TRANSIENT EQUIVALENT CIRCUIT OF SINGLE-PHASE EARTH FAULTS ON ISOLATED NEUTRAL SYSTEM

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ABSTRACT

A method for transient equivalent circuit establishment of single-phase earth faults on isolated neutral system is proposed in this paper. Firstly, the simplification principle was discussed. It can be described as: to ensure the power-frequency equivalent impedances equal, the first resonant frequency equal and comprehensive error of equivalent impedance in lowest frequency band minimum. Then, a transient circuit composed by equivalent resistance, inductance and capacitance, serially is established. Above all, the parameters calculation method is presented. On the other hand, a simple method is provided to meet the requirement of engineering application. Contrasts with traditional circuit, equivalent circuits established in this paper consider all modulus. So the simulation precision is higher than traditional circuits. Finally, the simulations verified these transient circuits are little impacted by fault point position and fault resistance.

INTRODUCTION

In recent years, transient protection technologies play an important part in distributed network, especially in fault detection of sing-phase earth fault in isolated neutral system [1-4]. The analysis of transient characteristics in single-phase earth fault can improve the reliability of transient protection technology. Otherwise, transient equivalent circuit is one of the important methods to analyze transient characteristics. Generally, transient respond can be divided into several resonant processes. It is impossible and unnecessary to simulate all processes by a *RLC* circuit. So define the largest one which can represent the characteristics of fault transient mostly as the main resonant frequency component [3]. The aim of the establishment of transient equivalent circuit is to simulate the main transient characteristics.

The research foundation of equivalent circuit is weak [5-6]. The traditional model is not perfect. It only considered zero-mode components. The most important is that the parameters calculation method is not proposed. It cannot be used to analyze corresponding electrical quantities quantitatively. So it is necessary to establish a transient equivalent circuit with high precision.

In this paper, two model simplification methods are proposed. Then, two transient circuits are established following the principles. One is with high precision and the other is to meet the requirement of engineering application. Finally, simulations verified the accuracy of transient circuits.

TRADITIONAL TRANSIENT CIRCUIT AND ITS PARAMETERS CALCULATION

A reasonable parameters calculation method of traditional circuit was been defined in this section.

Traditional equivalent circuit

Fig. 1 shows the traditional circuit of single-phase earth fault presented in [5-6]. Where, L_0, C_0 are the inductance, capacitance of zero modulus, respectively. R_0 is the sum of zero-mode equivalent resistance and three times of fault resistance. u_f is virtual power of fault point.

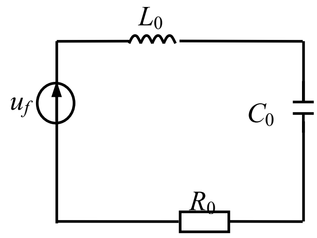

Fig.1 Traditional equivalent circuit of single-phase earth fault

Reference [5-6] list the circuit structure and meanings of parameters, but the calculation method of parameters was not introduced, especially L_0 and R_0. It can not be used for the analysis of electrical quantities quantitatively.

Parameters calculation of traditional transient circuit

Equivalent capacitance C_0

C_0 is the zero-mode capacitance, the sum of distributed capacitances. It can be calculated as:

$$C_0 = C_{u0} l = 3C_{up} l \tag{1}$$

Where, C_{u0} is per-unit-length capacitance of the conductors, C_{up} is per-unit-length capacitance of one

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conductor, l is the length of all lines.

Equivalent inductance L_0

For isolated neutral system, zero-mode inductance of transformer is infinite, so the equivalent inductance is determined by lines. It can be described as:

$$L_0 = L_{u0} l \qquad (2)$$

$$\text{or } L_0 = L_{u0} l_f \qquad (3)$$

Where, L_{u0} represents per-unit-length inductance of the conductors, l_f is the distance from fault point to bus.

Equivalent resistance R_0

Equally, resistance is defined as follow.

$$R_0 = R_{u0} l + 3R_f \qquad (4)$$

$$\text{or } R_0 = R_{u0} l_1 + 3R_f \qquad (5)$$

Where, R_{u0} is zero-mode resistance per unit length of line; R_f represents fault resistance.

Simulations demonstrate traditional equivalent circuit established by (3) (5) is more accurate than (2) (4). So in the follow discussions, the parameters are calculated by (3) (5).

COMPOUND NETWORK MODEL OF SINGLE-PHASE EARTH FAULT

Details on the establishment and simplification of transient compound network are discussed in this section. Firstly, transient circuit was uncoupled by Karrenbauer transform showed in fig.2 [7]. Each modulus can be divided into two parts from fault point, forwards and backwards. The forwards represent the part from fault point to bus, including healthy lines and the backwards is the part from fault point to load [4].

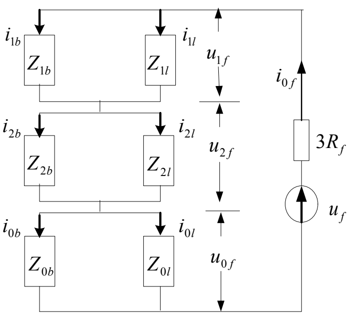

Fig.2 Compound network model

Where, Z_{0b},Z_{1b},Z_{2b} are the impedance of 0,1,2 modulus of the forward part of fault point respectively, Z_{0l},Z_{1l},Z_{2l} are impedance of 0,1,2 modulus of the backward part, i_{0b},i_{1b},i_{2b} are 0,1,2 modulus current of the forwards, i_{0l},i_{1l},i_{2l} are 0,1,2 modulus current of the backwards, u_{1f},u_{2f},u_{0f} are0,1,2 modulus voltage.

Form fig.2, it can be found that for single-phase earth fault, 0, 1, 2 modulus are connected serially. So the input impedance of each modulus can be described as:

$$Z_k = Z_{kb} // Z_{kl} \quad (k = 0,1,2) \qquad (6)$$

THE IDEA AND PRINCIPLE OF MODEL SIMPLIFICATION

The model simplification idea and principle will be presented in this section. Fig.3 shows the magnitude of transient currents characteristics of different detection points versus frequency [3].

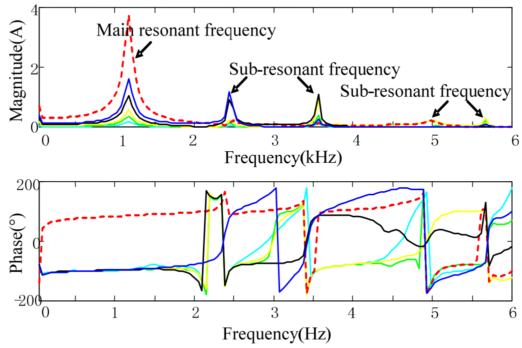

Fig.3 Magnitude of transient currents characteristics versus frequency

From fig.3, it can be seen that the transient is complicated. It contains many serial and parallel resonant processes. So it is unnecessary and different to simulate all process by a *RLC* circuit. Therefore, the circuits established in this paper aim to simulate main resonant frequency process accuracy, which can represent the transient process characteristics approximately.

The basic idea to establish the equivalent circuit is to simplify distributed parameter model step by step. Firstly, Karrenbauer transform was used to decouple to establish the module network. Then, simplify each part of module network from distributed parameter model to a lumped-Π model. And then combine and simplify Π models to one. Finally, convert Π model to Γ model in order to calculate corresponding electrical quantities easily. So, the key of the establishment of transient circuit is the simplification of compound network model.

The traditional method to convert distributed parameter model of lines into a lumped-Π model is usually be used to simulate steady state [8]. Meanwhile, there is no definite method to combine serial or parallel limp-Π models.

In order to analyze transients, so the models should simulate transient accuracy firstly, ensuring the models with a high application frequency band. Then, the equivalent impedances should be equal in order to remain impedance characteristics, especially power frequency impedance.

So the principle list followed should be abided.

1) Ensure power frequency equivalent equal of original and simplified model.
2) Equal the first resonant frequency of simplified model with the original model.
3) Make sure the error of equivalent impedance minimum in first resonant frequency band.

TRANSIENT CIRCUIT ESTABLISHMENT FOR SINGLE-PHASE EARTH FAULT

In this section, the simplification of zero modulus is showed as an example according to the principle above.

Simplification of distributed parameter model

Fig.4 shows the simplification process of healthy line. Where, u_{0m} represents zero-mode voltage; $i_{10}$is line-mode current; L_{u0}, R_{u0}, G_{u0}, C_{u0} are the per-unit-length inductance, resistance, conductance and capacitance of conductors respectively; L_{10l}, R_{10l}, C_{10l}, C'_{10l} are the inductance, resistance and capacitances of a lumped-Π model [3].

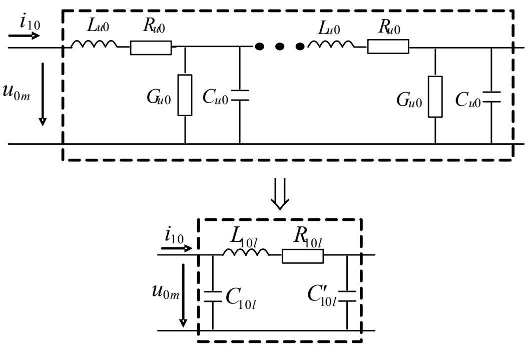

Fig.4 Simplification of healthy line

The first resonant frequency of healthy line is showed.

$$\omega_{10F} = \frac{\pi}{2l_1\sqrt{L_{u0}C_{u0}}} \tag{7}$$

Where, l_1 is the length of healthy line. The characteristics of the lowest resonant frequency band, 0~ω_{10F}, is capacitive and the equivalent capacitance is

$$C_{10F}(\omega) = \frac{2\omega_{10F}C_{u0}l_1}{\pi\omega} tg\left(\frac{\pi\omega}{2\omega_{10F}}\right) \ge C_{u0}l_1 \tag{8}$$

For a lumped-Π model, the first resonant frequency is

$$\omega_{10J} = \frac{1}{\sqrt{L_{10l}C'_{10l}}} \tag{9}$$

Equally, in the first resonant frequency it is also capacitive, and the equivalent capacitance is given as

$$C_{10J}(\omega) = C_{10l} + \frac{\omega^2 C'_{10l}}{\omega_{10J}^{\ 2} - \omega^2} \ge C_{10l} + C'_{10l} \tag{10}$$

So the constraint conditions are showed as followed.

$$\begin{cases} C_{10l} + C'_{10l} = C_{u0}l_1 \\ \omega_{10J} = \dfrac{1}{\sqrt{L_{10l}C'_{10l}}} = \dfrac{\pi}{2l_1\sqrt{L_{u0}C_{u0}}} = \omega_{10F} \\ \int_0^{\omega_{os}} \left(C_{10F}(\omega) - C_{10J}(\omega)\right)^2 d\omega \quad \text{minimum} \end{cases} \tag{11}$$

Then, the parameters of a lumped-Π model are

$$C'_{10l} \approx 0.8106 \cdot C_{u0}l_1 \tag{12}$$

$$C_{10l} \approx 0.1894 \cdot C_{u0}l_1 \tag{13}$$

$$L_{10l} \approx 0.5005 \cdot L_{u0}l_1 \tag{14}$$

The resistance of line is given as the same of inductance

$$R_{10l} \approx 0.5005 \cdot R_{u0}l_1 \tag{15}$$

Establishment of transient circuit

The zero and line modulus are simplified following the principle proposed above. Then, a transient circuit can be established showed in fig.5.

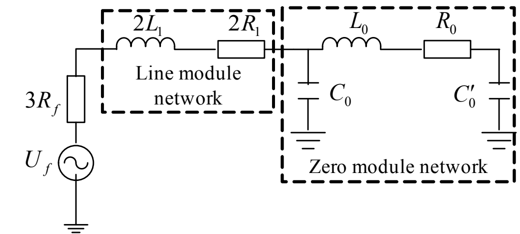

Fig.5 Transient equivalent circuit of lumped-Π model

In order to calculate more simply, lumped-Π model can be simplified into lump-Γ model. Then, the circuit becomes

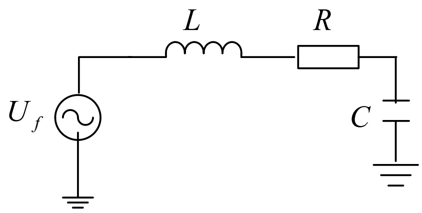

Fig.6 Transient equivalent circuit of lump-Γ model

SIMPLE ALGORITHM OF MODEL

The parameters calculation method above is complex. So a simple algorithm is also provided in this paper. The parameters are calculated as

$$C = C_{0\Sigma} = C_{u0}l$$

$$L = L_{u0}l_1 + 2L_{u1}l_1 + 4L_{TA}$$

$$R = R_{u0}l_1 + 2R_{u1}l_1 + 4R_{TA} + 3R_f$$

Where R_{u1}, L_{u1}, C_{u1} are per-unit-length inductance, resistance and capacitance of line-mode; R_{TA}, L_{TA} are line-mode resistance and inductance of transformer.

SIMULATIONS

Simulation models

A simulation model of a distribution network established by ATP was showed in fig.7. The length of lines are 3km, 6km, 9km, 12km, 15km, 20km, respectively. Transient circuits are established by the traditional way and the two methods proposed in this paper.

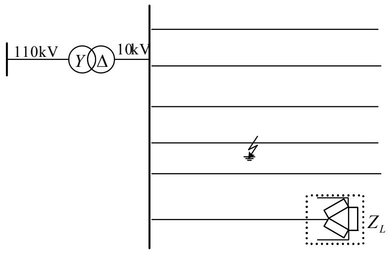

Fig.7 Simulation model of isolated neutral system

Analysis of simulation

Fig.8 shows the zero-mode currents of transient circuits.

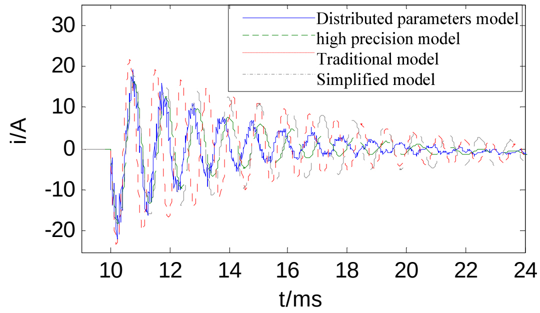

Fig.8 Zero-mode currents of transient circuits

From fig.8, it is seen that transient circuit established by the principle mentioned above (named high precision model) simulates accurately, especially the attenuation factor. Error of simplified model (established by simple algorithm) in frequency is littler than traditional model.

Fig.9 shows comprehensive simulation accuracy of each transient circuit according to the evaluation of models [9].

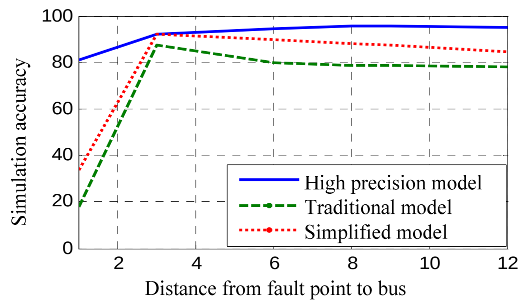

Fig.9 Simulation accuracy of transient circuits with different fault point

Fig.10 shows the simulation accuracy of transient circuits with different fault resistance.

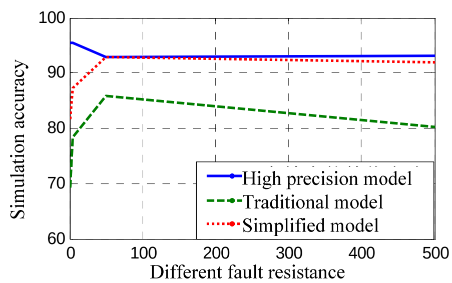

Fig.10 simulation accuracy with different resistance

Simulations demonstrate the precision of high precision model is the highest. And it is impacted little by the position of fault point and fault resistance. Because of considering the impact of line-mode components, simplified model also has higher simulation accuracy than traditional circuit.

Conclusions

A principle for transient circuit simplification is proposed in this paper. The principle is to ensure the power-frequency equivalent impedances, first resonant frequency equal and comprehensive error of equivalent impedance in lowest frequency band minimum. So a *RLC* transient circuit for isolated neutral system is established. Contrast with traditional circuit, the precision is the highest and it is impact little by the position of fault point and fault resistance.

And a simple method is also provided. The line-mode components are also considered in this circuit. So the simulation precision is higher than traditional circuits.

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