Research on Characteristics of Voltage Fault Traveling Waves of Transmission Line

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Abstract—A Line parameters of high voltage transmission lines, especially of EHV/UHV long distance transmission line, have the characteristics of distribution parameters obviously. When a fault is occurred on a transmission line, voltage fault travelling waves and current fault travelling waves generated by fault superimposed voltage source have abundant fault information which can be use as criteria for fault detection. The characteristic analysis of voltage fault travelling waves after a fault occurred on a transmission line concluded that: Voltage fault travelling waves after a fault consist of two components, pre-fault load travelling waves and post-fault fault travelling waves, and fault travelling waves can be classified into fault transient travelling waves and fault steady-state travelling waves according to time period, and fault transient travelling waves contain two characteristics, high-frequency wave-front and power frequency component, and the polarity of high frequency wave-front is the same as the initial polarity of power frequency component. Research on characteristics of voltage transient travelling waves provide an important theoretical basis for the establishment of new direction protection theory based on travelling waves.

Keywords—transmission lines; voltage fault traveling waves; fault transient traveling waves; fault steady-state traveling waves; high frequency wave-front.

I. INTRODUCTION

Fault analysis is the basis of relay protection. In traditional fault analysis, transmission line is modeled by lumped parameter equivalent circuit. But for ultra high voltage long transmission line, its parameters have clear characteristics of distributed parameter. Distributed parameter equivalent circuit should be used to analyze the fault characteristics to apply for relay protection [1].

According to the principle of fault superposition, a superimposed voltage will be imposed on the transmission line abruptly when a fault occurs on it. Consequently, there will be the voltage and current superimposed components that travelling along the transmission line. These travelling waves are generated by the fault contain abundant fault information such as fault direction ,fault location, time of fault occurring and so on[2-3] and they can be used as the fault detection criteria.

Transmission line fault detection technology based on travelling waves have been widespread studied by many scholars from 1940s.[4-6] Fault location method base on current travelling waves has been applied successfully in Chinese grid.[7-9] Now, capacitive voltage transformers (CVT) have been widely used in EHV/UHV power system. But the study has showed that the CVT can not transform voltage travelling waves effectively. It can only transform the voltage components which frequency is near the power frequency [10-11]. So many transmission line protection based on voltage travelling waves can not be applied to the power system with CVT utilized in it[12-14]. Actually, the characteristics of fault voltage travelling waves have not been studied deeply. And this paper will analyze the characteristics of fault voltage travelling waves deeply and extract the fault information which can provide theoretical basis for new transmission line protection algorithm based on travelling waves.

II. BASIC PRINCIPLE OF TRAVELLING WAVES PROPAGATION

In figure 1, when a sinusoidal voltage source is imposed onto the equivalent circuit of the transmission line, the voltage will be spreading along the distributed parameter equivalent circuit. However, because the distributed capacitance and reactance, the voltage or the current on these energy storage components cannot be changed abruptly and there is always a charge and discharge process. Magnetic field will be established in the distributed inductance and electric field will be established in the distributed capacitance. In the space around line conductor, energy of magnetic field is the same as it of electric field. The propagating process of voltage travelling waves and current travelling waves is an energy transmitting process of electromagnetic.

The relationship among voltage traveling waves, current traveling waves and the transmission line parameters can be represented by the wave equation:

$$\begin{cases} -\dfrac{\partial u}{\partial x} = L_0 \dfrac{\partial i}{\partial t} \\ -\dfrac{\partial i}{\partial x} = C_0 \dfrac{\partial u}{\partial t} \end{cases} \tag{1}$$

Above equations can be rewritten as:

$$\begin{cases} \dfrac{\partial^2 u}{\partial x^2} = L_0 C_0 \dfrac{\partial^2 i}{\partial t^2} \\ \dfrac{\partial^2 i}{\partial x^2} = L_0 C_0 \dfrac{\partial^2 u}{\partial t^2} \end{cases} \tag{2}$$

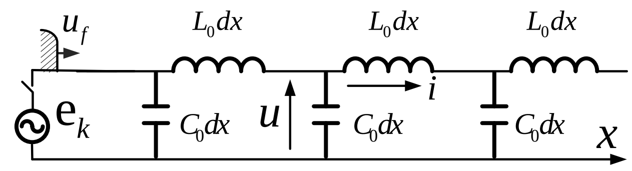


Fig. 1 Distributed parameter equivalent circuit and propagation of fault travelling waves for a single line

In equation (1) and (2), L_0 is the line reactance per length, unit is H/km, C_0 is the capacitance per length, unit is F/km; u and i represent the voltage and current at the location which is x km from fault point.

The general solution of above equation is formula (3):

$$\begin{cases} u = u_1(t-\frac{x}{v}) + u_2(t+\frac{x}{v}) \\ i = \frac{1}{Zc}\left[u_1(t-\frac{x}{v}) - u_2(t+\frac{x}{v})\right] \end{cases} \quad (3)$$

In equation (3), $Zc=\sqrt{\frac{L}{C}}$ is the surge impedance; $v=\frac{1}{\sqrt{LC}}$ represents the traveling waves' propagation speed; $u_1(t-\frac{x}{v})$ is the forward traveling wave which travels toward forward direction; and $u_2(t+\frac{x}{v})$ is the reverse traveling wave which travels towards reverse direction. According to a specified fault condition, a special solution of wave equation can be obtained.

As shown in figure 2(d), the initial travelling wave is generated by the fault additional voltage source. Assuming fault occurs at t_0, the superimposed voltage source is:

$$e_k(t) = -e_f \sin(wt+\varphi_{F1}) \quad (4)$$

III. ANALYSE OF FAULT TRAVELLING WAVES [15]

Take a single phase lossless transmission line as example. Assuming a fault occurs on the point F_1, as the figure 2(a) shows. According to the superimposed principle, the fault condition is equivalent to that two opposite and equal voltage sources superimposed at the fault point, voltage sources amplitude equal to pre-fault voltage at point F_1. Post fault network can be regarded as the superimposed circuits of the pre-fault load network and fault component network. And pre-fault load network is the normal power system before fault as the figure 2(c) shows. Fault component network only appears after fault as the figure 2(d) shows. The initial value of the voltage source at the fault component network is equal in magnitude and opposite in direction of the pre-fault voltage at the fault point. The fault travelling waves are originated by the fault superimposed source acting on the fault component network.

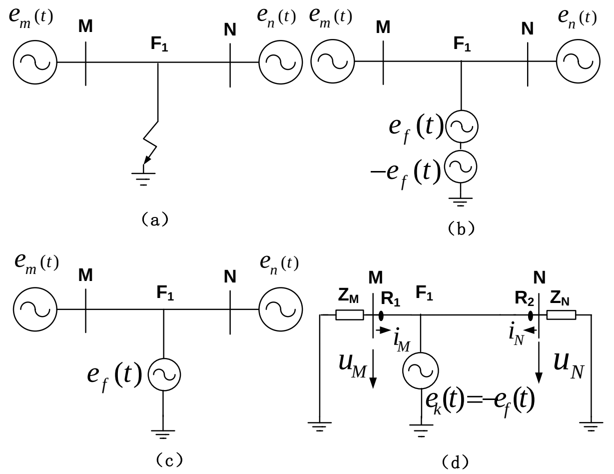


Fig. 2 Superposition theorem Schematic circuit

A. Load Travelling Waves

Power is transferred along power system transmission lines to the load in the way of electromagnetic waves. Assume the voltage and current at the bus M are u and i, which can be expressed in the formula (5a):

$$S_F = (u+Zi)/2$$
$$S_R = (u-Zi)/2 \quad (5a)$$

The corresponding current travelling waves form is the formula (5b):

$$S_F = (u+Zi)/2Z$$
$$S_R = -(u-Zi)/2Z \quad (5b)$$

In which Z is the surge impedance. In figure 2(c), the travelling waves in pre-fault load network are the load travelling waves.

B. Fault Travelling Waves[16]

A) Initial travelling wave

As shown in figure 2(d), the initial travelling wave is generated by the superimposed voltage source. Assuming fault occurs at t_0, the fault superimposed voltage source is:

$$e_k(t) = -e_f \sin(wt+\varphi_{F1}) \quad (6)$$

Where e_f is the amplitude of the superimposed voltage source, φ_{F1} is the fault inception angle.

Wave-front can be defined as the initial value of the voltage fault transient travelling waves, and is represented by u'_{fth}.

$$u'_{ftth} = -e_f \sin(wt_0 + \varphi_{F1}) \qquad (7)$$

The wave-front is an abrupt signal, equaling to a step response. If the wave-front is analyzed in frequency domain, it is a full frequency signal including much high frequency components. Consequently the wave-front is called high frequency wave-front of initial voltage fault travelling wave.

The power frequency components of voltage fault transient initial travelling wave are represented by u'_{fttp}.

$$u'_{fttp} = -e_f \sin(wt + \varphi_{F1}) \qquad (t > t_0) \quad (8)$$

And fault inception angle is

$$\varphi_f = wt_0 + \varphi_{F1} \qquad (9)$$

After the fault, the polarity of u'_{fttp} will keep the same as it of u'_{fttp} before the phase angle of the superimposed voltage source reaches to 0° or 180°. And one of the important characteristics of initial f voltage fault travelling wave is the same polarity of u'_{ftth} and u'_{fttp}.

B) The propagation of fault travelling wave[17]

As shown in figure 2(d), when metallic fault occurs at F_1, voltage and current fault travelling waves in bus M and N are:

$$\begin{cases} u_M(t) = e_k(t-\tau_M) + k_{ML}e_k(t-\tau_M) - \\ \qquad k_{ML}e_k(t-3\tau_M) - k_{ML}^2 e_k(t-3\tau_M) - ... \\ i_M(t) = \dfrac{-e_k(t-\tau_M) + k_{ML}e_k(t-\tau_M)}{Z_C} + \\ \qquad \dfrac{k_{ML}e_k(t-3\tau_M) - k_{ML}^2 e_k(t-3\tau_M) + ...}{Z_C} \end{cases} \quad (10)$$

$$\begin{cases} u_N(t) = e_k(t-\tau_N) + k_{NL}e_k(t-\tau_N) - \\ \qquad k_{NL}e_k(t-3\tau_N) - k_{NL}^2 e_k(t-3\tau_N) - ... \\ i_N(t) = \dfrac{-e_k(t-\tau_N) + k_{NL}e_k(t-\tau_N)}{Z_C} + \\ \qquad \dfrac{k_{NL}e_k(t-3\tau_N) - k_{NL}^2 e_k(t-3\tau_N) + ...}{Z_C} \end{cases} \quad (11)$$

Where M, N means the two terminals of the transmission line; k_{ML}, k_{NL} mean reflection coefficient at terminal M and N respectively; τ_M, τ_N mean travelling time from fault point to terminal M and N respectively.

Figure 3 is the Lattice diagram of voltage fault travelling waves after an internal fault.

When $t_0 \le t < t_0 + \tau_M$, the initial voltage transient travelling wave u_{ftt1} has not reached bus M, so the detected voltage of relay is zero.

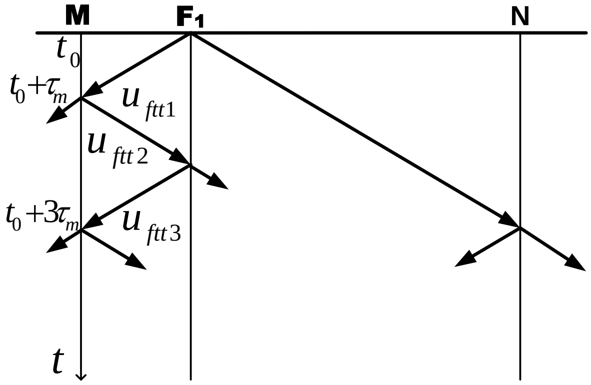


Fig. 3 Lattice diagram of travelling waves for internal fault

$$u_{ftt} = 0 \qquad (t_0 \le t < t_0 + \tau_M) \qquad (12)$$

When $t = t_0 + \tau_M$, initial travelling wave reaches bus M, relay gets the wave-front of u_{ftt1},

$$u'_{ftth} = e_k(t-\tau_M) = e_k(t_0) \qquad (t = t_0 + \tau_M) \, (13)$$

The wave-front of voltage initial travelling wave reflects immediately at M. Let u_{ftth} be the actually detected wave-front of voltage initial travelling wave:

$$u_{ftth} = (1+k_{ML})u'_{ftth} = (1+k_{ML})e_k(t_0) \qquad (t = t_0 + \tau_M) \, (14)$$

When $\tau_M < t < 3\tau_M$, the actually detected voltage initial travelling wave is the composition of u_{ftt1} and its reflection wave at M named u_{ftt2}

$$u_{fttp} = (1+k_{MR})u'_{fttp} = (1+k_{MR})e_k(t-\tau_M)\varepsilon(t_0)$$
$$(t_0 + \tau_M < t < t_0 + 3\tau_M) \qquad (15)$$

By substitution the superimposed source in formula (6) into equation (14) and equation (15), formula (16) can be got:

$$u_{ftt} = \begin{cases} 0 & (t_0 \le t < t_0 + \tau_M) \\ -(1+k_{ML})e_f \sin(wt_0 + \varphi_{F1}) & (t = t_0 + \tau_M) \\ -(1+k_{ML})e_f \sin[w(t-\tau_M) + \varphi_{F1}]\varepsilon(t_0) & \end{cases}$$
$$(t_0 + \tau_M < t < t_0 + 3\tau_M) \qquad (16)$$

It can be seen that, when $t_0 + \tau_M < t < t_0 + 3\tau_M$, voltage fault travelling wave is power frequency component which is another important character of voltage fault travelling waves .

C) The characteristics of voltage fault travelling wave

When $t = t_0 + \tau_M$, the expression of high frequency wave-front of actually detected voltage fault transient travelling wave at bus M is given in formula(14), and formula(15) gives the expression of power frequency component of actually detected voltage fault transient travelling waves when $t_0+\tau_M<t<t_0+3\tau_M$.

And the reflection coefficient of voltage traveling wave at bus which satisfies

$$-1\le k_{ML}\le 1 \qquad (17)$$

The reflection coefficient of voltage traveling wave equals -1 when infinite amount transmission lines are connected to the bus, which is impossible in real power system. So formula (18) can be got:

$$1+k_{ML}\ge 0 \qquad (18)$$

The polarity of power frequency component of actually detected voltage fault transient traveling wave u_{fttp} has the same polarity of power frequency component of initial voltage fault transient traveling wave u'_{fttp} When $t_0+\tau_M<t<t_0+3\tau_M$. Meanwhile, u'_{ftth} and u'_{fttp} have the same polarity which has been concluded in section A).

Consequently, we can get the conclusion that u'_{ftth} and u_{fttp} have the same polarity. And that is the actually detected power frequency component of voltage fault transient traveling wave and high frequency wave-front of initial voltage fault travelling wave have the same polarity. And this conclusion is a significant characteristic of initial voltage fault travelling wave.

C. The Classification of Post-fault Travelling Wave

As showed in Fig. 3, fault travelling wave will be reflected and refracted at the discontinuity point of surge impedance. Theoretically it will reach stable state after infinite reflection and refraction. However, due to the power consumption in superimposed networks, fault travelling wave will reach the stable state after finite reflection and refraction.

$$u_M=\begin{cases}u_{prel}+u_{ftt} & (t_0\le t<t_t)\\ u_{prel}+u_{fst} & (t\ge t_t)\end{cases} \qquad (19)$$

In formula (19), u_{prel} indicates load component of voltage travelling wave generated in pre-fault load network according to Fig. 2 (c), while u_{fst} indicates fault steady-state traveling wave of superimposed networks when $t\ge t_t$ according to Fig. 2(d). Considering the requirement of the operation speed of protection, the research on travelling waves is focused on post-fault voltage transient travelling wave u_{ftt}.

According to the analysis of the preceding in this paper, fault transient travelling wave contain two important characteristics: high-frequency wave-front u_{ftth}, and power frequency component u_{fttp}

IV. EMTP SIMULATION

Figure 4 shows a 750kV transmission line system equivalent circuit, assuming that fault occurs at F_1.

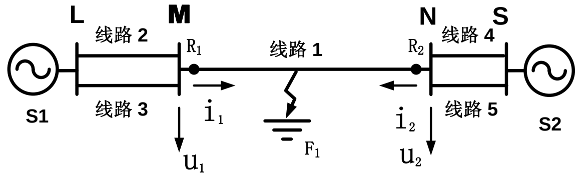
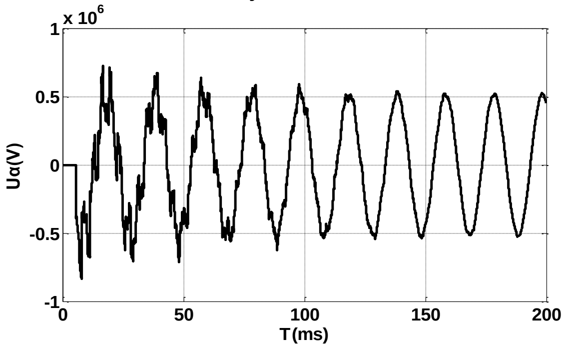


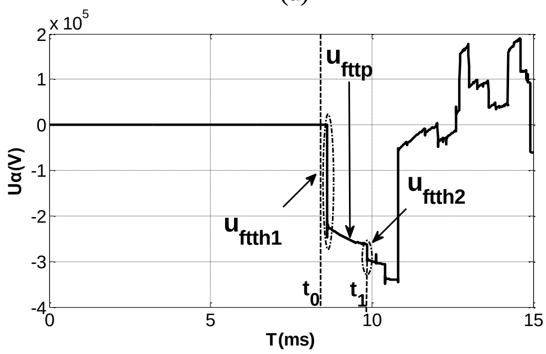
Fig. 4 750kV transmission line system equivalent circuit

Karenbauer phase-modal transformations are applied to decouple the three-phase transmission system in the paper.

Assuming that A phase-to-ground fault occurs at 100kM from the bus M, fig 5 shows the voltage fault travelling wave, taking modal u_α for example which indicates that the voltage fault travelling wave goes through a transition process from transient state to steady state.



(a)



(b)

Fig. 5 Voltage Fault travelling waves

Fig. 5 (b) is a local enlarged diagram of Fig. 5(a), where u_{ftth1} is the actually detected high frequency wave-front of voltage fault transient travelling wave; u_{ftth2} is derived from u_{ftth1} after two times reflection at bus M and the fault point ;

$$t_1=t_0+2\tau_M \qquad (20)$$

Between u_{ftth1} and u_{ftth2} , there is the power frequency component of voltage fault transient travelling wave

u_{fttp} .Fig. 5 also indicates the consistency of initial polarity of u_{ftth1} and u_{fttp}

V. CONCLUSION

The paper analyses the characteristics of voltage fault travelling wave of the transmission line, following points are the conclusions.

1) The post-fault voltage travelling wave contains load travelling wave and fault travelling wave.
2) The fault traveling wave can be classified as fault transient travelling wave and fault stable travelling wave.
3) The fault transient travelling wave contains two significant characteristics: the high frequency wave-front of the fault transient travelling wave and the power frequency component of the fault transient travelling wave.
4) The polarity of high frequency wave-front of initial voltage fault transient traveling wave and the initial polarity of power frequency component of the fault voltage transient traveling wave has consistency.

ACKNOWLEDGMENT

Thanks for the financial support by the National Natural Science Foundation of China (Grant Nos. 50937003) and The Foundation of State Key Lab on Power System（Grant Nos. SKLD09M04）, the Key International Cooperative Project of Tsinghua-Areva T&D Research Centre.

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