Why Neutral Earthing Resistors are Ineffective for Autotransformers with the Delta Tertiary Winding

Chinthaka SENEVIRATNE[1], and Cagil OZANSOY[1], *Member, IEEE*

College of Engineering and Science, Victoria University, Melbourne, Australia
chinthaka.seneviratne@live.vu.edu.au, cagil.ozansoy@vu.edu.au

Abstract

Neutral Earthing Resistors (NERs) are effective in limiting single-phase fault currents at the Low Voltage (LV) side of a two winding transformer. This paper aims to demonstrate that NERs are not an effective solution to limit the earth fault current on the LV side of autotransformers with delta tertiary windings. In a ground fault condition, the delta tertiary winding used in the autotransformers forms a shared path between the NER and the delta tertiary. This shared path of the zero-sequence model of an autotransformer substantiates why earth fault currents on the LV side of autotransformers cannot be effectively limited using the NER in the way they can be on conventional Delta-Star (Dyn) transformers. The findings demonstrate that significantly larger NERs are needed in autotransformer applications to limit the fault current compared to the conventional transformer.

1. Introduction

In industrial or commercial power systems, NERs have been recognized for many years, and they are connected between ground and neutral of transformers to limit single phase fault currents [1]. This paper only focuses on the single-phase to ground (1ph-g) fault currents, which are referred to as fault currents from hereon. The size of the NER depends on the reduction required in the fault current on the Low Voltage (LV) side of the installation. NERs help in realizing several benefits such as reduction in the ground potential rise associated with faults on the LV network, reduced physical damage to connected equipment and extended life of the connected equipment [2]. However, NERs are not significantly effective [3] in the fault current limiting of autotransformers with a delta tertiary winding. This paper aims to highlight and prove this ineffectiveness, which is a real problem that all power systems engineers should be fully aware of.

Employing NERs is not a new concept [4], but it is important to appreciate that an NER is not an effective solution to the fault current limitation of autotransformers. This fact can be overlooked by the high effectiveness of NERs with conventional transformers. Autotransformers are usually employed with delta tertiary windings [1], which allows several functions such as stabilizing the transformer flux linkage, providing station load, providing provision to connect reactive power compensation equipment and/or to suppress third harmonics. Yet, the delta tertiary winding of the autotransformer limits the fault current control capability using NER(s).Therefore, it is critical to highlight this since the anticipated benefits or safety requirements may not be achieved following the NER installation with autotransformers. This limitation of NERs in autotransformer applications has been insufficiently reported in the literature. Consequently, this paper fills an important gap by highlighting the need for the consideration of non-NER options to limit fault currents in autotransformer applications.

Section (2) reviews the zero-sequence transformer models and shows how the zero-sequence model of an autotransformer is more complicated than a conventional transformer. Section (3) presents the typical data used in NER sizing calculations and then shows the fault current calculation with a '10 ohms' NER comparing and contrasting autotransformers with conventional transformers. Conclusions are drawn in Section (4).

2. Zero sequence transformer model

In power system analysis, engineers use the symmetrical components method to determine unbalanced short-circuit currents. The sequence components for an unsymmetrical fault are calculated by connecting the three sequences (positive, negative and zero) networks in a specific way at the point of fault [5]. The zero sequence equivalent circuit of a transformer depends on the transformer vector group and grounding connection [2]. This section presents transformer zero-sequence modelling techniques and their applications to the symmetrical components for the types of transformers considered in the analysis: Star-Delta transformer and autotransformer with a tertiary winding. Generally, auto transformers are Y-connected transformers and their tertiary is a delta winding [6]. In this analysis, the sequence network is represented by its Thevenin equivalent voltage and impedance seen from the short-circuit location. In the considered fault current calculation, positive, negative and zero sequence components are connected in series [7] as shown in Fig.1.

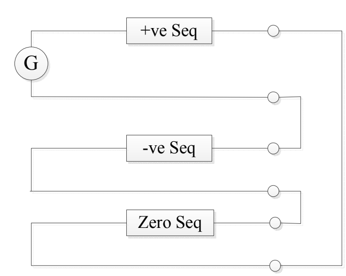

Fig.1. Sequence components connected in series

2.1. Transformer Zero Sequence Modelling

The flow of zero sequence current in a transformer depends on flux linkages that exist within the transformer and therefore is influenced by the transformer core, as well as winding and tank constructions [2]. The transformer flux linkages can be represented as a Tee-Model bus which is widely accepted and applied as in [2, 5]. The representation of this Tee-Model to the reference bus in the Zero Sequence is shown in Fig. 2. Typically, the values of the components of the Zero Sequence Tee-Model are derived from transformer tests. The model highlights that in the zero-sequence network, transformer construction will dictate the various flux linkages and resulting current flow paths in determining the total fault current. For example, depending on the construction, a path for zero sequence currents (I_o) to pass through the transformer primary and/or secondary windings may or may not exist.

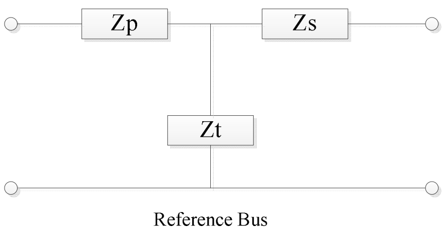

Fig.2. Transformer zero sequence Tee model diagram

2. 2. Modelling Zero Sequence of Ynyn and Δyn Transformer with NER

For a Ynyn transformer with impedance earthed neutrals as shown in Fig. 3 (a), the zero sequence current paths created for the various flux linkages can be seen in Fig. 3 (b) [8].

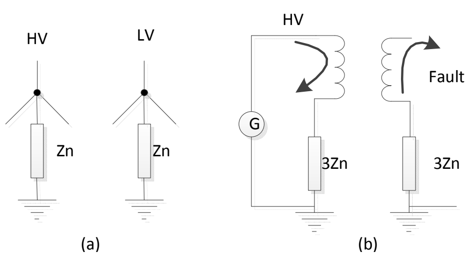

Fig. 3. YNyn Transformer zero sequence configuration

This gives rise to the equivalent Zero Sequence diagram for the YNyn transformer vector group shown in Fig. 4. It can be seen that there is a path of I_o current to pass through the transformer and furthermore a local I_o current within the transformer created by the magnetizing impedance which is high and usually ignored.

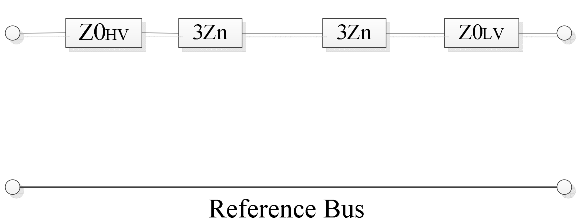

Fig. 4. YNyn zero sequence model

For a Δyn transformer with impedance earthed neutrals as shown in Fig. 5(a), the zero sequence current paths created for the various flux linkages can be seen in Fig. 5 (b) [8]. As shown, there is a path for zero sequence current through the winding with NER.

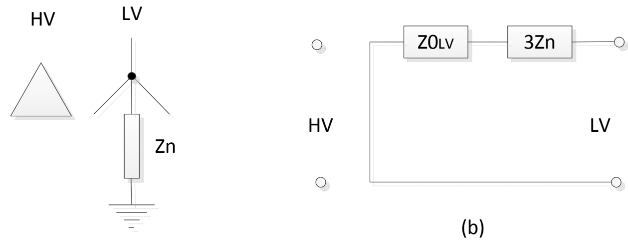

Fig.5. Δyn Transformer zero sequence configuration

2.3 Modelling Autotransformer Zero Sequence with NER

The autotransformer modelling differs from the two winding YNyn transformer considered above. The autotransformer has a single tapped winding in place for two separate windings. The full winding, which constitutes the High Voltage (HV) winding, is considered to have 'N1' turns and the common portion, which constitutes the LV winding, is considered to have 'N2' turns. Hence, the HV to LV turns ratio is considered to be N1/N2. For the autotransformer configuration with an impedance earthed neutral as shown in Fig. 6 (a), the zero sequence current paths created for the various flux linkages can be seen in Fig.6 (b).

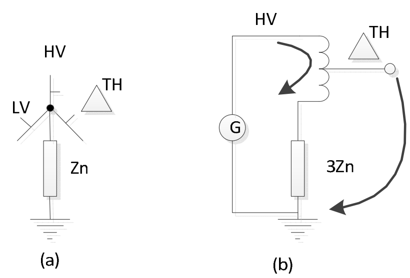

Fig. 6. YNd transformer configuration

The resulting zero sequence model for the transformer is shown in Fig. 7. From the zero sequence model, it can be seen that the zero sequence currents from the system have a similar path through the transformer HV and LV terminals as they did for the YNyn transformer, but slightly complicated by the fact that the flux linkages giving rise to these paths involve a shared winding, neutral resistor and a delta tertiary.

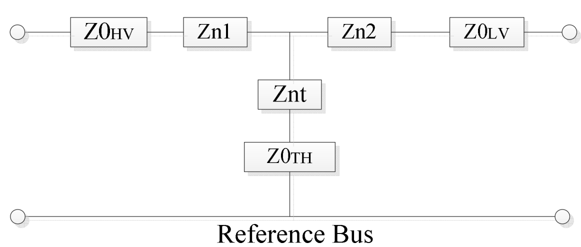

Fig. 7. YNa0d transformer zero sequence model

It is important to appreciate that influences of the neutral earthing impedance for the autotransformer appear in the three branches connected to the HV, LV, and tertiary windings (TH). It can be seen that the neutral earthing impedance influences the zero sequence model of the autotransformer appearing in each terminal. The values are given by the expressions in (1) to (3) in accordance with AS 3851 [8]:

$$Zn1 = -3\,Z_n\left(\frac{N1}{N2} - 1\right) \quad (1)$$

$$Zn2 = 3\,Z_n\left(\frac{N1}{N2}\right)\left(\frac{N1}{N2} - 1\right) (2) \qquad Z0t = 3Z_n\left(\frac{N1}{N2}\right) (3)$$

Where

Zn = the per unit earthing impedance based on the voltage of the primary (HV) winding, N1/N2 = Primary winding (full winding) / Secondary winding (tapped winding)

3. Sample calculations and analysis

This section comprises two sections. The first sub-section presents the typical data used for the NER sizing calculations and the second sub-section shows the fault current calculations, for the various transformer connections, with 10 ohms NER using the typical data presented in the first sub-section.

3.1 Typical Network Data for Example Calculations

In order to minimize the impact of data, a single machine bus system is considered and it is given in Fig. 8. The typical data used in this study for the source (supply) end, Δyn transformer, and the autotransformer are shown in Tables 1-3.

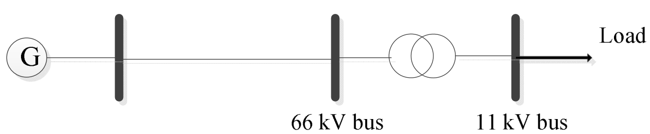

Fig. 8. Single machine bus system

Table 1. Δyn transformer data

Parameter	Unit	Value
Rating of HV and LV windings	MVA	10
HV winding voltage	kV	66
LV winding voltage	kV	11
Positive sequence impedance	p.u. on transformer MVA base	12.5% [9]
Negative sequence impedance	p.u. on transformer MVA base	12.5%
Zero-sequence impedance	p.u. on transformer MVA base	10% (see note below)

Table 2. Source end data

Parameter	Unit	Value
Supply voltage	kV	66
Indicative three phase fault level at the point of connection	kA	20 [10]
Earthing	#	The supply side is earthed

Note: Zero-sequence impedance is considered as 10% on TF MVA base (0.8×Zpositive [11]) (Deriving zero sequence impedances may be difficult in the absence of proper transformer test results because zero impedances will depend on a number of factors such as transformer steel, core and winding manufacturing methods [2])

Table 3. Autotransformer transformer data

Parameter	Unit	Value
Rating of HV, LV and TH windings	MVA	10/10/2
HV winding voltage	kV	66
LV winding voltage	kV	11
TH winding voltage	kV	6.6
Measured positive sequence impedance HV to LV	p.u. on transformer 10 MVA	7%
Measured positive sequence impedance HV to TH	p.u. on transformer 2 MVA	4%
Measured positive sequence impedance LV to TH	p.u. on transformer 2 MVA	3%
Measured zero sequence impedance supply on the HV side with LV open circuited	Ohm/phase	5.06
Measured zero sequence impedance supply on the HV side with LV short-circuited	Ohm/phase	3.05
Measured zero sequence impedance supply on the LV side with HV open circuited	Ohm/phase	1.02
Measured zero sequence impedance supply on the LV side with HV short circuited	Ohm/phase	0.54

3.2 Calculation of the LG fault current with a 10 ohm NER

This section shows the step by step calculation of the fault current with a 10 ohm Neutral Earthing Resistor. First, the calculation is performed for a delta-star transformer. Then, the calculation is repeated for an autotransformer.

Example calculation for the delta star transformer:

HV bus voltage	66 kV	(4)
Fault level at the HV bus of substation at nominal voltage	$\sqrt{3} \times 66 \times 20$ $= 2286\ MVA$	(5)
Supply end positive sequence impedance on 100 MVA	$\frac{100}{2286} = 0.043\text{i p.u.}$	(6)
Supply end equivalent positive sequence impedance as seen at the HV bus	$0.043i$ p.u.	(7)

It is assumed that system negative and zero sequence impedances at the HV bus are equal to the positive sequence impedance as at the HV bus.

Delta–star transformer positive sequence impedance	$\frac{12.5\% \times 100}{10}$	(8)
	$= 1.25\ p.u.\ on\ 100\ MVA$	(9)
Delta–star transformer negative sequence impedance	$1.25\ p.u.\ on\ 100\ MVA$	(10)
Delta–star transformer zero sequence impedance	$\frac{10.0\% \times 100}{10}$	
	$= 1.00\ p.u.\ on\ 100\ MVA$	(11)
Transformer Z based on the 11 kV low voltage on 100 MVA base	$\frac{11\times11}{100} = 1.210\ ohm$	(12)
Size of the NER	$10\ ohm\ or$	(13)
	$\frac{10}{1.210}$	
	$= 8.264\ \ in\ \ p.u.\ on\ 100\ MVA$	
Zero sequence impedance of the NER; the time actual NER value	$24.793\ in\ \ p.u.\ on\ 100\ MVA$	(14)

For the network given in Figure 8.

Total positive sequence impedance	$0.043i + 1.25i = 1.293\ i$ p.u.	(15)
Total negative sequence impedance	$0.043i + 1.25i = 1.293\ i$ p.u.	(16)
Total zero sequence impedance	$24.793 + 1.0i$ p.u.	(17)
Total impedance	$24.793 + 3.587i$ p.u.	(18)
Total ground current ($3i_0$) in p.u.	$abs\left[\frac{3}{24.793 + 3.587i}\right]$	
	$= 0.1198\ p.u.$	(19)
Transformer low voltage base current	$\frac{100\times1000}{\sqrt{3}\times11} = 5248.64$ A	(20)
Total ground current ($3i_0$) in amps	$0.1198 \times 5248.64 = 660\ A$	(21)

Example calculation for the autotransformer:

HV bus voltage	66 kV	(22)
Fault level at the HV bus of substation at nominal voltage	$\sqrt{3}\ \times 66 \times 20 = 2286\ MVA$	(23)
Supply end positive sequence impedance on 100 MVA	$\frac{100}{2286} = 0.043i$ p.u.	(24)
Supply end equivalent positive sequence impedance as seen at the HV bus	$0.043i$ p.u.	(25)

It is assumed that system negative and zero sequence impedances at the HV bus are equal to the positive sequence impedance as at the HV bus.

Z_H positive(negative) sequence impedance on 100 MVA	$\frac{.07\left(\frac{100}{10}\right) + .04\left(\frac{100}{2}\right) - .03\left(\frac{100}{2}\right)}{2} = 0.6i$	(26)
Z_L positive(negative) sequence impedance on 100 MVA	$\frac{.07\left(\frac{100}{10}\right) + .03\left(\frac{100}{2}\right) - .04\left(\frac{100}{2}\right)}{2} = 0.1i$	(27)
Z_T positive(negative) sequence impedance on 100 MVA	$\frac{.03\left(\frac{100}{2}\right) + .04\left(\frac{100}{2}\right) - .07\left(\frac{100}{10}\right)}{2} = 1.4i$	(28)
Z_H zero sequence T-model impedance	-0.81i p.u.	(29)
Z_L zero sequence T-model impedance	0.64i p.u.	(30)
Z_T zero sequence T-model impedance	1.97i p.u.	(31)
Transformer Z base on the 66 kV high voltage on 100 MVA base	$\frac{66 \times 66}{100} = 43.56\ ohm$	(32)
Transformer Z base on the 11 kV low voltage on 100 MVA base	$\frac{11 \times 11}{100} = 1.21\ ohm$	(33)
Transformer Z base of the 6.6 KV tertiary voltage on 100 MVA base	$\frac{6.6 \times 6.6}{100} = 0.436\ ohm$	(34)
Size of the NER	$10\ ohm$ or	
	$\frac{10}{43.56} = 0.23\ \ in\ \ p.u.\ on\ 100\ MVA$ on the HV voltage	(35)
NER contribution to HV side	$-3\times 0.23 \times \left(\frac{66}{11} - 1\right) = -3.44 + 0i$	(36)
NER contribution to LV side	$3\times0.23\times \frac{66}{11} \times \left(\frac{66}{11} - 1\right) = 20.66 + 0i$	(37)

NER contribution to TH side	$3{\times}0.23{\times}\frac{66}{11} = 4.13 + 0i$	(38)
Total positive sequence impedance	$0.043i + 0.6i + 0.1i = 0.743\ i$	(39)
Total negative sequence impedance	$0.743\ i$	(40)
Total zero sequence impedance	$9.857 + 5.0352i$ (Based on the sequence network connection)	(41)
Total impedance	$9.857 + 6.521i$	(42)
Total ground current ($3i_0$) in p.u.	$abs\left[\frac{3}{9.857 + 6.521i}\right]$ $= 0.254\ p.u.$	(43)
Transformer low voltage base current	$\frac{100{\times}1000}{\sqrt{3}{\times}11} = 5248.64$ A	(44)
Total ground current ($3i_0$) in amps	$0.254 \times 5248.64 = 1371\ A$	(45)

The calculations above show that 10 ohm resistor helps to limit the fault current to 660 Amps with star delta transformer. However, 10 ohm resistor only helps to limit fault current to 1371 Amps with an autotransformer. Fault currents for the same autotransformer have been calculated for a range of resistor values and results are given in Fig. 9. It demonstrates that autotransformer needs a significantly larger NER to limit the fault current compared to the conventional transformer. Further, beyond a certain size, NER may not help to reduce the fault current of an autotransformer. The above-abridged derivation of the zero sequence models of an autotransformer highlights why earth fault currents on the LV side of autotransformers cannot be effectively constrained using neutral earthing transformers (NER) in the way they can be on conventional Dyn transformer vector groups. This abridge in the autotransformer provides the electrical and magnetic coupling between primary and secondary, unlike delta star transformer has only a magnetic coupling with respect to the zero sequence current. The conclusion is that NERs are not effective in limiting the earth fault current on the LV side of autotransformers. Therefore, considerations for non NER options need to be explored to limit these fault currents.

4. Conclusions

This paper has presented a systematic analysis to demonstrate the ineffectiveness of neutral earthing resistors in limiting the earth fault current on the LV side of autotransformers. The zero sequence model of an autotransformer has been developed and it has been shown that there will be a shared path between the NER and delta winding due to ground-fault conditions. Subsequently, calculations have been carried out to determine the single-phase to ground fault currents with a 10 ohm NER for first a delta-star transformer and then for an autotransformer. Comparing and contrasting the calculated fault currents show that a significantly larger NER is required for limiting the fault current of an autotransformer compared to the conventional transformer. Furthermore, it has also been shown that beyond a certain size, NER does not reduce the fault current of an autotransformer. The overall finding and conclusion is that non-NER options need to be explored for limiting fault currents of an autotransformer.

5. References

[1] I. Institute of Electrical and Electronics Engineers, "Grounding of Industrial and Commercial Power Systems," vol. IEEE Std 142™-2007, ed, 2007.

[2] J.Winders, *Power Transformers Principles and Applications*: Marcel Dekker, Inc., 2002.

[3] D. Kouba and K. Prochazka, "The analysis of efficiency of shunt resistor during a single-phase earth fault using the two-port network theory," in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1-4.

[4] L. Yu and R. L. Henriks, "Selection of system neutral grounding resistor and ground fault protection for industrial power systems," in *Petroleum and Chemical Industry Conference, 1991, Record of Conference Papers., Industry Applications Society 38th Annual*, 1991, pp. 147-153.

[5] W. D. Stevenson, *Elements of Power System Analysis*, International Edition ed. Singapore: McGraw-Hill Book Company, 1982.

[6] O. T. Farry, "Tertiary windings in autotransformers," *Electrical Engineering,* vol. 80, pp. 359-359, 1961.

[7] ABB, *Protection Application Handbook*. Sweden: ABB Switchgear, 2001.

[8] Standards Australia International, "The calculation of short-circuit currents in three-phase a.c. system," vol. AS3865, ed, 1991.

[9] AREVA. (2005). *Network Protection & Automation Guide*.

[10] Energy Services Commission, "Electricity Distribution Code " vol. Version 6, ed, 2011.

[11] Standards Australia International, "Power transformers Part 8: Application guide," ed, 2000.

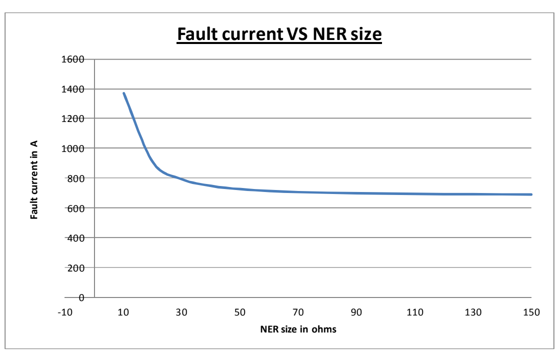

Fig. 9. Autotransformer fault current (Amps) vs NER (ohm)