Analysis on propagation characteristics of voltage sag through different types of transformers

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Abstract: Transformer is a key factor that can not be ignored in the process of voltage sag propagation. In this paper, the transmission characteristics of voltage sag caused by different types of short circuit are analyzed through the different transfer matrix of transformer with different connection methods, including amplitude change, waveform distortion and phase jump. The distribution network model is established by PSCAD, and the propagation characteristics are verified. The conclusion has certain significance for judging the type of voltage sag from the load side, evaluating the degree of voltage sag, and selecting the treatment measures of voltage sag.

1. Introduction
Voltage sag is one of the unavoidable problems in the study of power quality. In recent years [1], compared with the traditional loads, the application of a large number of power and electronic equipment has weak withstand capacity to voltage drop, and the frequency of voltage sags is much greater than that of power outages [2]. In the process of electric energy transmission, the transformer is an inevitable link, and the waveform before and after the voltage sag passes through the transformer may be different. The propagation of voltage sags in transmission lines and transformers satisfies the superposition theorem, and two or more transformers can also be equivalent to a single transformer [3]. The transformer types can be divided into three categories according to the literature [4], and then combined with the transfer matrix of each transformer to analyze the impact of different types of voltage sags. Since most voltage sags are caused by system short circuits, this article simply divides the voltage sags into four types-single-phase, two-phase, three-phase ground faults, and interphase short-circuit faults. A large number of domestic and foreign documents also show the research conclusions. The literature [5] analyzes the propagation characteristics of the voltage sag through the transformer in different zero-point grounding methods from the theoretical level, but it lacks simulation experiments to support it. Literature [6] studies the propagation law of voltage sag from the point of failure to the point of common connection (PCC), but it assumes that the voltage sag will have no loss during the process of propagation from high potential to low potential in PCC, which is obviously true. The state of the power system is different. The literature [7-8] counts the starting position of the fault and the range of the phase offset from a large number of sag waveforms, but this is nothing more than the lack of further mining of statistical data.

2. Theoretical analysis
The transformer can be classified according to the connection method of the transformer winding and the neutral point grounding method when studying the subject of this article, because these two are the
main factors that affect the spread of voltage sags in the transformer. Based on this, this article sorts out the transfer matrix of three types of transformers from the high voltage side to the low voltage side. Among them, $T_{P,P}$ and $T_{P,N}$ are the line voltage and phase voltage transfer matrix respectively.

### 2.1. First class transformer
This type of transformer is a Yn-Yn connected transformer, that is, the high-voltage side and the low-voltage side are both star-connected and the neutral point is grounded, that is, the phase difference is zero. The phase voltage is consistent with the line voltage before and after passing through the transformer, and the transfer matrix is the identity matrix $E$. which is:

$$
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

(1)

It can be known from the transfer matrix that when any type of voltage sag is transferred from the high-voltage side to the low-voltage side through the first-type transformer, the type of voltage sag will not change, and no other faults will occur during the transmission process. If the transformer is an ideal transformer, the depth of voltage sags detected on the high-voltage side and low-voltage side should be equal.

According to the phasor diagram in Figure 1, when the types of voltage sag are single-phase grounding, two-phase grounding and three-phase grounding, the voltage sag only changes the amplitude of the fault phase when it passes through the first type of transformer. The phases of both the faulty phase and the non-faulty phase do not change; when the voltage sag type is a phase-to-phase fault, not only the amplitude of the two phases that have failed, but the phase also changes, and the amplitude and phase of the non-faulty phase do not occur.

![Figure 1 Characteristic phasor diagram of voltage sag of the first type transformer](image)

### 2.2. Type 2 transformer
Such transformers include Y-Y0, Y0-Y connected transformers, and Y-Y connected transformers whose neutral points on either or both sides are not grounded. This type of transformer will isolate the transmission of zero sequence voltage to a certain extent. But because the line voltage has nothing to do with the zero sequence voltage, the line voltage transfer matrix is $E$. which is:

$$
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}; \quad \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix}
$$

(2)

Since this type of transformer can isolate the zero-sequence voltage propagation to a certain extent, when the type of voltage sag passing through this type of transformer is single-phase or two-phase short circuit, the phase and amplitude of the voltage waveform on both sides of the transformer will change.

Both single-phase and two-phase short-circuit faults will produce zero-sequence components, and the propagation of zero-sequence components will be blocked when the voltage sag passes through the...
second type of transformer. It can be concluded that the voltage sags caused by these two problems are passed through the first type of transformer. During the propagation of the second type transformer, the phase and amplitude of the low and high potential voltages on both sides of the transformer will change; since the phase-to-phase fault and the three-phase ground fault will not produce zero sequence components, it can be concluded that these two problems are caused When the voltage sag passes through the second type transformer, the fault type does not change.

It can be seen from Figure 2 that when a single-phase short-circuit fault occurs (phase A is grounded), after the voltage sag passes through the second type transformer, the voltage amplitude of the faulty phase (phase A) decreases, the phase remains unchanged, and the non-fault phase (B-phase and C-phase) voltage amplitude decreases and their phase difference with A-phase becomes smaller; similarly, when a two-phase short-circuit fault (B-phase and C-phase) occurs, the voltage phase of the non-faulty phase (A-phase) and the amplitude does not change, the voltage amplitude of the fault phase (phase B and C) decreases and the phase difference between them and phase A becomes larger.

![Figure 2 Characteristic phasor diagram of voltage sag of the second type transformer](image)

2.3. Type 3 transformer

Such transformers include transformers connected to Y-△, Y0-△, and △-Y0. According to the relationship between line voltage and phase voltage, that is, the high-voltage side has a 30° lag behind the low-voltage side, the transfer matrix of this type of transformer can be obtained, which is:

\[
T_{P,N} = \frac{1}{\sqrt{3}} \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
= T_{P,P}
\]

The line voltage of this type of transformer is the same as the phase voltage transfer matrix. The amplitude and phase of the voltage will change when the voltage sag is passed through this type of transformer except for the three-phase ground fault. The third type of transformer will also block the propagation of the zero sequence component, so the phase voltage does not contain the zero sequence component after the conversion to the line voltage. The phase increases by 30° counterclockwise. If the phase increases by 90° counterclockwise, it is equivalent to a counterclockwise increase 120°, the commutation is realized. Since the counterclockwise increase by 90° in the conversion, the converted voltage needs to be multiplied by -j.

As shown in Figure 3, when the voltage sag caused by a single-phase fault (phase A fault) passes through the third type transformer, the amplitude of the non-faulty phases (phase B and phase C) decreases and they are in line with the fault phase (phase A) The phase difference becomes larger, similar to the voltage sag caused by the phase-to-phase fault of the first two types of transformers.

When a phase-to-phase fault occurs (phase B and phase C), after the voltage sag passes through the third type transformer, the voltage amplitudes of both the faulty phase and the non-faulty phase will decrease. The faulty phase (phase B and C) Phase A) The phase difference is reduced, similar to the voltage sag caused by the single-phase ground fault of the second type transformer.
The voltage sag caused by a two-phase ground fault (phase B and phase C) after passing through the third type transformer, the phase change of the fault phase (phase B and phase C) is similar to the voltage caused by an interphase fault (phase B and phase C). The sags pass the phase change of the fault phase of the third type transformer. The difference is that the reduction of the voltage amplitude of the fault phase caused by a two-phase ground fault is greater than that of an interphase fault.

Based on the above analysis of the propagation characteristics of different types of voltage sags through the three transformers, we can get the following conclusions:

(1) The propagation characteristics of a three-phase ground fault after passing through different transformers remain unchanged.

(2) According to the propagation law of different voltage sags after passing through the three types of transformers, it can be found that the voltage sags caused by different faults may derive the same type of sag even through different transformers, and the number of sag types is also fixed. Several kinds.

(3) According to the three types of transformer voltage sag characteristic phasor diagram, when we know the type of transformer in the power system, we can infer the type of fault that may cause the voltage sag in the system through the monitored voltage sag type. Assuming that the type of fault in Figure 3(a) is monitored, and it is known that the fault passes through the third type transformer in the system, then we can conclude that the fault that causes the voltage sag in this system is a single-phase ground fault.

3. Simulation model and parameter settings

In order to verify the correctness of the above theoretical analysis of the propagation characteristics of the voltage sag passing through the transformer, a distribution network model was built with the aid of PSCAD software for simulation experiments. The simulation model is shown in Figure 4.

The main model parameters are as follows: The positive sequence, zero sequence impedance and capacitance of a 10kV distribution line are:

\[ Z_1 = (8.5 + j19) \text{W/km}, \quad Z_0 = (11.5 + j86) \text{W/km}, \quad C_1 = 73.12 \text{nF/km}, \quad C_0 = 48.29 \text{nF/km}. \]

Transformers T1-T4 adopt Y/Y, Y/Y, Y/Y and Yn/Yn connection modes respectively, and assume that all transformers are ideal transformers. Set up a single-phase (phase A to ground) ground fault at point A between the transformer T1 and the power supply and set up four monitoring points M1-M4. The fault start time is 0.1s, and the fault duration is 0.2s.
In the actual experiment, we obtained the voltage waveform diagram of the monitoring points M1-M4 and analyzed the relationship between them by making a single-phase (phase A) ground fault occur at point A.

Table 1 shows some parameters of each component in the simulation model.

| Transformer parameters | Overhead line parameters |
|-----------------------|-------------------------|
| Number | Connection method | Transformation ratio | impedance /Ω | Number | Length /Km |
| T1 | Y/Δ | 220/110 | 3.76+j32.1 | L1 | 40 |
| T2 | Y/Δ | 110/10 | 4.21+j6.08 | L2 | 20 |
| T3 | Y/Y | 220/110 | 3.76+j32.1 | L3 | 10 |
| T4 | Yn/Yn | 110/10 | 4.21+j6.08 | —— | —— |

### 4. Results & Discussion

Analyze the voltage waveform after the voltage sag caused by the single-phase (phase A) ground fault monitored at the monitoring point passes through the transformer to verify the correctness of the above theoretical analysis of the propagation law of the voltage sag through the transformer.

In the simulation model in Figure 4, when a single-phase (phase A) ground fault occurs at point A, the voltage waveforms at monitoring points M1-M4 are as follows:

(a) Waveform diagram of voltage sag at point M1

(b) Waveform diagram of voltage sag at point M2
There is a Y-△ -connected transformer T1 (Type III transformer) between the monitoring point M3 and the fault point A. Since the phase voltage of the third type transformer is converted to line voltage without zero sequence component, the phase increases by 30° counterclockwise. Observing Figure 5(c), it can be found that the voltage amplitude of one phase is the same as the original voltage, and the voltage amplitude of the other two phases is equal and approximately equal to the original voltage amplitude. After commutation, the phase with the same amplitude as the original voltage is the fault phase (phase A), and the other two phases with the same amplitude are the non-fault phases (phase B and phase C). It conforms to the propagation characteristics of a single-phase fault passing through the third type transformer, and the amplitude change is consistent with the theoretical analysis of the third type transformer propagation matrix above.

The voltage waveform diagram of the monitoring point M4 is the voltage waveform after the single-phase ground fault at point A passes through the transformer T3 and then passes through the Yn/Yn connected transformer T4. Therefore, comparing Figure 5 (d) and (b), it can be found that the two voltage waveforms are of the same type, that is, the voltage amplitude of the fault phase (phase A) is 1/3 of the original voltage amplitude, and the non-fault phase (phase B) same as phase C) voltage amplitude. It shows that the waveform M2 after the single-phase ground fault voltage sag passes through the transformer T3 does not change the type of voltage sag after the first type transformer T4. This is consistent with the theoretical analysis of the voltage sag passing through the first type of transformers.

The simulation experiment results also confirmed the correctness of the theoretical analysis. According to the voltage waveform diagram of the voltage sag caused by single-phase grounding after passing through different transformers, it verified part of its propagation characteristics.

5. Conclusions
(1) The same type of voltage sag can only derive one type of sag when passing through the same type of transformer, but different types of voltage sags may also derive the same type of sag when passing through different transformers.

(2) The voltage sag is transmitted through the transformer and is affected by the neutral grounding method of the transformer and the winding method. Therefore, based on the corresponding relationship, the type of voltage sag on the user side can be inferred, and when the type of sag is known, the cause of the fault can be inferred.

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