power impedance value is up, the zero positive frequency impedance is down, the single phase grounding over voltage value is down.

Therefore, we can conclude that, when the ratio of power positive frequency impedance accounts for system equivalent positive sequence impedance is big, such as the 200km, the power frequency over voltage value is up along with the power positive frequency impedance value is down. When the ratio is small, such as 400km, or it has shunt reactor, the power frequency overvoltage value is up along with the power positive frequency impedance value is up.

4. Scheme of Shunt Reactor Configuration and Chosen of Capacity

In China, the shunt reactor has function of limit the power frequency overvoltage and limit the secondary arc current, as well as avoiding factors such as resonance overvoltage and reactive balance and so on. Therefore, the author combines the present research of character s of UHV transmission line, point out the principle of UHV transmission line high configuration:

1). the shunt reactor shall be big enough to limit the UHV transmission line's temporary overvoltage value is within the allowed range.

2).The shunt reactor's configuration shall benefit the UHV transmission's reactive balance.

3).The shunt reactor's configuration shall benefit the UHV transmission voltage to be uniformly distributed in reasonable range.

4).Each switch station has better to have only one standard of high pressure reactor.

5).The shunt reactor shall meet the needs to limit the secondary arc current.

6).The capacity of the shunt reactor cannot be too big to cause non full phase power frequency resonance over voltage.

4.1 Character of the Shunt Reactor Limiting Power Frequency Overvoltage

According to the compensation points we can divide the way of compensation into single end compensation and both ends. Below we will analysis them from different angle of limiting overvoltage

4.1.1 Single Compensation

（1）Single compensation only can limit the single phase grounding three phases load shedding power frequency overvoltage at the end that connected shunt reactor.

The equivalent circuit is as below chart, the power flow from m end to m end.

Figure 5:Schematic diagram of Equivalent circuit

Connect the shunt reactor in n end. For the 200km—400km lines, when the single phase grounding is occurred, calculate the power frequency overvoltage that three phases tripping in n end, at different compensation degree. The result is shown in Fig.6:

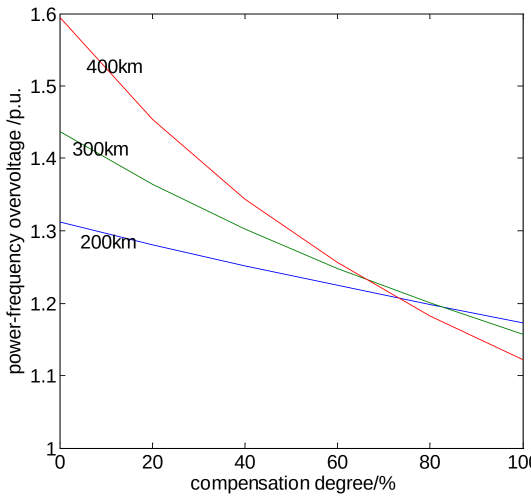


Figure 6: The influence of compensation degree to power-frequency overvoltage when HV shunt reactor at receiving end of the line

Under same condition, for 200km-400km lines, when the single phase grounding is occurred in m end, calculate the power frequency overvoltage value of three phases tripping at different compensation degree. The result is shown in Fig.7:

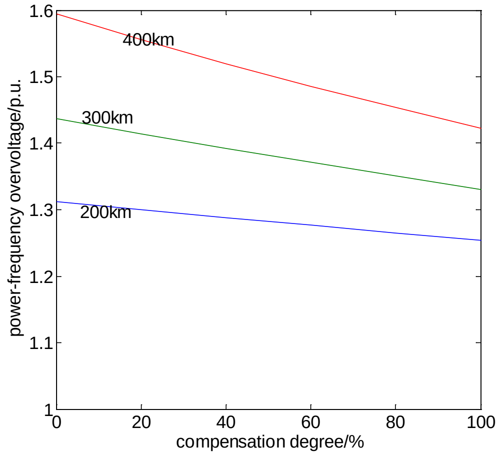


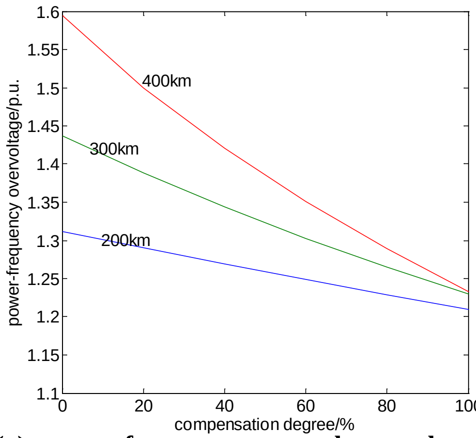
Figure 7: The influence of compensation degree to power-frequency overvoltage when HV shunt reactor at sending end of the line

We can see from the calculated result that, different length of line, shunt reactor can efficiently limit the single grounding and three phases load tripping power frequency overvoltage in its end. But shunt reactor cannot efficiently limit the power frequency overvoltage when the single grounding and three phases load tripping happened at the other end.

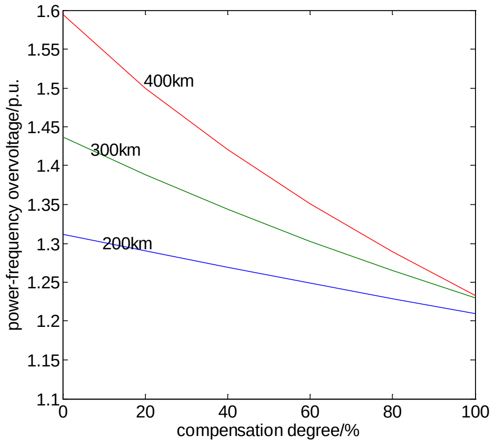
Therefore discussing from the point of limiting power frequency overvoltage, single end compensation solution is only suit for the circuit which only one end happens single phase grounding load shedding power frequency overvoltage value is overweight. If the single phase grounding load shedding overvoltage of both end of the circuit is overweight, we should consider both end compensation solution.

4.1.2 Both End Compensation

For 200km-400km and both end compensation UHV transmission circuit, calculate power frequency overvoltage in different total compensation degree. Calculate the power frequency overvoltage in m end and n end which after the single phase load shedding is happened. The result is shown in Fig.8:



(a) power-frequency overvoltage when m end three-phase tripping



(b) power-frequency overvoltage when n end three-phase tripping

Figure 8: The relationship between power-frequency overvoltage and compensation degree when shunt reactor at both end

From the comparison of chart8 and chart 6, we can see, to have the best result of limit power frequency overvoltage (that is the highest compensation degree), single end compensation can limit the power frequency overvoltage under 1.2 p.u. Both end compensation can limit the power frequency overvoltage between 1.2-1.25 p.u. and can limit the load shedding effectively in any end.

4.2 Preliminary Determination of Min Value of Compensation Degree

The configuration of shunt reactor needs to benefit the reactive balance of the UHV transmission line. The shunt reactor can effectively limit power frequency overvoltage and maintain the system working safely. But if the transmission line runs in heavy-duty, the shunt reactor will consume extra reactive power and produce extra voltage dropping, which is a waste unnecessary. Therefore, the chosen of compensation degree should not be too big.

For the single end compensation circuit, it suit for the circuit which only one end's phase grounding load shedding overvoltage is overweight. According to the chart 6, calculate the line power frequency overvoltage when increasing the paralleling compensation degree from zero. When the shunt reactor value excesses certain value, it can effectively limit the power frequency overvoltage under 1.4 p.u. This certain value is the minimum value of compensation degree which we primarily determined.

Because shunt reactor can only limit the single grounding three phases load shedding power frequency overvoltage, while not effectively limit the three phases load shedding power frequency overvoltage, therefore, for the both end compensation circuit, we should gradually increase the compensation degree of shunt reactor and calculate the three phases load shedding overvoltage. It happens to be able to limit the power frequency overvoltage value under degree of 1.4 p.u, and primarily calculated the minimum value of the shunt reactor. Then use the same way to calculate the compensation degree of the other end.

4.3 Sectional Compensation

The configuration of shunt reactor needs to benefit the equal distribution along the line of the UHV line. Along with the line length increases, the power frequency overvoltage value gets bigger. For the longer UHV line, the single grounding power frequency overvoltage in the middle line cannot be limited effectively when to compensate in both end. Therefore we need to analysis this.

According to the former conclusion of our analysis, in the worse situation of power frequency overvoltage (power positive sequence impedance, zero positive sequence impedance ratio, power angle difference are all set as the maximum value), the compensation degree all set 80% for different length line's overvoltage along the line. The result is shown in Fig.9:

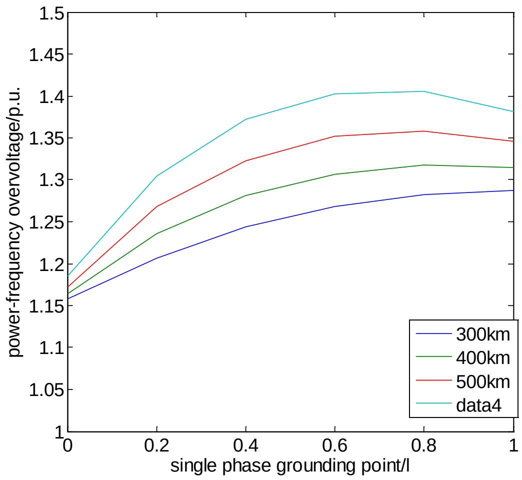


Figure 9: power-frequency overvoltage when single phase grounding at different point

The two figures above show：

1).onvex curve is the fault location of maximum power-frequency overvoltage, moving forward to the middle of the line. And the line is longer, the curve raised more obvious. For 500kM and 600kM lines, the voltage of the maximum power-frequency overvoltage has far surpassed the terminal grounded voltage.

2).In the most severe cases, when the line length more than 600kM, the power-frequency overvoltage exceeds 1.4 p.u. Therefore, when the line longer than 550 km, the piecewise compensation should be adopt. Because two end compensation mode is no longer effective to restrain the UHV line UHV transmission lines along the voltage distribution in a suitable range, are distributed in the appropriate range.

Needs to be pointed out is, because the volume and weight of UHV shunt reactor are large and too difficult to transport, it is best to avoid remote standby. Therefore, when determining compensation scheme, there is best specification of the high pressure reactor capacity for each switching station or substation to reduce the number of spare shunt reactor.

4.4 The Suppression of Arc Current

In order to ensure the safe operation of the single-phase reclosing circuit, it is necessary to suppress arc current. Super and UHV line in our country usually use high resistance neutral grounding reactor way to compensate for the capacitive coupling. So configuration of shunt reactor also needs to meet the needs of suppression of arc current [6]. To Figure10 as an example, the grounding fault phase *C* trip hanging, phase *A* and *B* power supply operate normally, by the capacitive coupling *CM* to *C* with arc current, high resistance lines for *Lp*, neutral grounding via small reactor LN.

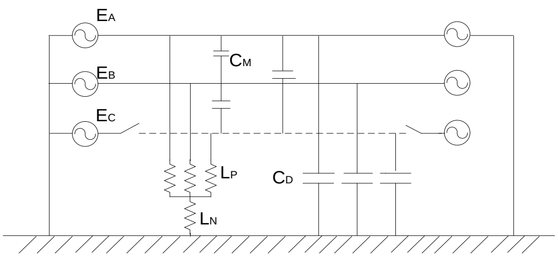


Figure 10: Schematic diagram of open-phaseoperation

Fig.10 can be transformed into Fig.11.

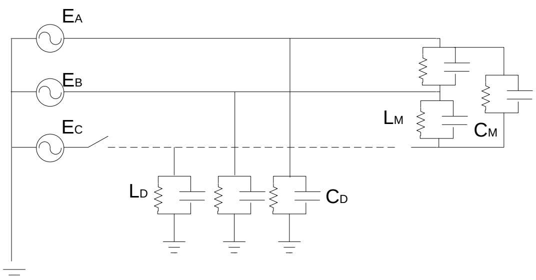


Figure 11: The equivalent figure of open-phase operation with high voltage shunt reactor

$$\begin{cases} X_{LD} = 3X_{LN} + X_{LP} \\ X_{LM} = \dfrac{X_{LP}^2}{X_{LN}} + 3X_{LP} \end{cases} \tag{3}$$

Choosing the right small reactance for X_{LN} makes phase-to-phase reactance X_{LM} fully compensated interphase capacitance X_{CM} and parallel resonance occurs, thus inhibiting arc current through phase-phase capacitor.

Set $X_{LM} = X_{CM}$, Combined equation (3) :

$$\frac{X_{LP}^2}{X_{LN}} + 3X_{LP} = X_{CM} \tag{4}$$

Also because $\frac{U_N^2}{X_{LP}} = K\frac{U_N^2}{X_{C1}}$, so $X_{LP} = \frac{X_{C1}}{K}$, put it into equation (2),we can find

$$X_{LN} = \frac{X_{C1}^2}{K^2 X_{CM} - 3KX_{C1}} \tag{5}$$

According to the line parameter, to meet high voltage shunt reactor completely compensate the capacitance between phases, We calculate therelationship between degree of compensation of high voltage shunt reactor and neutral small reactance value, As shown in the figure below:

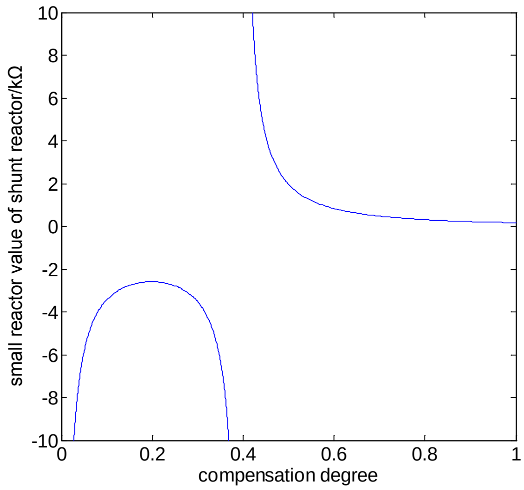
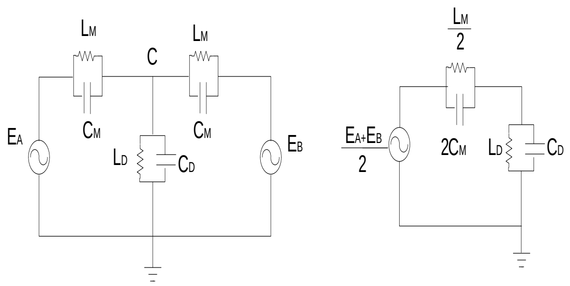


Figure 12: The relationship between small reactor value of shunt reactor and compensation degree

By calculating, we can see: firstly, to meet the needs of resisting secondary arc current, High voltage shunt reactor must be greater than a certain value (in fig.12 is about forty percent). Secondly, the smaller of the degree of compensation, the bigger of small reactance value of high voltage. Therefore, to resist the secondary arc current, and to ensure small reactance value in a reasonable range, the degree of compensation of high voltage must be higher than a certain value. The value can gain by the above method. By according to the parameter of line, the length of line and the level of production, we can calculate that.

4.5 Avoid Open-phase Operation Resonance Overvoltage

The reason of open-phase operation resonance over voltage is that when a phase of line faults trips, Line normal phase can form the reactant current by capacitance between phases and high voltage shunt reactor [7].As shown in figure 10 and 11. It may continue to simplify to fig.13.



(a) The equivalent figure of open-phaseoperation
(b) Simplified diagram

Figure 13: Simplified diagram of open-phaseoperation

Set $\begin{cases} X_M = X_{LM} \square X_{CM} \\ X_D = X_{LD} \square X_{CD} \end{cases}$, X_M is the impedance between two phases of lines. X_D is the impedance between phase and ground. U is phase voltage. If it has the improper parameter configuration, $\frac{1}{2}X_M + X_D = 0$, it can produce resonance and resonance overvoltage is very high .

4.5.1 Resonance Overvoltage Caused by Small Reactor Deviation

Set reactive power by X_M and X_D are Q_M and Q_D.We can find:

$$\begin{cases} Q_M = \frac{(\sqrt{3}U)^2}{X_M} = \frac{(\sqrt{3}U)^2}{X_{LM}} - \frac{(\sqrt{3}U)^2}{X_{CM}} = Q_{LM} - Q_{CM} \\ Q_D = \frac{U^2}{X_D} = \frac{U^2}{X_{LD}} - \frac{U^2}{X_{CD}} = Q_{LD} - Q_{CD} \end{cases}$$

Set $n = Q_M / Q_D = 3X_D / X_M$ .According to the fig.13,we can get $U_C = \frac{X_D}{\frac{X_M}{2} + X_D} \times \frac{U}{2} = \frac{n}{2n+3}U$ .Making relationship between voltage of disconnected phase and n. As shown in Fig.14:

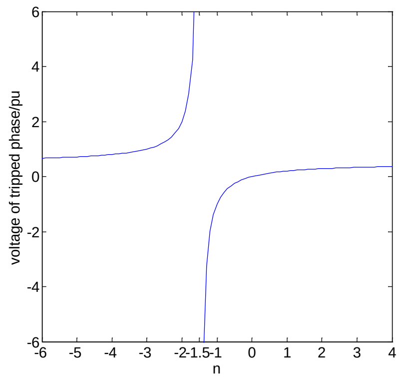


Figure14: The relationship between voltage of tripped phase and n

As can be seen from Figure, when n is in the range (-3, -1), C-phase voltage larger than normal voltage，when n = -1.5，Resonance occurs entirely.

Because $n = Q_M / Q_D < 0$, just under two conditions, n is less than 0:

1). $Q_M < 0, Q_D > 0$

Because $-3 < Q_M / Q_D < -1, \text{ so} |Q_M| > |Q_D|$ .We can find $Q_M + Q_D < 0$ 。

$$Q_M + Q_D = Q_{LM} - Q_{CM} + Q_{LD} - Q_{CD}$$
$$= (Q_{LM} + Q_{LD}) - (Q_{CM} + Q_{CD}) < 0$$

That compensation degree of reactor is less than 100%.

2). $Q_M > 0, Q_D < 0$

Because $-3 < Q_M / Q_D < -1$, so $|Q_M| > |Q_D|$. We can find $Q_M + Q_D > 0$. That compensation degree of reactor is more than 100%.This case generally does not appear on the actual line. Therefore, the high amplitude low reactance impedance resistance deviation caused by resonance Overvoltage occurs only in the case of $Q_M < 0, Q_D > 0$. The small reactance theory is based on the principle of full compensation to alternate configuration. According to the equation $X_{LM} = X_{LP}^2 / X_{LN} + 3X_{LP}$, When small reactor smaller than the theoretical value, X_{LM} larger than when full compensation，that $Q_M<0$。Therefore, only a small reactor resistance smaller than the theoretical value, it may generate high amplitude resonance over-voltage. According to the literature [8], currently deviation of the small reactor resistance is generally within plus or minus 10%.

According UHV line parameters, calculate deviation of Small reactance when 300km lines occurs resonance at different compensation degree. First calculate theoretical values of a small reactance when phase-phase fully compensated; then small reactance multiplied by a coefficient of variation g，calculated parameter values equivalent circuit when small reactor had deviation. Lastly calculate relationship between compensation degree and deviation of Small reactance. The results are shown in Fig.15:

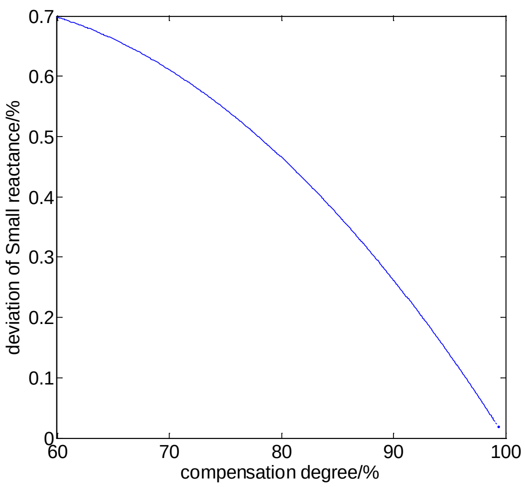


Figure 15: The relationship between compensation degree and deviation of Small reactance

Fig. 15 shows that the higher compensation degree of shunt reactor, the smaller deviation of Small reactance when resonance occurs. That is the more prone to resonance. Therefore, in order to avoid the occurrence of a non-phase resonance, compensation degree should not be too high. Considering deviation of small reactor in 10 compensation degree should be less than 96%.

4.5.2 Resonance Overvoltage Caused by System Frequency Deviation

In some fault conditions，the system frequency will drop to below 50HZ. This may also lead to a non-wholly-phase resonance over-voltage. Under normal circumstances, compensation degree of HV shunt reactor is less than 100%, small resistance value is set by principle of fully compensated phase-phase capacitance. We can find:

$$\begin{cases} \dfrac{(\sqrt{3}U)^2}{\dfrac{1}{2\pi f_n C_M}} = \dfrac{(\sqrt{3}U)^2}{2\pi f_n L_M} \\ \dfrac{U^2}{\dfrac{1}{2\pi f_n C_D}} > \dfrac{U^2}{2\pi f_n L_D} \end{cases}$$

In the above equation f_n=50Hz.

In some fault conditions, when system frequency dropped to $f_n<50$ Hz, that：

$$\begin{cases} \dfrac{(\sqrt{3}U)^2}{\dfrac{1}{2\pi f_n C_M}} < \dfrac{(\sqrt{3}U)^2}{2\pi f_n L_M} \\ \dfrac{U^2}{\dfrac{1}{2\pi f_n C_D}} > \dfrac{U^2}{2\pi f_n L_D} \end{cases}$$

Resonance may happen. When system frequency rises, fn>50Hz, phase-phase and phase-ground are both undercompensating. Resonance does not occur.

According parameters of UHV line, calculate resonant frequency at different compensation degree of HV shunt reactor. The result is shown in Fig.15:

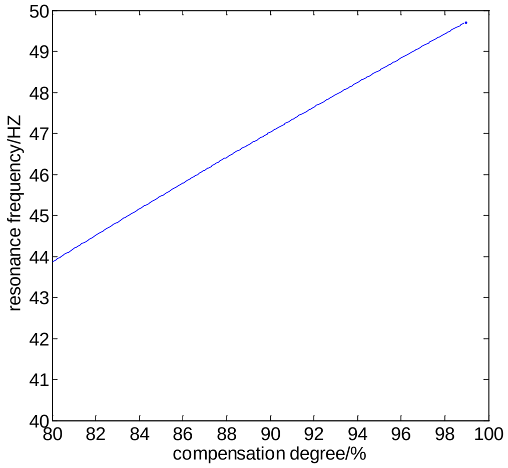


Figure 16: resonance frequency under different compensation degree

By calculation we can see, the greater the compensation degree of high reactor, the resonance frequency corresponding to the resonance closer to 50Hz, that is more prone to non-wholly-phase resonance over-voltage. Avoiding non-phase resonance over-voltage, the compensation degree of reactor cannot be too large. According to the literature, the general system frequency is not less than 47Hz, so compensate degree of reactor is not more than 90%.

5. Conclusion

1). Power frequency over-voltage relates to power angle difference, the power of positive sequence impedance, and the zero positive sequence impedance ratios. The larger the power angle difference, the more serious frequency overvoltage; the larger zero positive sequence impedance, the more serious frequency over voltage. When the power of positive sequence impedance is different, it should be analyze based on parameters calculated.

2). HV shunt reactor can only effectively suppressed power frequency overvoltage that load throw-off happened at the some end with shunt reactor. Under the same degree of compensation, the best result of two-junction compensation mode is less ideal than single-junction compensation mode. But two-junction compensation mode can effectively suppress to any end happened three-phase tripping.

3).To protect the voltage along the line are located in the appropriate range, sectional compensation is needed when the line is longer than 550km. When sectional compensation mode chosen, the best way of each switching station is used a specification of the reactor.

4).The smaller compensation degree of shunt reactor, the greater reactance values required suppressing secondary arc current. Combined with small reactor production level, the compensation degree should be calculated to check weather meets the need to suppress arc current.

5). When the small reactor of neutral is small and the frequency drop, the phase operation may lead to Non-phase operation resonance over-voltage. The larger compensation degree of reactor, the more prone to resonance. High degree of resistance to the compensation should be calculated based on the parameters, and avoid resonance over-voltage. Its value should not be too large.

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