RESEARCH OF UHV CIRCUIT BREAKER TRANSIENT RECOVERY VOLTAGE CHARACTERISTIC

Baina HE[1], Yunwei ZHAO[2]

The most critical transient a circuit breaker has to endure during its operation is the transient recovery voltage (TRV). The important factor influencing the circuit breaker tripping is transient recovery voltage amplitude and climbing rate. In order to study the working condition of UHV circuit breakers and determine the parameters of TRV for the test of UHV circuit breakers, the paper analyzes the effect electrostatic induction and electromagnetic induction on TRV, and conducts a detailed theoretical derivation. Based on the UHV demonstrative project as the background, the effect induction voltage on TRV parameter are researched under the condition of different fault location by using the electromagnetic simulation software EMTP–ATP. The simulation results show that the induced voltage makes the circuit breaker TRV amplitude and climbing rate all over the standard specified value, which bring forward higher requirements for the circuit breaker insulation level and provide theoretical basis for structural design of circuit breaker.

Keywords: UHV; Transient Recovery Voltage; Induced Voltage; Climbing Rate

1. Introduction

Generally speaking, circuit breakers in a system are applied based on available short circuit capability at that point in the circuit. Transient recovery voltage (TRV) for high-voltage circuit breakers is the voltage that appears across the terminals after current interruption. For arc extinguishing point of view, TRV is a decisive factor while the breaker is interrupting short circuit fault [1-4].

TRV influences the breaking performance of a circuit breaker, and it is desirable to achieve inherent circuit interruption using an ideal circuit breaker. Besides the features of the breaker itself, the characteristics of TRV are mainly affected by the characteristics of the system connected on both terminals of the circuit-breaker [5-8]. While outlining standards or regulations for breaker's working conditions, different systems should be taken into consideration.

A proper determination of the TRV of breakers in power grid is an important issue in regulating circuit breakers' working conditions and test conditions. It is also very important for the stability and safety of operation of UHV system [9-11].

[1] College of Electrical and Electronics Engineering, Shandong University of Technology, ZiBo, China; E-mail: hbn770425@163.com

[2] Department of Electric Engineering, Shandong Industry Polytechnic College, ZiBo, China

TRV are contingent upon the circuit condition sand parameters of the circuit. Thus, making it extremely essential to study them for application of circuit breakers, however, it is not easy to evaluate the inherent TRV due to the influences of the arc voltage and forward voltage drop.

2. Standards of TRV for UHV Circuit Breakers

With reference to the Electrical Power Industry Profession Standard of China, DL/T402-2007, “Specification of highvoltage alternating-current circuit-breaker”, the specified standard values for the TRV of UHV breakers are given in Tab.1 [12].

Table 1

Standard Values of Prospective TRV-Rated Voltage of 1100kV and 550kV Representation by four Parameters (T100, T60, OP1 and OP2) of Two Parameters (T30, T10)

Rated voltage (kV)	Test duty	First pole to Clear factor	Amplitude factor	TRV peak Value (kV)	Rate of Rise (kV/us)
550	T100	1.3	1.4	817	2.0
	T60	1.3	1.5	876	3.0
	T30	1.3	1.54	899	5.0
	T10	1.5	1.53	1031	7.0
	OP1-OP2	2.0	1.25	1123	1.54
1100	T100	1.3	1.4	1634	2.0
	T60	1.3	1.5	1751	3.0
	T30	1.3	1.53	1798	5.0
	T10	1.3	1.53	1786	10.0
	OP1-OP2	2.0	1.25	2245	1.54

By comparing the test condition of 1100kV circuit breaker in Tab.1 and that of 550kV circuit breaker in the standard, it can be found that the main difference between them is the TRV peak value. The peak values in Tab.1 are 1.76 to 2 times of the values for 550kV circuit breaker. However, the standard value of rate of rise of TRV for 1100kV circuit breakers is still the same as that of 550kV circuit breakers. It can be moderately modified the standard value of rate of rise of TRV for UHV breaker according to the research results.

3. Influence of Induced Voltage to TRV

After the transmission line fails, the induced voltage generated between the non-fault phase and fault phase will cause the circuit breaker transient recovery voltage change. Suppose A phase single-phase Erath fault occurs, as shown in Fig.1, U_{jg} is the induced voltage generated in the electrostatic induction on line terminal department, U_{cg} is the induced voltage generated in the electromagnetic induction on line terminal department, C_0 is the line-to-ground capacitance of unit length, C_{12} is interphase capacitance of unit length, C_1 is equivalent capacitance of unit length, L is line inductance of unit length, L_1 is equivalent inductance of unit length, M is line mutual inductance of unit length.

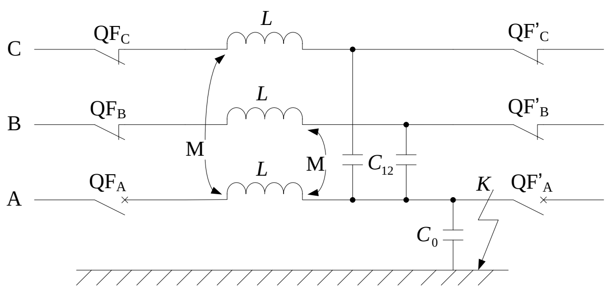

Fig. 1. Faulty line

3.1 Influence of Electrostatic Induction Voltage to TRV

As shown in Fig.1, the first step in seeking electrostatic induction voltage U_{jg} between the non-fault phase and fault phase.

$$j\omega_0 C_{12}(\dot{U}_B - \dot{U}_{jg}) + j\omega_0 C_{12}(\dot{U}_C - \dot{U}_{jg}) = j\omega_0 C_0 \dot{U}_{jg} \tag{1}$$

$$\dot{U}_{jg} = \frac{C_{12}}{C_0 + 2C_{12}}(\dot{U}_B + \dot{U}_C) = -\frac{C_{12}}{C_0 + 2C_{12}}\dot{U}_0 \tag{2}$$

By the formula (2) , it can be shown that A and B difference of phase 180 °, so that electrostatic induction voltage between B, C phase and A phase vector diagram shown in Fig.2.

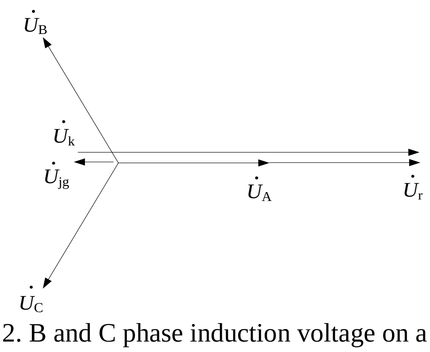

Fig. 2. B and C phase induction voltage on a phase

In Fig. 2, $\dot{U}_k$ is the difference between the peak of TRV at the contact point of the circuit breaker and the electrostatic induction voltage at the end of the short circuit line, that is $\dot{U}_k = \dot{U}_r - \dot{U}_{jg}$.

So, when the circuit breaker arc is extinguished, taking into account the influence of electrostatic induction voltage, the TRV of circuit breaker arc gap is shown below.

$$U_r = U_0(1-\cos\omega_0 t) - \left(-\frac{C_{12}}{2C_{12}+C_0}U_0\right) = U_0\left(\frac{3C_{12}+C_0}{2C_{12}+C_0} - \cos\omega_0 t\right) \tag{3}$$

when $\omega_0 t = \pi$:

$$U_{r\max} = \frac{2C_0+5C_{12}}{C_0+2C_{12}}U_0 \tag{4}$$

By the formula (4), it can be seen that the electrostatic induction voltage results in an increase interstitial breaker arc voltage, which leads to the peak of TRV is greater than $2U_0$, that is $U_r \geq 2U_0$.

3.2 Influence of Electromagnetic Induction Voltage to TRV

Electromagnetic induction is caused by the load current of the non-fault phase through the mutual inductance, the greater the load, the greater the shift of phase angle δ on both sides of transmission lines, the higher the induced voltage on the broken line. Assumes that the transmission line operates with nature transmission power, regardless of the line resistance and ground conductivity. Then the propagation constant $\gamma = j\omega\sqrt{L_1C_1}$, the wave impedance $Z = \sqrt{\frac{L_1}{C_1}}$ The voltage along the removed line is shown below.

$$\dot{U}_{xA} = \dot{U}_A e^{j\omega x\sqrt{L_1C_1}} \tag{5}$$

Due to $\delta = \lambda = \omega l\sqrt{L_1C_1}$, the induced electromotive force of per unit length is shown below.

$$d\dot{E} = j\omega M(\dot{I}_{xB} + \dot{I}_{xC})dx = j\omega M\frac{\dot{U}_{xB}+\dot{U}_{xC}}{Z}dx = -j\omega M\frac{\dot{U}_{xA}}{Z}dx = \frac{j\omega M\dot{U}_A}{Z}e^{j\frac{x}{l}\lambda}dx \tag{6}$$

Therefore, the longitudinal induced electromotive force between short circuit fault point and the head end of line is shown below.

$$\dot{E} = \int_{l_x}^{0} -\frac{j\omega M\dot{U}_A}{Z} e^{j\frac{x}{l}\lambda} dx = \int_{l_x}^{0} -\frac{j\omega M\dot{U}_A}{Z}\frac{l}{j\lambda} e^{j\frac{x}{l}\lambda} d(j\frac{x}{l}\lambda) = j\frac{2M\dot{U}_A}{L_1}\sin\left(\frac{l_x}{2l}\lambda\right)e^{j\frac{x}{2l}\lambda} \quad (7)$$

For UHV transmission line, $\frac{l_x}{2l}\lambda$ is generally relatively small, so $\sin\left(\frac{l_x}{2l}\lambda\right) = \frac{l_x}{2l}\lambda$, and therefore equation (7) can be written as:

$$\dot{E} = j\frac{2M\dot{U}_A}{L_1}\cdot\frac{l_x}{2l}\cdot\omega l\sqrt{L_1C_1}e^{j\frac{x}{2l}\lambda} = j\frac{\omega M l_x \dot{U}_A}{Z} \quad (8)$$

In the formula (8), $j\frac{\omega M l_x \dot{U}_A}{Z}$ is longitudinal induced electromotive force between short circuit fault point and the head end of line after circuit breaker tripped. Therefore, the induced voltage of circuit breaker line side generated by line electromagnetic induction is $\dot{U}_{cg} = \dot{E} = j\frac{\omega M l_x \dot{U}_A}{Z}$, $\dot{U}_{cg}$ and $\dot{U}_A$ differ 90 °, the vector shown in Fig.3.

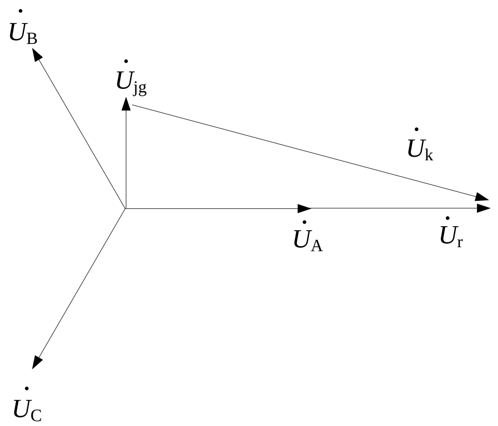

Fig. 3. Electromagnetic induction effect on the arc gap voltage

The frequency of $\dot{U}_{cg}$ is equal to that of the system, which is much greater than the frequency of TRV, the TRV of circuit breaker arc gap is shown below.

$$U_r = \sqrt{[U_0(1-\cos\omega_0 t)]^2 + \left(\frac{\omega M l_x U_A}{Z}\right)^2} \quad (9)$$

When $\omega_0 t = \pi$, the peak of TRV is shown below:

$$U_{max} = U_0 \sqrt{4 + \left(\frac{\omega M l_x}{Z}\right)^2} \tag{10}$$

By the formula (10), it is known that the electromagnetic induction voltage between the lines lead to the increase of the peak value of the TRV.

From the above analysis, it can be known that the electrostatic induction and electromagnetic induction voltage between the lines can increase the peak value of transient recovery voltage, which has a negative effect on the circuit breaker to cut off the fault line quickly and reliably, and put forward higher request to the reliability of the circuit breaker constant insulation.

4. Simulation and Analysis

Taking the line of the Jindongnan-Nanyang in UHV demonstration project as the research object, this paper builds line model considering the influence of the induced voltage, and analyzes the transient process of TRV. In the simulation model, the failure time of the system is 0.03s, considering the inherent switching time of circuit breaker, the trip time of circuit breaker is set to 88ms. Respectively to simulate all kinds of fault types, analysis of TRV under different fault types, and analyze line induction voltage on the influence of TRV.

4.1 Single-phase Ground Fault

When the fault occurs at any point of the line, it should be considered the effect of the electrostatic induction and electromagnetic induction phenomenon on the TRV. TRV parameters of single-phase ground fault at different locations of the line are shown in Table 2, L_x is the distance between fault point and line head end, U_{1max} is the peak of the first oscillation period considering the effect of induction voltage on TRV, U_{2max} is the maximum value of TRV considering the effects of induced voltage, U_y is the maximum value of TRV without considering the effects of induced voltage, t_0 is the time when the TRV reaches the first peak, k_{s1} is the rate of rise of TRV considering the effects of induced voltage.

Table 2

TRV parameters of different fault location

L_x(km)	0	90.75	181.5	272.25	363
U_{1max}(kV)	882	913	914	881	911
U_{2max}(kV)	996	997	1012	1037	1069

U_y(kV)	995	996	1004	1016	1027
t_0(μs)	260	260	270	290	260
k_{s1}(kV/μs)	3.39	3.51	3.39	3.04	3.50

It can be seen from Table 2 that when single-phase ground fault occurs on the line, the electrostatic induction and electromagnetic induction between the lines makes the maximum value of TRV increase. When the fault occurs at the end of the line, the peak value of TRV is the largest, as shown in Fig.4.

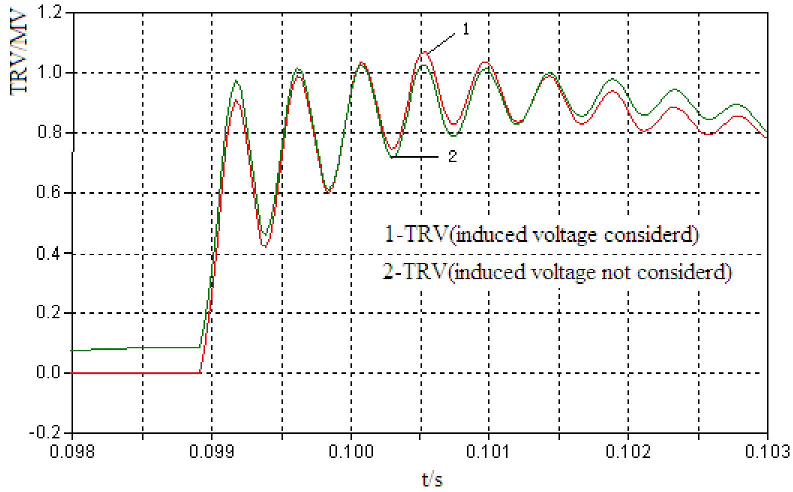

Fig. 4. Induced voltage on impact of TRV (single-phase end ground fault)

4.2. Two-phase Short Circuit Fault

(1) TRV parameters of two-phase non-ground fault at different locations of the line are shown in Tab.3, the table symbol as previously described.

Table 3

TRV parameters of two-phase non-grounded fault

L_x(km)	0	90.75	181.5	272.25	363
U_{1max}(kV)	1501	1606	1353	1250	1360
U_{2max}(kV)	1501	1606	1367	1580	1760
U_y(kV)	950	856	1077	1001	880
t_0(μs)	260	280	280	240	260
k_{s1}(kV/μs)	5.77	5.74	4.83	5.21	5.23

As it can be seen from Table 3, when it occurs a two-phase non-ground short circuit fault at any point on the line, the peak value of TRV is increased in different degrees due to the existence of line induced voltage. The peak value and the rise rate of TRV is relatively low when the neutral point is in fault, and the simulation waveform is shown in Fig.5. When the fault occurs at the end of the line, the peak value of TRV is up to 1760kV, the rise rate is up to 5.23 kV/μs, as shown in Fig. 6.

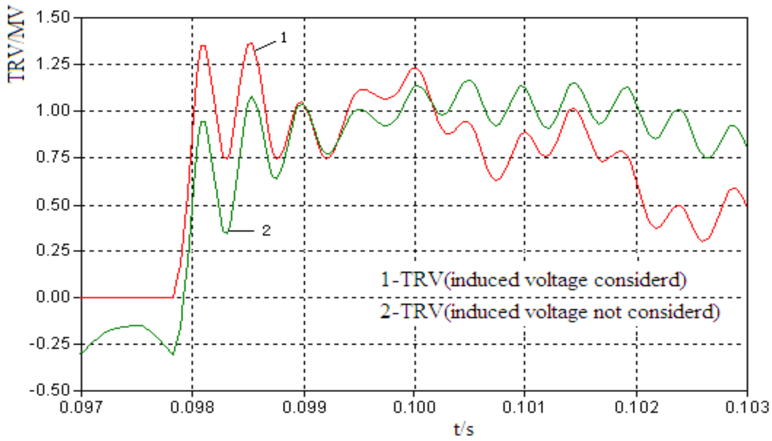

Fig. 5. Induced voltage on impact of TRV (two-phase non-grounded midpoint fault)

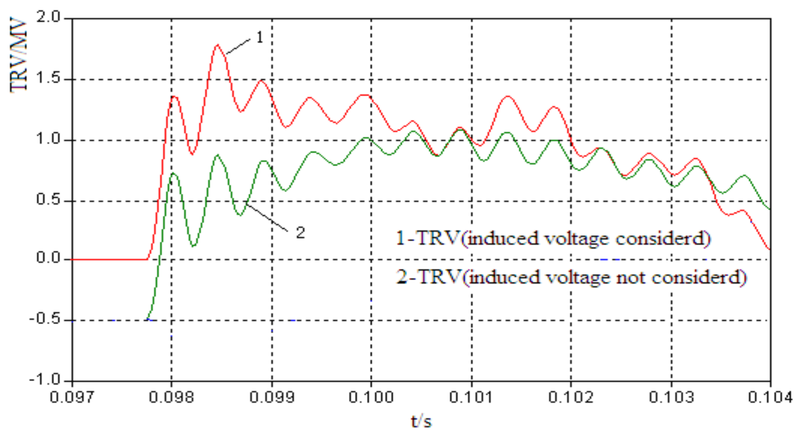

Fig. 6. Induced voltage on impact of TRV (two-phase non-grounded end fault)

(2) TRV parameters of two-phase ground fault at different locations of the line are shown in Tab.4, the table symbol as previously described.

Table 4

TRV parameters of two-phase ground fault

L_x(km)	0	90.75	181.5	272.25	363
U_{1max}(kV)	1075	1354	1423	1331	1432

U_{2max}(kV)	1193	1408	1423	1671	1572
U_y(kV)	1072	1208	1338	1325	1337
t_0(μs)	240	260	260	280	260
k_{s1}(kV/μs)	4.48	5.21	5.47	4.75	5.51

As it can be seen from Table 4, a two-phase ground fault occurs in the first end of the line, the peak and rise rate of the transient recovery voltage is small, and the fault occurs at the end of the line, the TRV being more serious.

Compared to the Table 3 and Table 4, it can be known that the peak value of TRV specific to the two-phase ground fault is larger than that of two-phase non-ground fault, when the induction voltage is not considered. When considering the effect of induced voltage, the result is just the opposite.

4.3. Three-phase Short Circuit Fault

(1) Simulation of three-phase non-grounded fault, due to three-phase short circuit current is not zero at the same time, so there is still electrostatic induction and electromagnetic induction phenomenon, so the impact of induction voltage on TRV is considered. TRV parameters of three-phase non-ground fault at different locations of the line are shown in Table 5.

Table 5

TRV parameters of three-phase non-grounded fault

L_x(km)	0	90.75	181.5	272.25	363
U_{1max}(kV)	1752	1429	1911	1715	1481
U_y(kV)	1600	1503	1601	1660	1471
t_0(μs)	230	230	230	250	270
k_s(kV/μs)	7.62	6.23	8.31	6.86	5.48

As it can be seen from Table 5, the most serious TRV generated by the three-phase non-ground fault occurs in the line midpoint, the maximum peak value of TRV is up to 1768kV, the rise rate of TRV is up to 6.80 kV/μs, the TRV waveform is shown in Fig. 7:

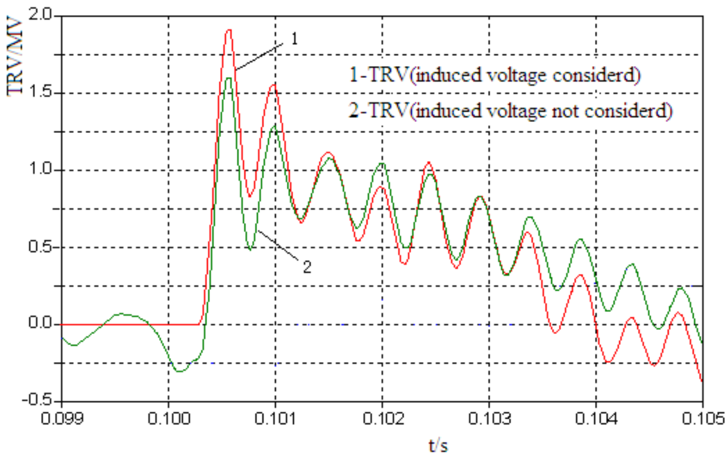

Fig. 7. Induced voltage on impact of TRV (three-phase non-grounded midpoint fault)

(2) TRV parameters of three-phase ground fault at different locations of the line are shown in Table 6.

Table 6

TRV parameters of three-phase ground fault

L_x(km)	0	90.75	181.5	272.25	363
U_{1max}(kV)	1618	1363	1746	1610	1414
U_y(kV)	1618	1537	1617	1659	1462
t_0(μs)	260	220	270	290	280
k_s(kV/μs)	6.22	6.20	6.47	5.55	5.05

It is known from Table 6 that the most serious TRV of the three-phase ground fault occurs in the line midpoint, the maximum peak value of TRV can reach 1746kV, and the rise rate of TRV is up to 6.47kV/μs, considering the induced voltage.

Compared to Table 5 and Table 6, it can be known that the induced voltage amplitude of three-phase non-ground fault is larger than that of three-phase ground fault, which resulted in the fact that the TRV specific to the three-phase non-ground short circuit fault is more serious.

5. Conclusion

Based on different types of faults and different fault location for a large number of simulation calculation, it was shown that, when considering the effect of line induction voltage, the peak and rising rate of TRV is the largest in the midpoint of the line of three-phase ground short circuit, the maximum peak is up to 1911kV and the maximum rising rate is 8.31kV/μs. These are beyond the requirements of the T10 standard 1786kV and 7.0kV/μs in Table 1 proposed in the 1100kV circuit breaker test. The increase of the peak value and rising rate of TRV increases the difficulty of circuit breaker opening, which may cause the circuit breaker to be difficult to break off successfully, and put forward a new test to the breaking capacity of the circuit breaker. Therefore, the simulation of the TRV under the condition of induction voltage has been considered. The simulation results provide a theoretical basis for the fracture structure design and insulation design of high voltage circuit breakers.

Aknowledgement

The research is supported by Shandong Province science and technology plan projects (J14LN27) and Shandong University of Technology Science and Technology Funded Project (103121 and 103233).

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