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The Study on Single-Phase Adaptive Reclosure of Transmission Lines with Series Capacitance

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Abstract. To solve the problem of single-phase adaptive reclose in line with series compensation, this paper proposes a criterion using the different frequency components belonged to the recovery voltage to defect transient faults and permanent faults. Firstly, this paper analysis the frequency characteristics after fault-phase circuit breaker tripped in single-phase ground fault, establishes the recovery voltage identification model including the DC component and each component. When single-phase-to-ground fault occurs and both sides of the circuit breaker open, the recovery voltage as a known quantity, each frequency component is obtained by least square fitting. The amplitudes of various frequency components are adopted to distinguish the permanent faults from transient faults. Through theoretical analysis and PSCAD simulation show that the criterion is correct and effective and can detect the nature of single-phase fault quickly.

1. Introduction

Automatic reclosing is widely used in transmission lines, but the failure may cause impact on the system again, will shorten the service life of circuit breaker and electric equipment. Therefore, adaptive reclose widely research that can improve the success rate [1].

In order to limit EHV transmission line power frequency overvoltage, the shunt reactors are usually installed on both ends of the line or end. In order to improve line transmission ability and system operation stability[2],the series compensation capacitance often is installed in the limit/ehv transmission line. The existence of the low frequency component increases the difficulty of the fault judging. Series compensation device itself protection operation, on the other hand, will bypass the series capacitors, also increase the difficulty of the fault judging.

Firstly, this paper analyzes and calculates the frequency of recovery voltage on the transmission line with series compensation capacitors and shunt reactor, establishes the recovery voltage model that contains aperiodic component, power frequency component and free oscillation component. This paper uses least-squares draft count to solve each frequency component. By comparing the difference between the various frequency identify the nature of the fault. Simulation results indicate the effectiveness of the proposed algorithm.

2. Series compensation capacitor and the protection of MOV

Figure 1 is a transmission line series compensation capacitor device wiring diagram. C is series capacitor banks, MOV is Zinc oxide varistor. G is discharge gap, QF is bypass breaker, using for arc extinguishing of discharge gap G and investment and return of the series capacitor.

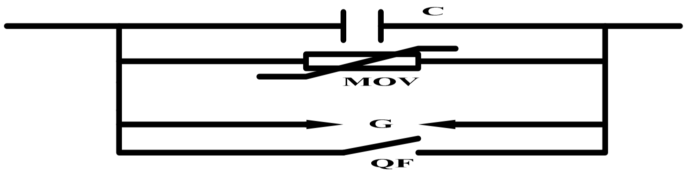


Fig.1. Series capacitor compensation device

3. Transient recovery voltage characteristics and the influence of series compensation

3.1. Simulation model

The recovery voltage characteristics of transient fault and permanent fault is demonstrated in a 500kV translation line model.

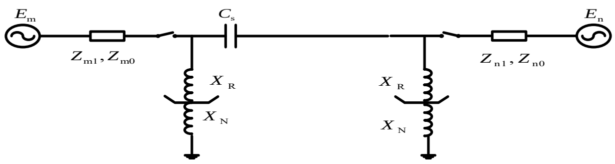


Fig.2. The model of 500kV translation line

In Fig.2 above, the positive sequence resistance (R_1) is 0.347Ω/km, positive sequence capacitance (C_1) is 0.00868μF/km, positive sequence inductance (L_1) is1.343mH/km, zero-sequence resistance (R_0) is0.30002Ω/km, zero-sequence inductance (L_0) is 3.638mH/km, zero-sequence capacitance (C_0) is0.00617μF/km.The parameters in M side: Z_{m1}=6.139+j529.8Ω, Z_{m0}=j130.6Ω. The parameters in N side: Z_{n1}=17.56+j46.11Ω, Z_{n0}=1.6+j65.13Ω. The parameter of the reactors which paralleled in the circuit is equal to that in Neutral point is: X_R=1708.16Ω, X_N=569.39Ω. The length of transmission line is 300km. C_s is the series compensation capacitor and the series compensation degree is 30%.

3.2. The characteristic of recovery voltage in normal operation

(1) At single-phase ground fault， breaker tripped at the phase which is fault, the equivalent circuit for low-frequency component after secondary arc extinguishing is represented in Fig 3.

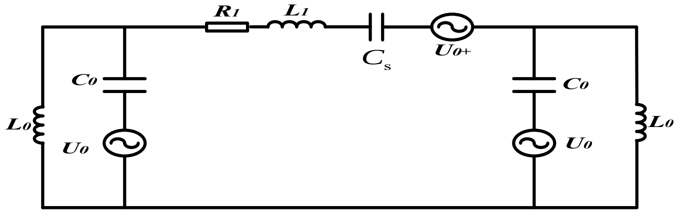


Fig.3. Low frequency equivalent circuit diagram

Where U_{0+} is the voltage of series capacitor compensation and $U_0$is the voltage of the capacitance to ground resulting from the initial storage of electric charge. According to Laplace transform, the eigenvalue equation can be shown in Equation (1) below:

$$(s^2 L_0 C_0 + 1)[s^4 L_0 C_0 L_1 C_z + S^3 R_1 L_0 C_0 C_z + s^2(2C_z L_0 + L_1 C_z + L_0 C_0) + sC_z R_1 + 1] = 0 \tag{1}$$

Putting the parameters in Fig.1 into Eq. (1), the eigenvalues can be listed in Table 1:

Table 1solutions gent equation

S=a+jb	s1, s2	s3, s4	s5, s6
Extreme point	-94±j2706	-34±j82	±j1408

Where the real part is the attenuation coefficient of recovery voltage and the imaginary part is the angular frequency. Eigenvalues(s3&s4) decays slower than others, which is low-frequency component and its frequent (f_1) is 13.06Hz。

In instantaneous earth fault, the fault phase forms a resonance circuit with reactors and capacitors which can generate free oscillation component after secondary arc extinguished.. Based on the second principle of compensation, free-running frequency (f_2) can be calculated as 38.5Hz[3].

Due to electromagnetic coupling effect in faulty phase, the recovery voltage also contains power frequency component (f_2) which is 50Hz.

(2) At single-phase ground fault and secondary arc is not extinguished position, low-frequency component is generated by the oscillation circuit which is formed by residual charges from reactors, capacitors and arc track resistance. Since the fault point exists, Arc will not extinguish. Therefore, there is no free oscillation component. Thus, when the arc current does not extinguish, there are only low-frequency component and power frequency component in the recovery voltage.

3.3. The characteristic of recovery voltage after series compensation capacitor protection action

There are two protection actions for series capacitor compensation, which are:

(1) Bypass switch series capacitor compensation: when the energy absorption MOV is saturated, a trigger pulse is send to short the discharge gap and bypass breaker. In another condition, the gap bypass Series Compensation triggered by line protection linkage.

The equivalent circuit of capacitor compensation and MOV shorted by bypass breaker is shown in Fig 4 below:

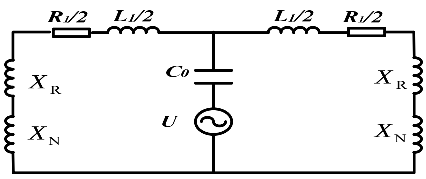


Fig.4. Series compensation is bypass transient fault equivalent circuit diagram

According to Laplace transform, the eigenvalue equation can be shown in Equation (2) below:

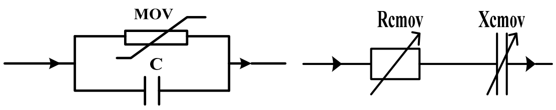
$$\frac{sL_N + sL_P + \frac{R_1}{2} + \frac{sL_1}{2}}{2} + \frac{1}{sC_0} = 0 \tag{2}$$

The Laplace expression of the free oscillation component in recovery voltage is determined in(3):

$$s=-\frac{R_1}{2(L_1+2L_P+2L_N)}\pm j\frac{\sqrt{(4R_1+8L_P+8L_N)C-(R_1C_1/2)^2}}{(L_1+2L_P+2L_N)C_0} \quad (3)$$

Therefore, s=-0.345±j321. The free oscillation component in recovery voltage (f_4) is 51.11Hz.When series capacitor compensation is bypassed， low-frequency component is eliminated which is detected by simulation.

(2) When the line fault zone occurs and the current is large, series compensation capacitors are protected by MOV .After breaker tripped, current flows on MOV but bypass switch is not closed. Paper [4]shows that series compensation can be represented by linear resistors and capacitors when MOV is conducting (in Fig. 5).



(a）parallel circuit　　(b) equivalent circuit

Fig.5. MOV protection operation Series Compensation equivalent circuit

Comparing figure 5 (a) and (b) to be seen, MOV conduction compared with MOV without conduction. The fault phase equivalent circuit is equivalent to only change the line resistance and series compensation capacitor value. In the case of with series compensation capacitor free oscillation frequency calculation is $\omega_2=1/\sqrt{L_0C_0}$, Series circuit resistance and capacitance values of the impact is not big.

4. Methods for identifying fault properties

4.1. The least squares algorithm model[5]

In order to discriminate fault properties, recovery voltage model is set up as shown in eq. (4):

$$u_0(t)=Ue^{-\frac{1}{T}t}+U_1e^{-\frac{1}{T_1}t}\sin(\omega_1 t+\theta_1)+U_2e^{-\frac{1}{T_2}t}\sin(\omega_2 t+\theta_2)+U_3e^{-\frac{1}{T_3}t}\sin(\omega_3 t+\theta_3)+U_4e^{-\frac{1}{T_4}t}\sin(\omega_4 t+\theta_4) \quad (4)$$

In the formula(4)： t=0,Circuit breakers on both sides are tripped； $\omega_1=2\pi f_1$； $\omega_2=2\pi f_2$； $\omega_3=2\pi f_3$； $\omega_4=2\pi f_4$； u, T are the DC component of the amplitude and the decay time constant； T_1, T_2, T_3, T_4 are the decay time constant of each component corresponding f1, f2, f3, f4； u_1, u_2, u_3 ,u_4 are amplitude of each component corresponding f1, f2, f3, f4； θ_1, θ_2, θ_3 ,θ_4 are first phase angle of each component corresponding f1, f2, f3, f4.

In order to facilitate the calculation， $e^{-\frac{1}{T}t}$ can be instead as $1-\frac{t}{T}$. In addition, after the fault phase circuit breaker tripping, Super/UHV line the time constant of free oscillation component and low frequency components is bigger, so $e^{-\frac{1}{T_2}t}$,$e^{-\frac{1}{T_3}t}$, $e^{-\frac{1}{T_4}t}$ are approximately taken as 1. Then, eq. (4) can be simplified to eq.(5).

$$u_0(t)=U-U\frac{t}{T}+U_1\sin\omega_1 t\cos\theta_1+U_1\sin\theta_1\cos\omega_1 t+U_2\sin\omega_2 t\cos\theta_2+U_2\sin\theta_2\cos\omega_2 t+U_3\sin\omega_3 t\cos\theta_3+U_3\sin\theta_3\cos\omega_3 t+U_4\sin\omega_4 t\cos\theta_4+U_4\sin\theta_4\cos\omega_4 t \quad (5)$$

Eq. (5) can be written in matrix form, as shown in eq. (6).

$$AX=B \quad (6)$$

Which:

$$A=\begin{bmatrix} 1 & t_1 & \sin\omega_1 t_1 & \cos\omega_1 t_1 & \sin\omega_2 t_1 & \cos\omega_2 t_1 & \sin\omega_3 t_1 & \cos\omega_3 t_1 & \sin\omega_4 t_1 & \cos\omega_4 t_1 \\ 1 & t_2 & \sin\omega_1 t_2 & \cos\omega_1 t_2 & \sin\omega_2 t_2 & \cos\omega_2 t_2 & \sin\omega_3 t_2 & \cos\omega_3 t_2 & \sin\omega_4 t_2 & \cos\omega_4 t_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & t_N & \sin\omega_1 t_N & \cos\omega_1 t_N & \sin\omega_2 t_N & \cos\omega_2 t_N & \sin\omega_3 t_N & \cos\omega_3 t_N & \sin\omega_4 t_N & \cos\omega_4 t_N \end{bmatrix}$$

$$X=\left[U, -\frac{U}{T}, U_1\cos\theta_1, U_1\sin\theta_1, U_2\cos\theta_2, U_2\sin\theta_2, U_3\cos\theta_3, U_3\sin\theta_3, U_3\cos\theta_3, U_3\sin\theta_3, U_4\cos\theta_4, U_4\sin\theta_4\right]'$$

$$B=[u_0(t_1), u_0(t_2), \ldots, u_0(t_N)]^T \tag{7}$$

A is coefficient matrix, can be offline calculation; X is the unknown parameter matrix, it contains 10 parameters, B is a constant matrix, is sample values of the recovery voltage. Taking N sampling values of recovery voltage u_0 into the eq. (6)， can constitute N equations. Using Least square algorithm solve eq.(6), can obtain the free oscillatory component (i.e. f_2, f_4) we need.

4.2. Criterion

From Section 2, in the series capacitor compensation of various conditions, Permanent fault state recovery voltage contain only frequency components and low frequency components; While the recovery voltage of transient fault contained labor frequency components, free oscillatory component and low frequency component. The series compensation protection without action, the frequency of the free oscillation component is f_2, the f_2 component amplitude is not 0; the series compensation protection action, the frequency of the free oscillation component is f_4,the f_4 component amplitude is not 0.

Using the eq. (6) to calculate the amplitude of f_2, f_4 component: U_2 and U_4, if :

$$U_2=0 \text{ and } U_4=0 \tag{8}$$

It is judged as a permanent fault, latching reclosing.if:

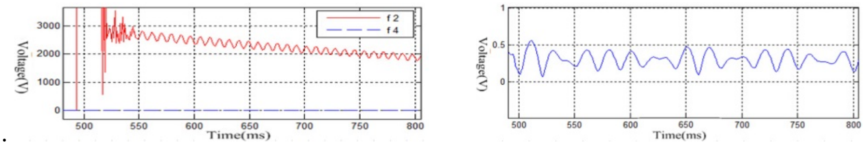
$$U_2\neq 0 \text{ or } U_4\neq 0 \tag{9}$$

It is judged as a transient fault, fault phase recloses circuit breaker.

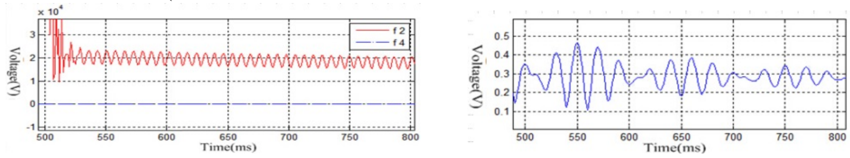
5. Emulation proof

Using PSCAD established a circuit simulation model as Figure 1 for simulation. Assumed single-phase ground fault occurred at 300ms, after 50ms the circuit breaker tripped. Transient fault, the secondary arc immediately extinguished; permanent fault, the secondary arc is always present.

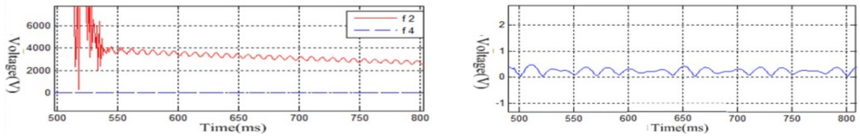
In order to verify the applicability criterion, under different circumstances the fault location and fault resistance .Figure 9 shows the f2 and f4 components in the instantaneous failure and the free oscillation component in the permanent fault.



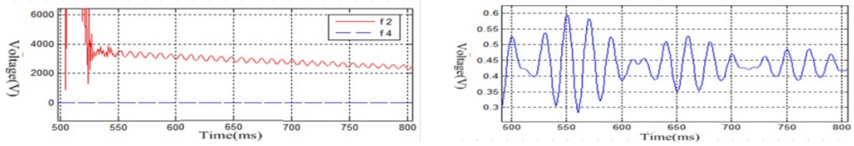
(a) The fault is 0 km from M with transition resistance 0.1 Ω



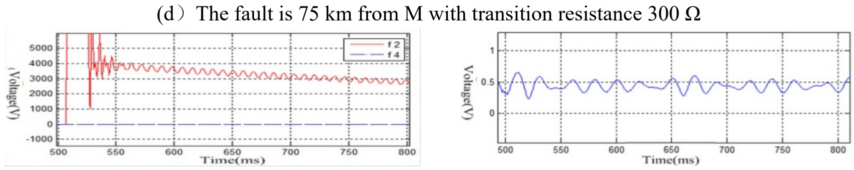
(b) The fault is 0 km from M with transition resistance 300 Ω



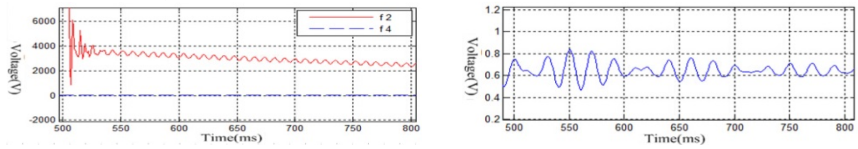
(c) The fault is 75 km from M with transition resistance 0.1 Ω



(d) The fault is 75 km from M with transition resistance 300 Ω



(e) The fault is 150 km from M with transition resistance 0.1 Ω



(f) The fault is 150 km from M with transition resistance 300 Ω

Fig.6 Free oscillation component contrast diagram under different conditions

Table 2 Free oscillation component amplitude

Series compensation not bypass

System operation	Fault location (distance to M)	Transition resistance (Ω)	Permanent fault (V)	Transient fault (V)
Minimum operating mode	0%	0	0.0520	3702
		300	0.1436	2669
	25%	0	0.2812	2954
		300	0.2743	3411
	50%	0	0.3982	3638
		300	0.4603	3703
Maximum operating mode	0%	0	0.0360	2892
		300	0.4325	2701
	25%	0	0.1670	4993
		300	0.7074	3505
	50%	0	0.5409	4463
		300	1.0480	3695

Series compensated by bypass

Fault location (distance to M)	Transition resistance (Ω)	Permanent fault (V)	Transient fault (V)
0%	0	4.526	3309
	50	0.5876	2433
	300	0.2413	2487
25%	0	0.7688	6710
	50	0.2935	4215
	300	0.4415	10350
50%	0	0.4337	9932
	50	0.5935	10170
	300	0.5631	11010

From figure 9 and table 2，With series compensated transmission lines, transient fault occurs when the series capacitor compensation protection is not action, The amplitude of free oscillation components is large; The amplitude of free oscillation is almost 0, when the permanent fault occurs. See from table 3 in the series compensation capacitor is bypass, Using the eq.(9) decomposes the recovery voltage, free oscillation amplitude component under different nature of the fault is difference, instantaneous failure is far greater than zero, under the permanent fault is about zero. As a result, regardless of whether the action series capacitor compensation protection, in different fault location and the transition resistance, the methods are reliable in judging fault properties in this paper.

6. Conclusions

For the line with series capacitor compensation proposed single-phase adaptive reclosure fault nature criterion, the following conclusions can be drawn:

(1) By analyzing the series compensation recovery voltage frequency characteristics under different conditions, recovery voltage include the component of the low-frequency components, free oscillation frequency component and labor component in transient fault； The recovery voltage only include low-frequency components and labor components in the case of a permanent fault.

(2) Under transient fault state, series capacitor compensation if bypassed, free oscillation components at different frequencies.

(3) Recovery voltage free oscillation amplitude component can be Obtained by the least squares algorithm. Whether the use of free oscillation frequency component of 0 discriminant fault properties. A lot of simulation shows the correctness and effectiveness of the method.

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