Three-Winding Autotransformer Fault Study and Impact on Protection Application

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Abstract: Autotransformers (ATs) have been widely used for many years. For large size ATs, a tertiary winding is usually included. Sometimes the tertiary winding is loaded for station service, local loads, VAR compensation, etc. Other times, the tertiary winding is buried and acts as stabilizing winding which provides a path for zero-sequence current and 3rd harmonic current. Three-winding ATs present some interesting and different problems for fault study and relay application. Some of these problems are not well understood among protection engineers. The delta-connected tertiary winding may not have large impact on positive and negative sequence network. However, it has a significant impact on the zero-sequence network. Very often we encounter one minus impedance in transformer equivalent T model. The minus impedance will further complicate the zero-sequence current magnitude and direction. If protection engineers do not have proper understanding of transformer model and the fault study, misapplication and misoperation of protection relays are likely to happen. This paper will discuss the equivalent model of 3-winding for fault study, zero-sequence current distribution, and impact on zero-sequence current based polarization and overcurrent application.

I. INTRODUCTION

Autotransformers (ATs) are widely used among utilities. Large size ATs are typically equipped with the delta-connected tertiary windings. The tertiary winding sometimes serves the station service, local load, VAR compensation, etc. Other times, it just acts as stabilizing winding, which provides a path for zero-sequence current and 3rd harmonic current in order to stabilize the neutral point of the fundamental frequency voltages and protect the transformer and the system from excessive third-harmonic voltages. The tertiary winding can effectively reduce the overall zero-sequence impedance and therefore alleviate the overvoltage problem during a ground fault.

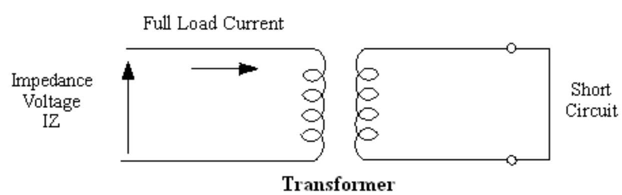
AT tertiary winding, if not connected to a generating source as usually the case, has little impact on the positive and negative sequence impedance network. However, the delta-connected tertiary winding has large impact on the zero-sequence network as it provides low impedance path for zero-sequence current to ground. Three-winding transformers are usually represented using the T model for fault studies. When converting the transformer measured impedances into equivalent T model, it is not uncommon to encounter one of the impedances to be negative in value. This negative impedance, while causing much confusion among protection engineers, can further complicate the zero-sequence current magnitude and direction. Analysis shows that AT neutral current can flow either in or out, or zero, and the current in the delta winding can also circulate in either direction or zero in magnitude. Fault study experience has shown that very peculiar results can happen. Special attention is needed when applying the transformer neutral current for overcurrent protection or polarization.

This paper discusses modeling of three-winding ATs, fault studies particularly the zero-sequence currents in the transformer neutral and tertiary winding, and unique challenges for relay application and coordination. Analysis will be given to indicate how the magnitude and direction of transformer natural current and delta-winding circulating current change with different transformer and system impedances. Examples will be given to show the "odd" fault current flow and relay misapplication and misoperation associated with three-winding ATs.

II. THREE-WINDING TRANSFORMER MODELING

The percentage impedance of a transformer is the voltage drop under full load current due to the winding resistance and leakage reactance expressed as a percentage of the rated voltage.

The impedance is measured by means of a short circuit test. For a 2-winding transformer, a voltage at the rated frequency is applied to the one winding sufficient to circulate full load current with the other winding shorted.

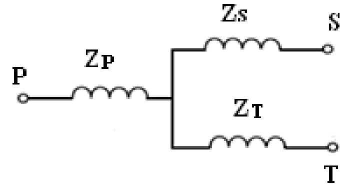


The percentage impedance can then be calculated as follows:

$$Z\% = \frac{Impedance\ Voltage}{Rated\ Voltage} * 100$$

For a 3-winding transformer, the impedances are measured between any 2 of the 3 windings, namely, primary vs. secondary (Z_{PS}), primary vs. tertiary (Z_{PT}) and secondary vs. tertiary (Z_{ST}), with the third winding open. The measured impedances are usually used to convert the transformer into equivalent T model as follows.

$$\begin{aligned} Z_P &= \frac{(Z_{PS}+Z_{PT}-Z_{ST})}{2} \\ Z_S &= \frac{(Z_{PS}+Z_{ST}-Z_{PT})}{2} \\ Z_T &= \frac{(Z_{PT}+Z_{ST}-Z_{PS})}{2} \end{aligned} \quad (1)$$

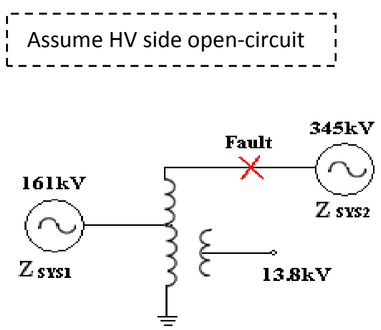


Here is an example of AT parameters: S=150MVA, 345/161/13.8kV, X_{PS}=5.33%, X_{PT}=68%, X_{ST}=54% (impedances are on 100MVA base.). When converted into the equivalent T model, the impedance will be X_P=9.67%, X_S=-4.33%, and X_T=58.33%. It can be noticed that the secondary impedance X_S is negative. While seemingly strange, it is not uncommon to see the negative impedance in the three-winding transformer equivalent circuit, which is mainly due to arrangement of the windings and coupling of the flux among the windings.

The negative impedance in the T model can provide some interesting phenomena for fault study. The zero-sequence current is affected by the negative impedance branch. The following section will discuss the fault study of the three winding autotransformer.

III. Fault Study of Three-Winding Autotransformer

Assume the above AT is connected to the system as Fig.3. A single-line-to-ground (SLG) fault occurs at the 345kV side. The sequence network for a SLG fault is connected as in Fig. 4. For simplicity while not losing generality, assume the 345kV side is open-circuit.



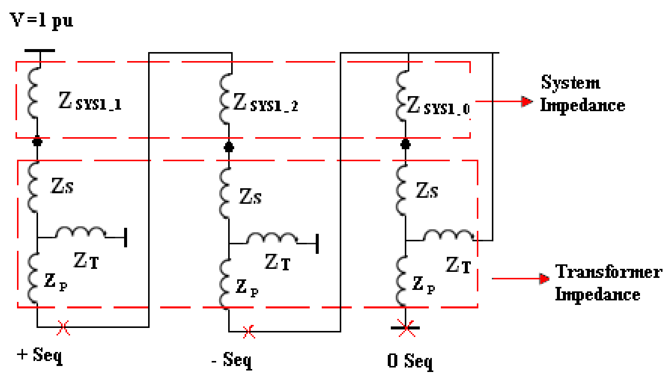


Fig. 3 Diagram for SLG on primary side   Fig. 4 Sequence network connection diagram

For SLG fault, the positive, negative and zero-sequence network are connected in series. Please notice in Fig. 4 that the tertiary is open-circuit in positive and negative sequence networks and it is short-circuit in zero sequence network.

The fault current can be calculated as (2)

$$I_1 = I_2 = I_0 = \frac{1.0\, pu}{Z_{1.eq}+Z_{2.eq}+Z_{0.eq}} \qquad (2)$$

Where I_1, I_2 and I_0 are the positive, negative and zero-sequence current respectively; $Z_{1.eq}$, $Z_{2.eq}$ and $Z_{0.eq}$ are the equivalent positive, negative and zero sequence impedance respectively.

a. Current circulating inside the tertiary winding

Let's examine the zero-sequence network and current closer as in Fig. 5. Zero-sequence current in transformer secondary and tertiary windings are shown in (3) and (4) respectively:

$$I_{0.S} = \frac{Z_T}{(Z_{SYS1.0}+Z_S)+Z_T} \times I_0 \qquad (3)$$

$$I_{0.T} = \frac{Z_{SYS1.0}+Z_S}{(Z_{SYS1.0}+Z_S)+Z_T} \times I_0 \qquad (4)$$

Because the secondary winding impedance Z_S is negative in this case, summation of $Z_{SYS1.0}$ and Z_S $(Z_{SYS1.0}+Z_S)$ in (4) can be either plus, minus, or zero, dependent upon the system zero-sequence impedance $Z_{SYS1.0}$. This will not only affect the magnitude of current in the delta winding, but also impact its direction. In another word, the zero-sequence current circulating in the tertiary winding can be either direction or can be zero in magnitude dependent on the transformer and system impedances. Therefore, it is improper to use this circulating current for polarization. When using this tertiary winding circulating current for overcurrent protection, the sensitivity may be questionable. A thorough study is recommended to ensure the proper application.

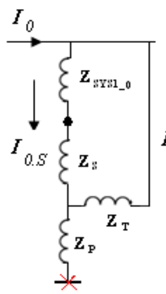


Fig. 5 Zero-sequence network & current distribution

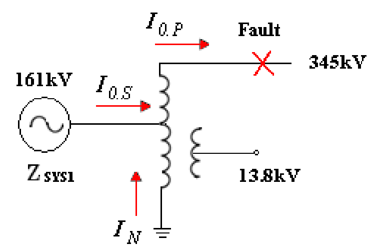


Fig. 6 Transformer neutral current

b. Zero-Sequence current in the common windings

Next let's take a look at the transformer neutral current. As shown in Fig. 6, the neutral can be calculated as in (5).

$$I_N = I_{0.P} - I_{0.S} \quad (5)$$

Please notice that per unit current values cannot be directly used in calculating I_N because AT primary and secondary currents are of different bases. Assume the primary-secondary transformer ratio is R (in Fig. 6, R is 345/161=2.14). Substitute $I_{0.S}$ of (3) into (5) and consider the transformer ratio R, we can derive I_N as in (6).

$$I_N = \left(1 - \frac{Z_T}{(Z_{SYS1.0}+Z_S)+Z_T} \times R\right) * I_{0.P} \quad (6)$$

Let I_N be zero, we will have the system zero-sequence impedance $Z_{SYS1.0}$ as in (7).

$$Z_{SYS1.0} = (R-1) \times Z_T - Z_S \quad (7)$$

When the system and AT zero-sequence impedances have the relationship as specified in (7), the AT neutral current will be zero. If system zero-sequence impedance is less than $((R-1) \times Z_T - Z_S)$, i.e., a stronger source connected to AT secondary side, the neutral current will flow out of (down) the AT. If system zero-sequence impedance is greater than $((R-1) \times Z_T - Z_S)$, i.e., a weaker source connected to AT secondary side, the neutral current will flow into (up) the AT. In another word, dependent on the transformer ratio, system and transformer impedances, the neutral can also either flow up or down, or zero in magnitude. Therefore, a thorough study is required when using this current for polarization or overcurrent protection.

c. SLG Fault at Transformer Secondary Side

If the SLG fault is on AT secondary side as shown in Fig. 7, the sequence network is connected as in Fig. 8. Please note that the source at the transformer secondary side, Z_{SYS1}, is ignored (the secondary side assumed to be open-circuit for simplicity).

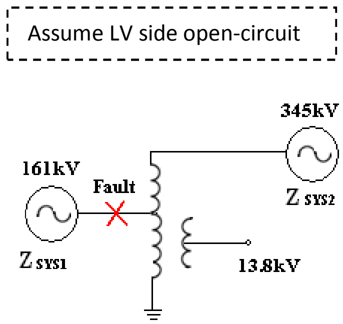


Fig. 7 Diagram for SLG on secondary side

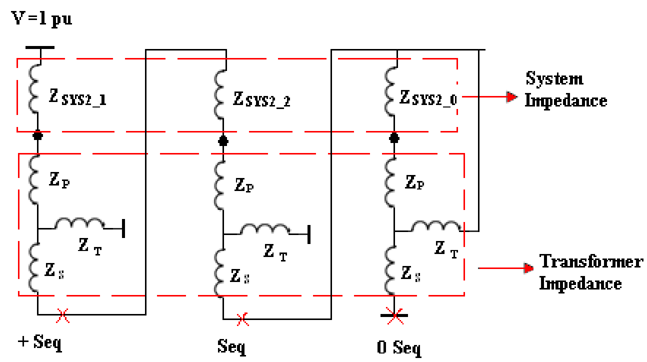


Fig. 8 Sequence network connection diagram

Following the same procedures as SLG on primary side, we can derive the fault phase and sequence currents for a SLG fault on AT secondary side.

$$I_{0.P} = \frac{Z_T}{(Z_{SYS2.0}+Z_P)+Z_T} \times I_0 \qquad (8)$$

$$I_{0.T} = \frac{Z_{SYS2.0}+Z_P}{(Z_{SYS2.0}+Z_P)+Z_T} \times I_0 \qquad (9)$$

It can be seen from (9) that, similar to a SLG fault on AT primary side, the tertiary circulating current, $I_{0.T}$, can flow either direction or zero in magnitude for a SLG fault on AT secondary side, dependent on the relation between system zero-sequence impedance, $Z_{SYS2.0}$, and AT primary branch impedance, Z_P.

We can also derive the AT neutral current for a primary side SLG fault as (10).

$$I_N = I_{0.S} - I_{0.P} \qquad (10)$$

After substituting $I_{0.P}$ of (8) into (10) and considering the AT ratio, we will have I_N as (11).

$$I_N = \left(1 - \frac{Z_T}{(Z_{SYS1.0}+Z_P)+Z_T} \times \frac{1}{R}\right) * I_{0.S} \qquad (11)$$

It is very unlikely for the neutral current to flow out of (down) the AT considering the practical AT and system parameters. Typically, the neutral current will flow into the AT when the SLG fault occurs on AT secondary side.

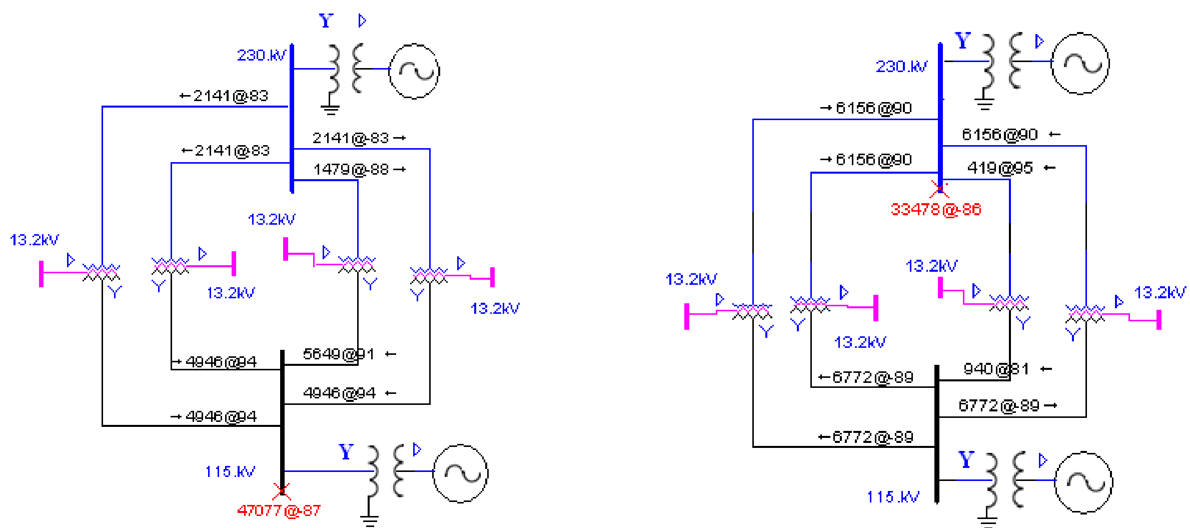
We can conclude that circulating current in AT delta winding can be either direction or zero in magnitude. The neutral current can also be either direction or zero in magnitude for a SLG fault on AT primary side. Therefore, it requires careful study when applying these current for polarization or overcurrent protection. Otherwise, misapplication and incorrect coordination are likely to happen. The following section discusses some actual examples of such misapplication.

IV. Examples of Autotransformer Impact on Fault study and Protection

A. Example of Fault Current Distribution of Autotransformers

This example describes the fault study at the switchyard of a large hydropower plant located at upstate New York. This plant has 16 generators. Eight units are connected to 115kV system and the other eight units are connected to 230kV system via step-up transformers. There are 4 three-winding ATs linking between 115kV and 230kV as shown in Fig. 9. Among the four ATs, three of them (No. 1, 2 and 4) are identical and the other one (No. 3) is half in size.

Fig. 9 (a) shows zero-sequence currents for a SLG on 115kV bus and (b) shows zero-sequence currents for a SLG on 230kV bus using ASPEN Oneliner. We can see that fault current in Fig. 9 (a) is more or less in normal pattern. However, fault current in Fig. 9 (b) is not readily straightforward. Currents in AT3 (3rd from left) are strikingly different from the rest both in magnitude and direction, which will complicate the relay application and coordination.



a. SLG on 115kVkV bus (secondary side) b. SLG on 230kV bus (primary side)

Fig. 9 SLG fault on buses of switchyard of a hydropower plant

Fig. 10 shows the currents in the same AT tertiary at two different system operating conditions. As we can notice, the tertiary current is opposite to each other ; therefore, it is not appropriate to be used for polarization.

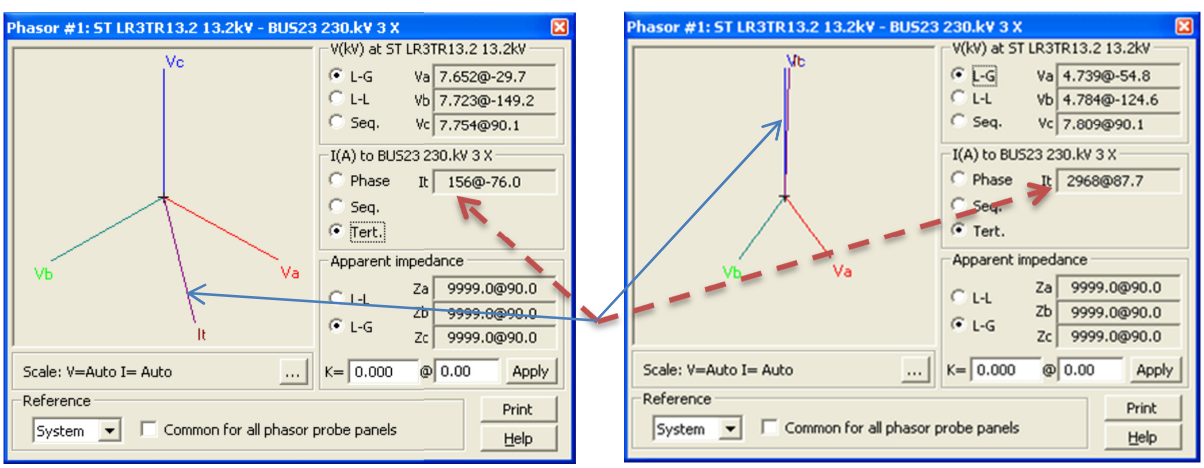


Fig. 10 Fault Current in the AT Tertiary

B. Relay Application at a Chemical Plant

Fig. 11 below is the one line diagram of a chemical plant power system. This plant has two generators connected at two 13.8kV buses respectively, which provide power for various motors.

There is a bus tie breaker. The plant also has two lines connecting to the utility grid via two autotransformers. The auto-transformers are located at the mid-point between the utility substation and the plant. AT1 is equipped with a delta-connected tertiary to supply local load, while AT2 is a Y-Y connected two winding transformer. AT1 and AT2 impedances are listed as below.

AT1:	4.5% Imp @ 34500Y/13800Y@ 6400kVA
	6.1% Imp @ 34400Y/2400D @ 2400kVA
	3.6% Imp @ 13800Y/2400D @ 2400kVA
AT2:	4.6% Imp @ 34500Y/13800Y@ 6400kVA

The plant has directional phase and ground overcurrent protection on the lines. Supposedly the protection should trip to breakers two isolate the plant from the grid during a fault in the utility system, so that two generators can continue to supply power for the motors. However, the plant experienced a number of total blackouts over the years during faults in the utility grid because the protection system failed to work as intended. The main reason for protection failure to operate is the misapplication, and lack of study and understanding of the fault current distribution during a ground fault.

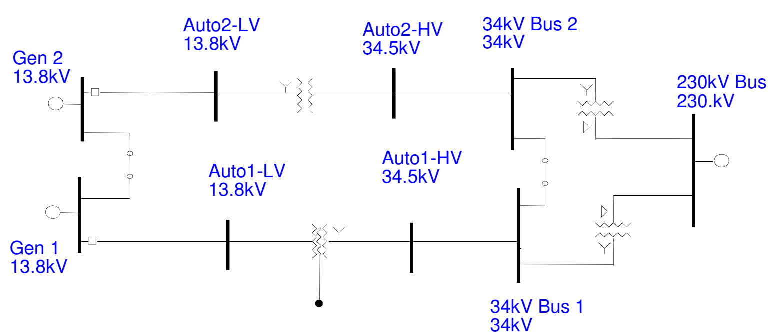


Fig. 11 One Line diagram of a chemical plant

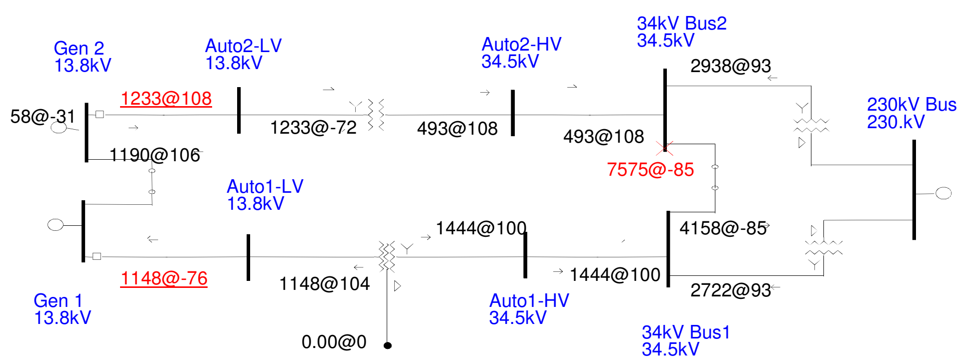


Fig. 12 Neutral current distribution for a SLG on Autotransformer high side

Fig. 12 shows the neutral current distribution for an autotransformer high-side SLG fault. We can see that neutral currents on Feeder 1 and 2 are 1148A and 1233A respectively, and they are opposite in direction. The directional ground overcurrent protection will trip Feeder 2 successfully as it sees slightly higher current and forward direction. However, after the Feeder 2 is tripped, the current will redistribute significantly as shown in Fig. 13. We can notice that the neutral current drops greatly, from 1148A prior to Feeder 2 tripping to 72A. This current is not enough for the ground overcurrent relay to trip. Therefore, generator 1 and 2 will continue to feed the fault until they are tripped by generator protection. The whole plant will completely blackout, which results in extended interruption for entire chemical plant. The underline cause of the plant blackout is the lack of fault study for an autotransformer. The wide range variation of neutral current associated with an autotransformer with delta winding needs to be carefully studied before applying the protection schemes.

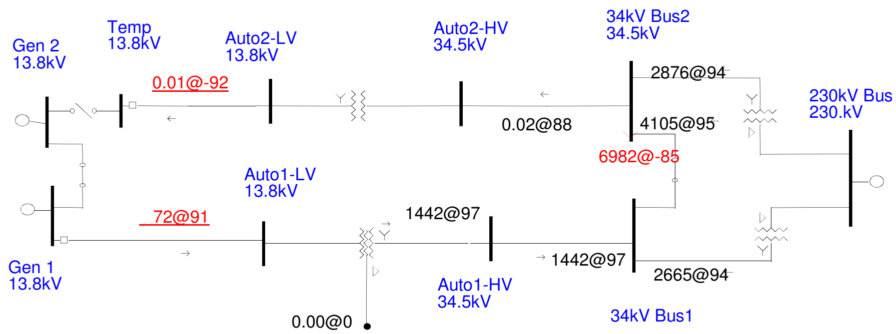


Fig. 13 Neutral current redistribution after Feeder 2 tripped

V. Conclusions

This paper discusses fault studies and protection related issues associated with autotransformers with delta-connected tertiary windings. From the discussions above, we can conclude three-winding ATs present some interesting and different problems for fault study and protection application. The fault current magnitude and direction can vary significantly from one situation to another. Special attention and careful studies are required when applying neutral current for polarization and overcurrent protection. Otherwise, relay misoperation operations are likely to happen. This paper also includes a couple of real world examples to show the peculiar results determined by fault studies and relay misapplication /misoperation due to the autotransformers.

VI. Reference

1. J. Lewis Blackburn, "Protective Relay Principle and Applications" Marcel Dekker, Inc, 1987

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