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Resonance mechanisms of a single line-to-ground fault on ungrounded systems

JUN JIANG, LING LIU

Shandong Polytechnic
China
e-mail: liuling95@163.com

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Abstract: As for a single line-to-ground fault in an ungrounded distribution system, the power-frequency current is too low to detect the fault. The transient current is more palpable than that at a power-frequency of 50 or 60 Hz. It is an effective method to estimate the fault using the transient fault current. To analyze and calculate the transient current of single line-to-ground faults, an equivalent circuit is proposed in this paper. This model is based on distributed parameters of power lines. And it contains positive, negative and zero sequence information. The transient equivalent circuit consists of equivalent resistance, equivalent inductance and equivalent capacitance. And the method of calculation the equivalent elements is also submitted. MATLAB simulation results show that the new transient equivalent circuit has higher accuracy and stronger adaptability compared with the traditional one.

Key words: power distribution faults, single line-to-ground fault, transient characteristics, ungrounded distribution system

1. Introduction

Ungrounded medium voltage (MV) distribution systems are still widely used in China. The fault current during a single line-to-ground fault condition is usually much less than 10 amps [1]. In overhead distribution circuits, the main advantage of an ungrounded system is that temporary faults clear themselves without opening a breaker or recloser. The ungrounded system can operate for a prolonged time with a single line-to-ground fault, and the arc can self-extinguish. So, ungrounded systems have higher reliability [2].

There are two types of methods commonly used to selectively detect ground faults on ungrounded systems, steady state methods and transient methods. Both methods use zero sequence fault currents to identify the faulted circuit. When a single line-to-ground fault occurs in an ungrounded system, there is no flow of a substantial fault current, merely an imbalance in the system charging currents [3]. The capacitive current flows from the upfaulted circuits to the faulted circuit. Therefore, the direction of the capacitive current can be used to determine the faulted circuit [4, 5]. Since the current is based on circuit capacitance to ground, it is significantly less than the load current and difficult to be detected. Another type of method is to use the transient voltage and current for fault diagnosis [6, 7]. The fault transient current and voltage are more stable and strong, thus better for identifying the faulted circuit.

For analyzing the transient voltage and current characteristics of the single line-to-ground fault, an equivalent circuit is necessary. The traditional transient equivalent circuit [1, 8] is a resistor–inductor–capacitor (RLC) series circuit consisting of zero-sequence network lumped parameter equivalent resistance, inductance and ground distributed capacitance. This model is only related to the zero sequence loop, ignoring positive and negative sequence networks, and lacking the parameter calculation method. The equivalent circuit [9, 10] using the Karrenbauer transformation is also proposed. This method has high accuracy, but the parameters calculation is too complex and difficult to apply in engineering practice. In this paper, based on the symmetric component method, a simplified transient equivalent circuit is given. The method of fault location based on the principal resonant frequency is given by combining the parameters of an overhead power line, and the simulation is carried out using MATLAB to verify the feasibility of the method.

2. MV Distribution networks

Electric power distribution systems deliver electricity from the highly meshed, high-voltage transmission circuits to retail customers through overhead lines or underground cables. Primary distribution circuits are medium-voltage circuits, typically 10 kV in China. Along most roads and streets, distribution circuits may be found. They are mainly underground in urban, overhead in rural, and mixed in suburban districts.

2.1. Distribution circuits

Distribution circuits are radial or looped. It generally starts with a switching device, located in a substation and extends to a set of open points (radial circuit), or to a second substation (looped circuit). The normal operation is radial, that is, there is only one power source for a specific user. A feeder is one of the circuits out of the substation. The main feeder is the backbone of the circuit, which is also called the mainline. The mainline is normally a modestly large conductor such as a 120 or 400 mm^2 aluminum or copper conductor. Utilities often design the main feeder for 400 ampere or above. Branching of the mainline consists of one or more laterals, which are also called branches, or branch lines.

Distribution systems in China are similar to that of Europe. They are designed and operated as three-phase three-wire ungrounded or ungrounded systems. Distribution circuits are overhead or underground. Generally, the overhead lines are cheaper than the underground cables. A distribution feeder has four electrical parameters: series resistance (R), series inductance (L), shunt conductance (G), and shunt capacitance (C). Since conductance G is very small, neglecting it has little effect on the transient process of fault analysis, so it can be ignored.

2.2. Overhead lines

Most conductors of overhead lines are either aluminum or copper. Aluminum is widely used for an overhead system. It is lighter and less expensive than the copper one. Copper has very good properties that limit corrosion in the presence of salts, so it is installed in coastal and corrosive areas. Most of overhead lines are bare conductors. They are exposed to the direct contact with the atmosphere. To limit tree faults and improve safety for residents, covered conductors are widely used in recent years, such as an aerial cable. An aerial cable has a covering of insulation capable of withstanding phase to ground voltages. It reduces the probability of a fault if tree branch bridges have two or more conductors.

In China, MV distribution overhead lines are three-wire systems (with no neutral). The parameters of overhead lines can be calculated according to the formula, or be checked against the engineering manual. For most urban areas, an all-aluminum conductor (AAC) is a good choice. It has sufficient strength and good thermal characteristics. In rural applications, smaller conductors and longer pole spans are used, so a higher-strength conductor as an aluminum conductor, steel reinforced (ACSR), is more appropriate. At present, utilities in China standardize on a set of following conductors: utilities use 120 mm^2, 150 mm^2, 185 mm^2 and 240 mm^2 cables for mainlines and 50 mm^2, 70 mm^2, 95 mm^2, 120 mm^2 cables for branch lines. The electrical parameters of lines can be calculated or looked up against the handbook. For example, AAC overhead line parameters with a conductor size of 150 mm^2, the average distance between wires 1.25 m, the electrical parameters are shown in Table 1.

Table 1. Electrical parameters of overhead line

	R **(Ω/km)**	***L*** **(mH/km)**	***C*** **(nF/km)**
Positive-sequence	0.222	1.09	10.76
Negative-sequence	0.222	1.09	10.76
Zero sequence	0.367	5.06	4.13

2.3. Underground cables

Much of the new distribution circuits are underground in urban areas. Underground cables are hidden from view, and are more reliable than overhead lines. They are also safer to the public than overhead lines. Underground cables are typically used for mainline feeders, network feeders, and other high current applications. Underground cables have significant capacitance, much larger than overhead lines. The fault current during line-to-ground fault conditions in underground systems is much stronger than that of an overhead line. So, underground cables are limited when used in an ungrounded distribution system.

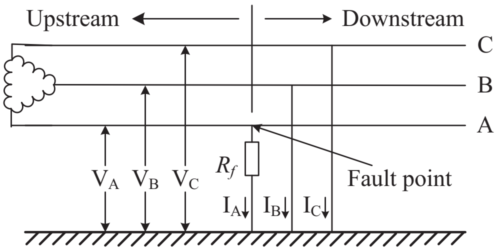
3. Equivalent circuit and simplification

During single line-to-ground faults (such as phase A), the voltage in the faulted phase drops to near zero and in the unfaulted phases (phase B and C) rises to $\sqrt{3}$ times the nominal value.

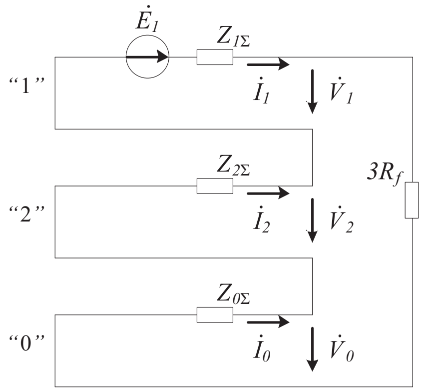
3.1. Compound sequences network model

A single line-to-ground fault is a type of unbalanced fault. The calculation of the current values involves the use of the method of symmetrical components, which requires the calculation of three independent system components. For a single line-to-ground fault in phase A, as shown in Fig. 1(a), the equivalent circuit for compound sequences (includes the positive sequence, negative sequence and zero sequence) is given in Fig.1(b), where:

– $Z_{1\Sigma}$ is the impedances of the system for the positive sequence.
– $Z_{2\Sigma}$ is the impedances of the system for the negative sequence.
– $Z_{0\Sigma}$ is the impedances of the system for the zero sequence.



(a) Line-to-ground fault on phase A



(b) Compound sequences equivalent circuit

Fig. 1. Line-to-ground fault on ungrounded system

In distribution networks, loads are distributed on the distribution circuits in turn. The impedance of the load is much higher than the impedance of the line and the short-circuit impedance at the fault point. For the simplification of the calculation, the influence of the load is ignored in the simplification of the model. It is considered that:

– Three-phase loads are completely balanced, and distribution lines are completely symmetrical without the coupling of the positive sequence, negative sequence and zero sequence. $Z_{1\Sigma}$ is equal to $Z_{2\Sigma}$.
– The ends of lines are open.

3.2. Positive (negative) sequence network

As shown in Fig. 1(a), we call the transformer of the substation to the fault point as fault upstream and the fault point to the line end as fault downstream. So, the positive sequence impedance $Z_{1\Sigma}$ is the result of paralleling the positive sequence impedance of the fault upstream

($Z_{1\Sigma-u}$) and the positive sequence impedance of the fault downstream ($Z_{1\Sigma-d}$). In the upstream of the fault point, each unfaulted line ($Z_{1\Sigma-1}$, $Z_{1\Sigma-2}, \ldots$) and transformer (Z_{1T}) are connected in parallel ($Z_{1T}//Z_{1\Sigma-1}//Z_{1\Sigma-2}//, \ldots$), and then connect with the positive sequence impedance of the fault line upstream (Z_{1-fu}). ($Z_{1\Sigma-d}$) is simply equal to the fault line downstream positive sequence impedance (Z_{1-fd}). So, the $Z_{1\Sigma}$ is:

$$Z_{1\Sigma} = \Big((Z_{1T}//Z_{1\Sigma-1}//Z_{1\Sigma-2}// \ldots) + Z_{1-fu}//Z_{1-fd} \Big), \tag{1}$$

where: $Z_{1\Sigma-1}$ is the positive sequence impedance of the first line, $Z_{1\Sigma-2}$ is the positive sequence impedance of the second line.

Regardless of the influence of loads, the positive sequence impedance of the unfaulted line is much larger than the positive sequence impedance of the transformer. So, $(Z_{1T}//Z_{1\Sigma1}//Z_{1\Sigma2}//\ldots) \approx Z_{1T}$. Furthermore, ignoring the loads, the end of the fault line is open. So, Z_{1-fd} is much greater than $Z_{1T} + Z_{1-fu}$, that is $(Z_{1T} + Z_{1-fu})//Z_{1-fd} \approx Z_{1T}$.

$$Z_{1\Sigma} = Z_{1T} + Z_{1-fu}. \tag{2}$$

The upstream impedance of the fault point (Z_{1-fu}) is the impedance of the line between the fault point and the transformer in the substation. Z_{1-fu} is the product of resistance per unit length (R_{u1}) and length (l_{fu}), $R_{1-fu} = R_{u1}\, l_{fu}$. Equation (2) can be simplified as an equivalent inductance and an equivalent capacitance. So,

$$\left. \begin{aligned} R_{2\Sigma} &= R_{1\Sigma} = R_{T1} + R_{u1} l_{fu} \\ L_{2\Sigma} &= L_{1\Sigma} = L_{T1} + L_{u1} l_{fu} \end{aligned} \right\}, \tag{3}$$

where: l_{fu} is the length of the line between the fault point and the transformer in the substation.

3.3. Zero sequence network

For the zero sequence networks of Fig. 1, the zero-sequence impedance $Z_{0\Sigma}$ is equal to the parallel of the upstream zero sequence impedance $Z_{0\Sigma-u}$ and the downstream zero sequence impedance at the $Z_{0\Sigma-d}$. The zero sequence impedance of all unfaulted lines ($Z_{0\Sigma-1}$, $Z_{0\Sigma-2}, \ldots$) is parallel to each other, and then connected with the upstream zero sequence impedance (Z_{0-fu}). The downstream of the fault is only the fault line, so Z_{0-fd} is equal to the downstream fault line zero sequence impedance (Z_{0-fd}). So, the $Z_{0\Sigma}$ is:

$$Z_{0\Sigma} = \Big((Z_{0\Sigma-1}//Z_{0\Sigma-2}// \ldots) + Z_{0-fu} \Big) //Z_{0-fd}, \tag{4}$$

where: $Z_{0\Sigma-1}$ is the zero sequence impedance of the first line, $Z_{0\Sigma-2}$ is the zero sequence impedance of the second line.

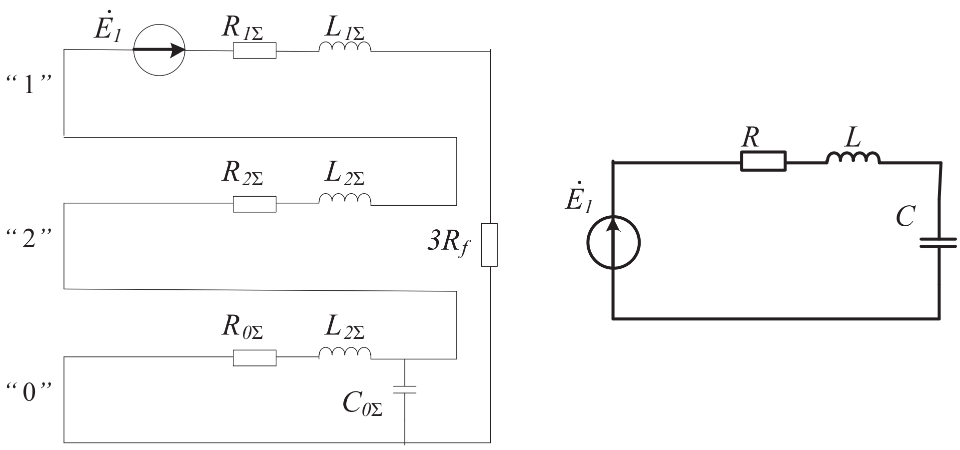
In the zero-sequence networks, the distributed capacitors are the main components of an unfaulted line. The whole capacitance of an unfaulted line can be expressed as the product of the capacitance per unit length and the length of the line, $C_0 = C_{u0}\, l$. The line upstream of the fault point can be equivalent to the comprehensive influence of resistance, inductance and capacitance. The line downstream of the fault point is mainly the effect of distributed capacitance to the ground. The calculation of the capacitor is the same as that of the healthy line. In summary, the zero sequence networks can be simplified as:

$$\left.\begin{aligned} R_{0\Sigma} &= R_{u0}\, l_{fu} \\ L_{0\Sigma} &= L_{u0}\, l_{fu} \\ C_{0\Sigma} &= C_{u0}\, l_{\Sigma} \end{aligned}\right\}, \tag{5}$$

where: l_{fu} is the length of the line between the fault point and the transformer in the substation, l_{Σ} is the whole length of all lines at the same bus.

3.4. Equivalent circuit

According to the simplification results as shown before, the circuits of the compound sequences in Fig. 1(b) can be simplified as in Fig. 2(a). Further, simplifying the resistance (R_{Σ}), inductance (L_{Σ}) and capacitance (C_{Σ}), it can simplify the circuit as shown in Fig. 2(b). In Fig. 2(b), R is the resistance of the equivalent circuit, L is the equivalent inductance, and C is the equivalent capacitance. E_1 is the power supply, $E_1 = V_m \sin(\omega_n t + \phi)$, where: ω_n is the nominal frequency, 100π (in China).



(a) Sequence network connections (b) Simplified equivalent circuit

Fig. 2. Equivalent circuit for transient calculation

In addition, the equivalent in Fig. 2(b), represented by R, L, C is shown as:

$$\left.\begin{aligned} &R = 3R_f + 2\left(R_{ul} l_{fu} + R_{T1}\right) + R_{u0} l_{fu} \\ &L = 2\left(L_{ul} l_{fu} + L_{T1}\right) + L_{u0} l_{fu} \\ &C = C_{u0}\, l_{\Sigma} \end{aligned}\right\}. \tag{6}$$

4. Transient analysis of a single line-to-ground fault

Using a transient equivalent circuit as in Fig. 2(b), the characteristic equation of a single line -to-grounding fault can be established, and the transient process can be analyzed.

4.1. Characteristic equation of equivalent circuit

The transient process of a single line-to-ground fault can be simplified to a second-order circuit as shown in Fig. 2(b), which is mainly composed of series resonance between inductors and capacitors. Using the voltage of the capacitor $C(v_c)$ as a variable, the transient equation of Fig. 2(b) is:

$$\left.\begin{aligned} LC\frac{\mathrm{d}^2 v_c}{\mathrm{d}t^2} + RC\frac{\mathrm{d}v_c}{\mathrm{d}t} + v_c = E_1 \\ i = C\frac{\mathrm{d}v_c}{\mathrm{d}t} \\ v_c\left(0_-\right) = 0 \\ i\left(0_-\right) = 0 \end{aligned}\right\}. \tag{7}$$

Equation (7) is a second-order differential equation whose solution consists of two parts, a general solution and a special solution. The general solution can be obtained according to the characteristic equation. Its characteristic equation is as follows:

$$LCp^2 + RCp + 1 = 0. \tag{8}$$

Its characteristic root can be evaluated by:

$$p_{1,2} = \frac{-R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}\,. \tag{9}$$

We set:

$$\delta = \frac{R}{2L}, \qquad \omega_0^2 = \frac{1}{LR}, \qquad \omega_s^2 = \omega_0^2 - \delta^2, \qquad I_m = V_m\omega_n C$$

and then

$$p_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2}\,. \tag{10}$$

Corresponding to different resistors R, the solutions of their characteristic roots are different, which can be divided into under-damped, critically damped and over-damped.

The special solution of (8) is:

$$v_{cp} = A_1 \sin\left(\omega_n t + \phi_1\right), \tag{11}$$

where

$$A_1 = \frac{V_m/(\omega_n C)}{\sqrt{R^2 + (\omega_n L - 1/(\omega_n C))^2}}, \qquad \phi_1 = \phi - \frac{\pi}{2} - \arctan\frac{\omega_n L - 1/(\omega_n C)}{R}\,.$$

For an overhead line, the capacitive reactance is much larger than the resistance and the reactance of the line. That is

$$\frac{1}{\omega_n C} \gg \omega_n L, \qquad \frac{1}{\omega_n C} \gg \omega_n R.$$

So, A_1 and ϕ_1 can be simplified as:

$$A_1 = \frac{V_m/(\omega_n C)}{\sqrt{R^2 + (\omega_n L - 1/(\omega_n C))^2}} \approx \frac{V_m/(\omega_n C)}{\sqrt{R^2 + (-1/(\omega_n C))^2}} \approx V_m$$

and

$$\phi_1 = \phi - \frac{\pi}{2} - \arctan\frac{\omega_n L - 1/(\omega_n C)}{R} \approx \phi - \frac{\pi}{2} - \arctan(-1/(\omega_n C)) \approx \phi.$$

So, the voltage and current of capacitor C is

$$\left.\begin{aligned} v_{cp} &= V_m \sin(\omega_n t + \phi) \\ i_{cp} &= I_m \cos(\omega_n t + \phi) \end{aligned}\right\}. \tag{12}$$

4.2. Underdamped

If $R < 2\sqrt{L/C}$, characteristic Equation (8) has two complex conjugate solutions. For overhead lines $\sqrt{L/C}$ is approximately equal to its characteristic impedance, about 300 ∼ 400 Ω. So, according to (6), if the grounding resistance R_f is less than 200 ohms, the voltage and current of capacitor C will oscillate. They are composed of the transient component attenuated with time and the steady component of constant amplitude sine oscillations, as (13).

$$\left.\begin{aligned} v_c &= V_m\left(K_1 \sin(\omega_s t) - \sin\phi\cos(\omega_s t)\right) e^{-\delta t} + v_{cp}\Big) \\ K_1 &= (-\delta\sin\phi - \omega_n\cos\phi)/\omega_s \\ i_c &= I_m\left(K_2 \sin(\omega_s t) - \cos\phi\cos(\omega_s t)\right) e^{-\delta t} + i\Big) \\ K_2 &= \frac{1/(LC)}{\omega_n\omega_s}\sin\phi + \frac{\delta}{\omega_s}\cos\phi \end{aligned}\right\}, \tag{13}$$

where: ω_s is the principal resonant frequency, ω_n is the power frequency $\omega_n = 2\pi f$, $f = 50$ Hz.

The principal resonance has the lowest frequency, the largest energy, and the most obvious feature. The principal frequency is:

$$\omega_s = \sqrt{-\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}, \tag{14}$$

where L, R, C can be calculated by (6).

It can be seen that the principal resonant frequency is determined by the line-to-ground distributed capacitance, the distance from the fault point to the transformer of the substation, the grounding resistance of the fault point, and the impedance of the transformer. For metal grounding, $R_f = 0$, the principal resonant frequency can be further simplified:

$$\omega_s \approx \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\left(2L_{u1}l_{fu} + 2L_{T1} + L_{u0}l_{fu}\right)C_{u0}l_{\Sigma}}}. \tag{15}$$

It can be seen that the larger the distributed capacitance of the phase to ground and the farther the fault point is from the transformer, the smaller the principal resonance frequency. For a system, the line-to-ground distributed capacitance $C_{u0} l_\Sigma$ is constant and does not change with the location of the fault point. The inductance of the transformer L_{T1} is also determined. So, the principal resonant frequency depends on the distance from the fault point to the transformer of the substation. Exploiting this property, the fault point can be located. The principal resonant frequency can be calculated according to the typical overhead line parameters, such as in Table 1. For example, total length of the distribution line is 100 km, $L_{T1} = 1.1$ mH. It can be calculated that when the fault point is 1 km away from the transformer, the principal resonant frequency is 2550 Hz, and when the fault point is 10 km away from the transformer, the principal resonant frequency is 907 Hz. The relationship between the location of the fault points and the principal resonant frequency is shown in Fig. 3.

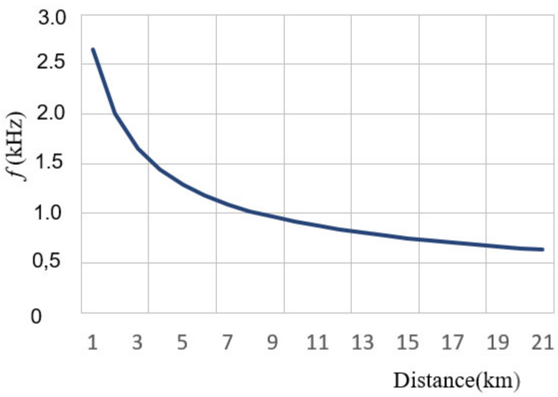


Fig. 3. Resonant frequency varies with the fault location

The attenuation factor δ is:

$$\delta = \frac{R}{2L} = \frac{3R_f + 2\left(R_{u1} l_{fu} + R_{T1}\right) + R_{u0} l_{fu}}{2\left(2L_{u1} l_{fu} + 2L_{T1} + L_{u0} l_{fu}\right)} \approx \approx \frac{2R_{u1} + R_{u0}}{2\left(2L_{u1} + L_{u0}\right)} + \frac{3R_f}{2\left(2L_{u1} + L_{u0}\right) l_{fu}} . \tag{16}$$

The value of δ is affected by the distance from the fault point to the transformer and the grounding resistance R_f. When the grounding resistance is constant, ignoring the influence of the resistance and inductance of the transformer, the attenuation factor changes with the distance from the fault point to the transformer. Therefore, as the distance increases, δ decreases gradually. The attenuation factor reflects the duration of the transient process. The larger the attenuation factor, the faster the attenuation speed, making fault detection more difficult. For overhead lines, the attenuation factor is generally high. As the grounding resistance $R_f = 1\ \Omega$, the fault point 1 km away from the transformer, δ is 241 (1/s) and the corresponding attenuation time is 4.1 ms; the fault point 10 km away from the transformer, δ is 76 and the corresponding attenuation time is 13.2 ms.

5. Simulation verification

We built a typical 10 kV distribution network circuit. The simulation was carried out by using MATLAB, and the distributed parameter model was used as a reference. Different equivalent circuits were used for comparison verification.

5.1. Simulation model

The simulation power distribution system includes an 110 kV power source, a 110/10.5 kV transformer, 8 overhead lines, and the total length of the line is 80 km. The transformer with capacity 50 MVA, impedance 10.5% is a three-phase two-winding transformer. There are 8 lines connected to the same transformer, and their lengths are 3 km, 5 km, 6 km, 9 km, 10 km, 12 km, 15 km, and 20 km, respectively. The impedance parameters of the lines are selected from Table 1. The fault occurred on the line which length is 15 km.

MATLAB is used to simulate and verify. With the reference of the distributed parameter model, the frequency, amplitude and attenuation factor of the principle resonant component of the transient current of a single-phase to ground fault are analyzed by using different equivalent circuits, such as distributed parameter circuits, a traditional equivalent circuit and equivalent circuit in this paper.

5.2. Traditional model

The traditional equivalent circuit only considers the zero sequence circuit of the fault line, and the calculation of the equivalent resistance, inductance and capacitance are mainly based on the zero sequence circuit as (17).

$$\left.\begin{aligned} R_{0\Sigma} &= R_{u0} l_f + 3R_f \\ L_{0\Sigma} &= L_{u0} l_f \\ C_{0\Sigma} &= C_{u0} l_\Sigma \end{aligned}\right\}, \tag{17}$$

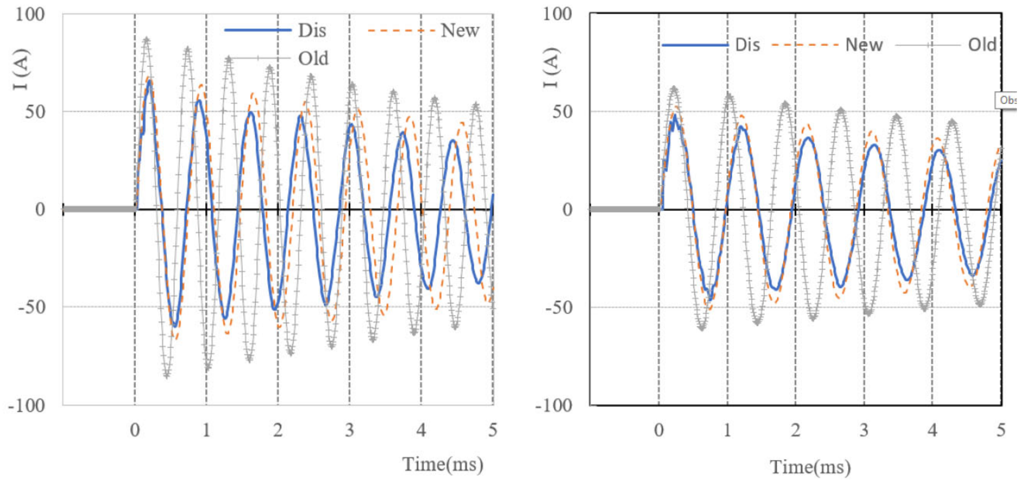
where: l_f is the length of the fault line, l_Σ is the whole length of all lines at the same bus.

5.3. Simulation verification

For example, a fault point is located on a 15 km line, and grounding resistance is 1 Ω. The fault point is located at a distance of 5 km, 10 km from the substation, and the transient zero-sequence current waveforms of each model are shown in Fig. 4.

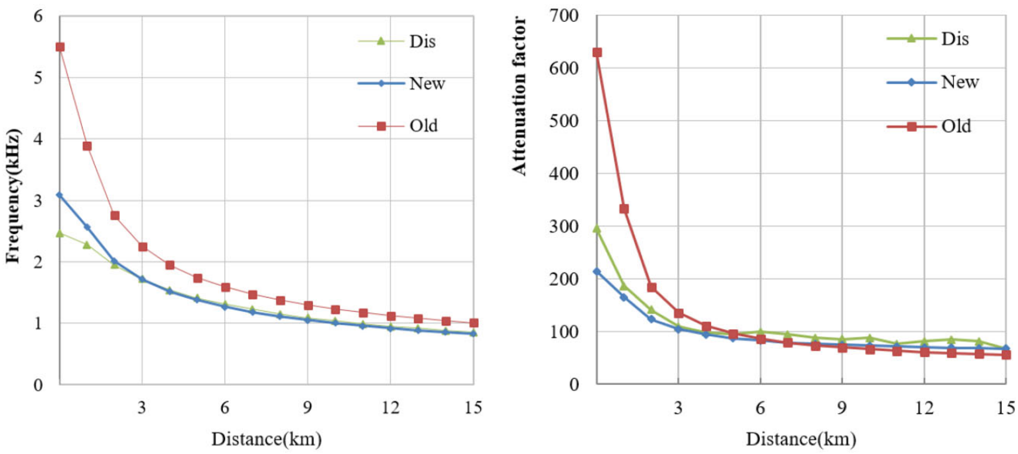
As can be seen from Fig. 4, the transient zero sequence current of the model proposed in this paper has a higher degree of compliance with the results of the distributed parameter model. It can well reflect the change process of the zero sequence current.

When the fault point is at different positions (0.5 ∼ 15 km from the substation) on the line of 15 km, different models (distributed parameter model (Dis)), the model proposed in this paper (New), traditional model (Old)) are used to calculate the transient zero-sequence current of the fault line. The frequency, amplitude, and attenuation factor of the zero-sequence current are shown in Fig. 5.



(a) Fault point distance of substation 5 km (b) Fault point distance 10 km

Fig. 4. Fault current of different models



(a) Frequency of zero sequence current (b) Attenuation factor of zero sequence current

Fig. 5. Principle resonance of zero sequence current for different models

It can be seen from Fig. 5:

1. The equivalent circuit established in this paper simulates the transient zero-sequence current significantly better than the traditional equivalent circuit. For faults near the substation, the effect of the simulation is closer to the result of the distributed parameters due to the influence of the positive (negative) sequence inductance considered.
2. The simulation of the zero sequence current in the transient equivalent circuit established in this paper has high precision and is less affected by the distance from the fault point to the substation, which has strong applicability.

6. Conclusions

The transient equivalent circuit of a single line-to-ground fault in an ungrounded distribution system can be used to analyze and simulate the principal resonant component of the transient state of zero sequence current, which is the basis of fault transient analysis. The traditional transient equivalent circuit ignores the positive (negative) sequence components, which are too rough. In this paper, a transient equivalent circuit of a series RLC is developed to simulate the transient process of a zero sequence current single phase to ground fault. In the new model, the equivalent resistance is the sum of the upstream fault line compound sequence (positive, negative and zero sequence) resistance, the transformer resistance and the grounding resistance. The inductance is also the sum of the upstream fault line compound sequence (positive, negative and zero sequences) inductance and the transformer inductance. The capacitance is the zero sequence distributed capacitance of the three phases to ground. The relevant parameters of the model are simple and can meet the engineering needs. A large number of simulation experiments and theoretical analysis were carried out to verify that the transient equivalent circuit has high simulation accuracy and strong adaptability to the principal resonance components of the transient zero sequence current of a single line-to-ground fault.

References

[1] *C37.230-2007 –IEEE Guide for Protective Relay Applications to Distribution Lines*, IEEE, 2008:1–100 (2008), DOI: 10.1109/IEEESTD.2007.4447926.

[2] Short T.A., *Electric Power Distribution Handbook*, Second Edition, Boca Raton: CRC Press (2014).

[3] Northcote-Green J., Wilson R.G., *Control and automation of electrical power distribution systems*, CRC Press, ISBN 9780824726317 – CAT# DK2951 (2006).

[4] Venkatesh C., Swarup K.S., *Steady-state error estimation in distance relay for single phase to ground fault in series-compensated parallel transmission lines*, IET Generation Transmission and Distribution, vol. 8, no. 7, pp. 1318–1337 (2014).

[5] Meng J. *et al.*, *Zero-sequence voltage trajectory analysis for unbalanced distribution networks on single-line-to-ground fault condition*, Electric Power Systems Research, vol. 161, pp. 17–25 (2018).

[6] Zhang X.-P., Chen H., *Analysis and selection of transmission line models used in power system transient simulations*, International Journal of Electrical Power and Energy Systems, vol. 17, no. 4, pp. 239–246 (1995).

[7] Wang Peng *et al.*, *A novel neutral electromagnetic hybrid flexible grounding method in distribution networks*, IEEE Transactions on Power Delivery, vol. 32, no. 3, pp. 1350–1358 (2017).

[8] Lehtonen Matti, Tapio Hakola, *Neutral earthing and power system protection: earthing solutions and protective relaying in medium voltage distribution networks*, ABB Transmit (1996).

[9] Xue Yongduan *et al.*, *Construction of Transient Equivalent Circuits of Single-phase Earth Fault for Isolated Neutral Systems*, Proceedings of the CEE (in Chinese), vol. 33, no. 34, pp. 223–232 (2013).

[10] Xue Yong Duan, Li J., Xu B.Y,. *Transient equivalent circuit of single-phase earth faults on isolated neutral system*, International Conference and Exhibition on Electricity Distribution IET, pp. 1–4 (2013), DOI: 10.1049/cp.2013.0741.