Back to Table of Contents

Series Low-Impedance Coupling Impacts Relay Settings

Relay Settings Could Be Impacted By Three-Winding Autotransformers With Low-Series Impedances Coupling In The Zero-Sequence Network

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SERIES LOW-IMPEDANCE COUPLING IMPACTS RELAY SETTINGS

Relay Settings Could Be Impacted By Three-Winding Autotransformers With Low-Series Impedances Coupling In The Zero-Sequence Network

GENERAL

When determining relay settings, protection engineers use I_{sc} data from computer short-circuit programs to obtain the current flowing through the system for various faults. The program can be directed to show the contribution of current by any element in the system, and for any fault in the system.

It is important that electric utility protection engineers know where the maximum fault current can be generated so that proper relay settings can be applied for a specific protection zone. Traditionally, engineers utilized the computer short-circuit program to see these values, and then set a non-directional instantaneous element above the highest external fault currents.

San Diego Gas & Electric (SDG&E) Company recently experienced false trips when several relays at one voltage level operated due to an external fault at a different voltage level. The fault was line-to-ground on the 230 kV system, and five non-directional overcurrent ground relays operated on the 138 kV system protecting wye-delta-wye transformer banks. After much analysis, it was determined that the 230/138 kV autotransformers allowed close coupling between the 230 and 138 kV zero-sequence networks. This, along with a major reduction in the positive and negative-sequence impedances, was the primary cause for the unexpected high current that caused the five relays to misoperate. The relays were set considering that the maximum zero-sequence fault current contribution from the transformer was at its terminals.

Many utility systems in the U.S., including SDG&E, have portions of their system where complete isolation of zero-sequence networks exists when transforming from one voltage level to another. Any wye-delta or delta-wye transformation will give this isolation. However, when using autotransformers, or wye-delta-wye transformers, the zero-sequence coupling between voltage levels can be strong and cause a redistribution of zero-sequence current.

PURPOSE

The purpose of this paper is to share with other protection engineers the knowledge and experience gained by the study of a utility relay misoperation. The traditional method of looking for the highest fault current must be altered when strong coupling exists in the zero-sequence network. There may be other cases where unexpected high, or even low currents, occur due to the complication of the system connections. This paper presents such a situation, with real fault data and calculations, which shows this unusual circumstance and explains how to avoid relay misoperations.

BACKGROUND

A short-circuit study of the system is required before protective relays can be set to properly isolate the faulted element from the rest of the system. Such a study was performed for setting ground overcurrent relays at one of SDG&E's substations when a STATCOM (Static Var Compensator) was added to the SDG&E system: this included three 33/44/55 MVA, 138/3.2 kV transformers connected in wye-delta-wye (Y-D-Y) with relays and breakers as shown in Figure 1.

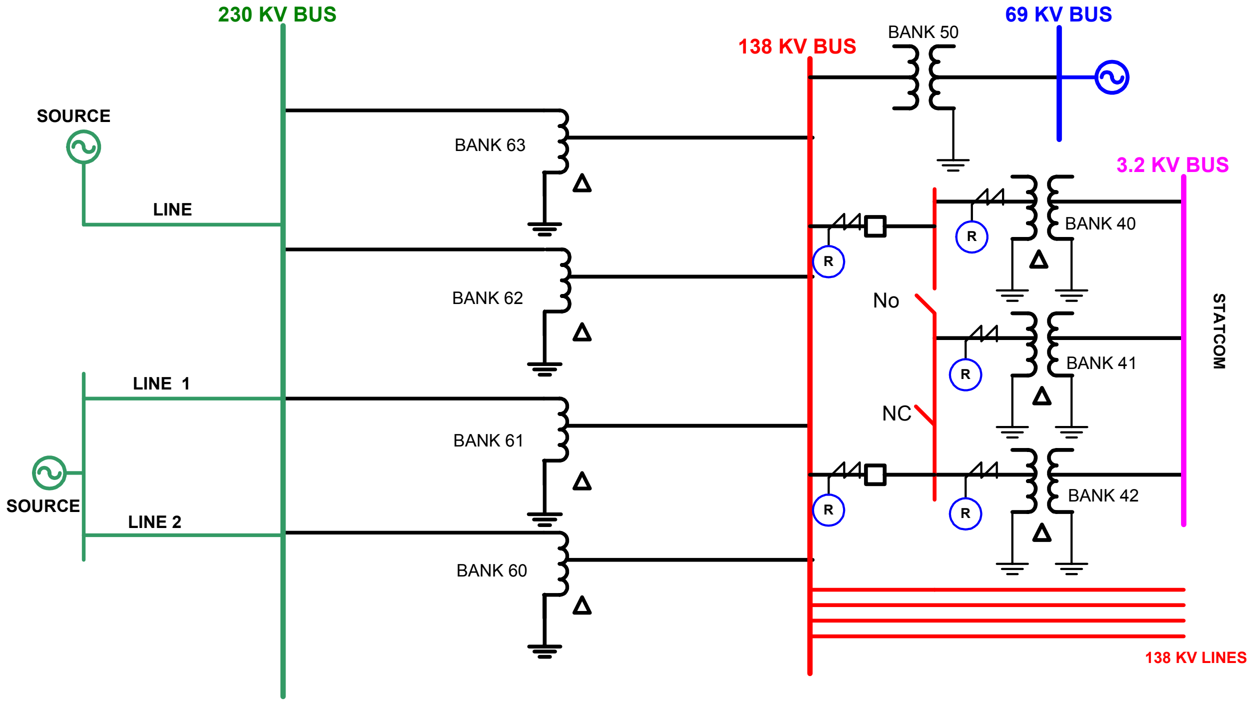


Figure 1. One-Line Diagram of an SDG&E Substation

SDG&E's substation is a transmission station with three 230 kV incoming lines, (four autotransformers at 230/138 kV), a 69 kV line connected to the 138 kV bus via a step-up transformer, and four 138 kV radial transmission lines connecting six distribution substations with 138/12 kV transformers and the three 138/3.2 kV transformers for the STATCOM. See Appendix A for transformer ratings.

The five relays shown in Figure1 operated incorrectly for a line-to-ground fault on one of the 230 kV lines close to this substation. The operating element for each microprocessor relay was $3I_0$ instantaneous as recorded on relay event report. What was unusual was that the magnitude of $3I_0$ was higher as compared to the earlier short-circuit study.

Not knowing the reason why this value was so high, a new short-circuit study was conducted, and upon faulting the 230 kV bus, it was a surprise to find that a higher $3I_0$ was flowing through each of the relays with a value above their settings. How can this happen?

To prove this phenomenon, a detailed analysis was performed using the old-fashioned method of hand calculation.

CALCULATIONS

Using symmetrical components for a line-to-ground fault, a model of the three sequence networks was developed as shown in Figures 2 through 4.

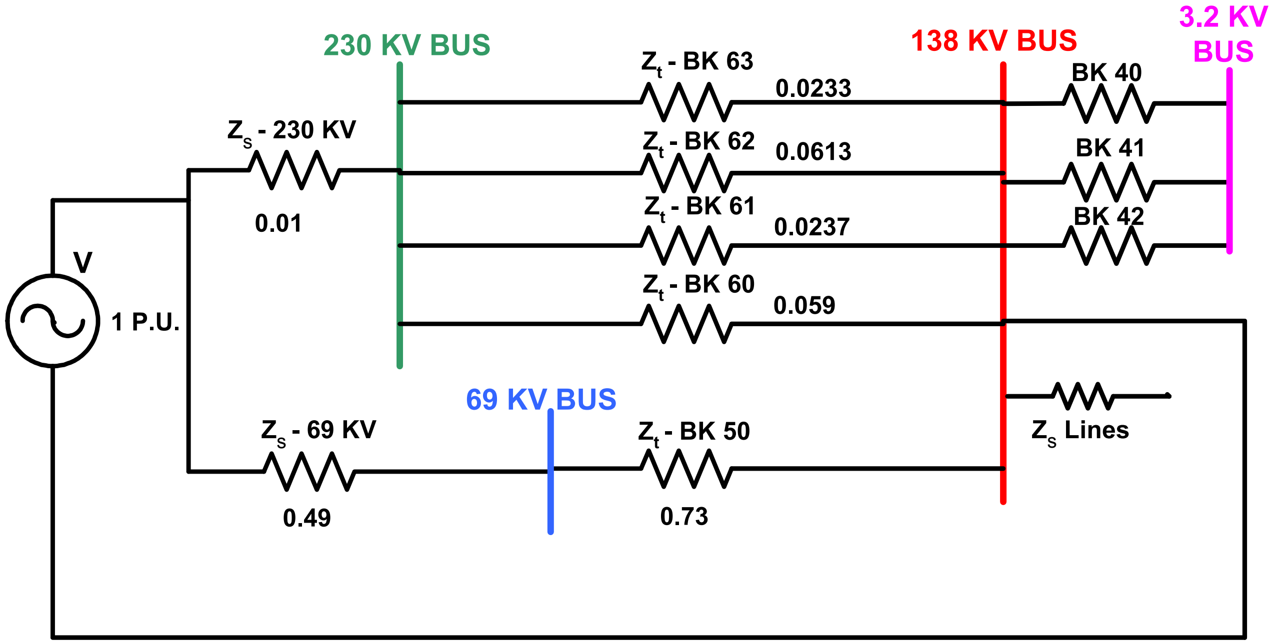


Figure 2. Positive-Sequence Network

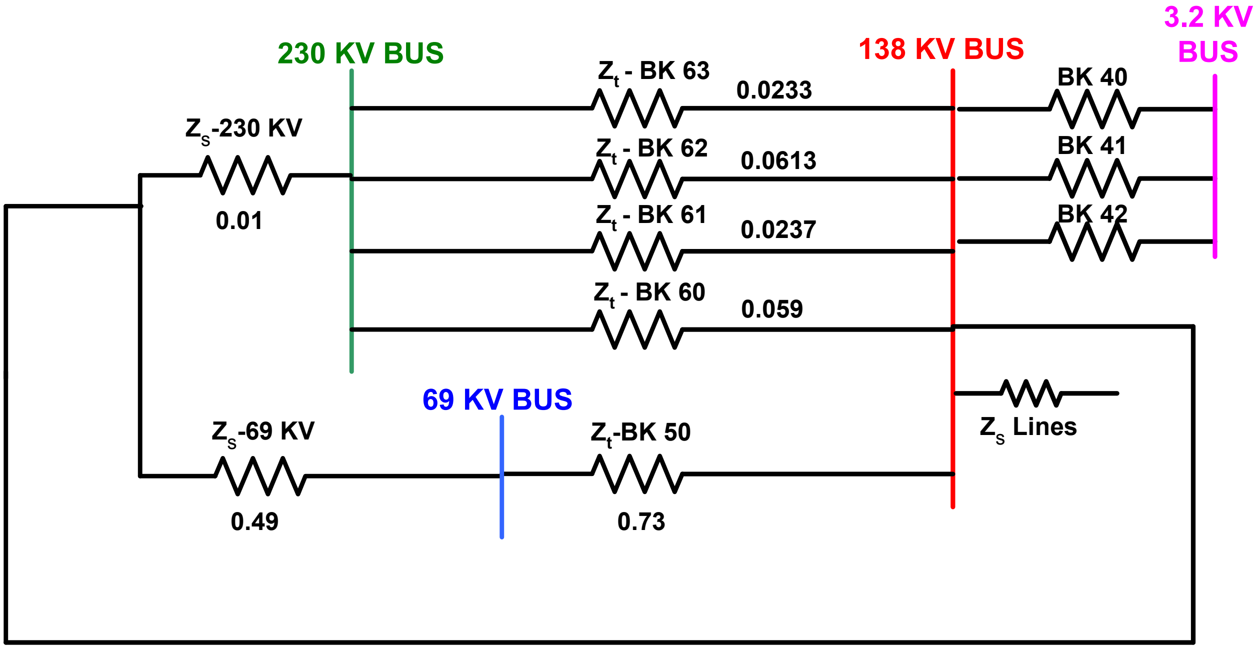


Figure 3. Negative-Sequence Network

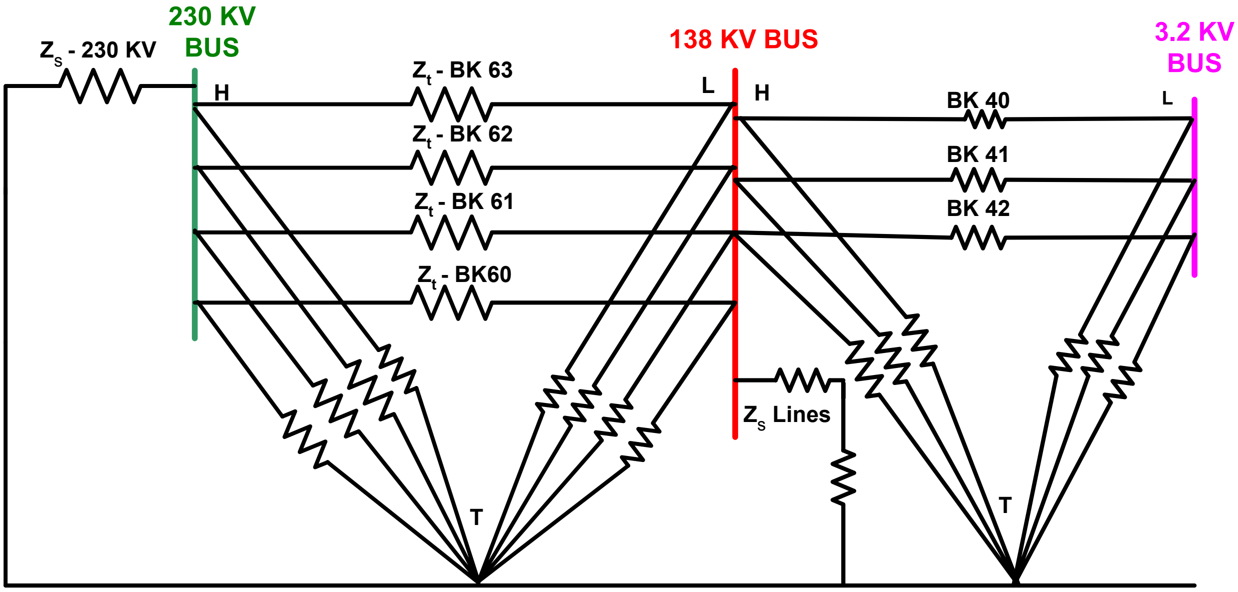


Figure 4. Zero-Sequence Network

The zero-sequence network shown in Figure 4 is further reduced to an equivalent "DELTA" network by combining all transformers, and is later transformed into a "T" network model as shown in the following equations and Figures 5 and 6.

REDUCTION OF THE ZERO-SEQUENCE NETWORK

All values in Per Unit (P.U.)

Parallel Reactance of 230/138 kV Transformers

Upper Branch H-L

$$\frac{1}{X_{H-L}} = \frac{1}{X_{60}} + \frac{1}{X_{61}} + \frac{1}{X_{62}} + \frac{1}{X_{63}} = \frac{1}{0.059} + \frac{1}{0.02} + \frac{1}{0.069} + \frac{1}{0.022} = 126.9$$

$$X_{H-L} = 0.00788$$

Left Branch *H-T*

$$\frac{1}{X_{H-T}} = \frac{1}{X_{60}} + \frac{1}{X_{61}} + \frac{1}{X_{62}} + \frac{1}{X_{63}} = \frac{1}{0.2587} + \frac{1}{0.0876} + \frac{1}{0.25} + \frac{1}{0.1264} = 27.25$$

$$X_{H-T} = 0.0367$$

Right Branch L-T

$$\frac{1}{X_{L-T}} = \frac{1}{X_{60}} + \frac{1}{X_{61}} + \frac{1}{X_{62}} + \frac{1}{X_{63}} = \frac{1}{0.1827} + \frac{1}{0.0595} + \frac{1}{0.1753} + \frac{1}{0.1023} = 37.73$$

$$X_{L-T} = 0.0265$$

Parallel Reactance of 138/3.2 kV Transformers

Upper Branch *H-L*

$$\frac{1}{X_{H-L}} = \frac{1}{X_{40}} + \frac{1}{X_{41}} + \frac{1}{X_{42}} = \frac{1}{0.2125} + \frac{1}{0.2125} + \frac{1}{0.2125} = 14.12$$

$$X_{H-L} = 0.0708$$

Left Branch *H-T*

$$\frac{1}{X_{H-L}} = \frac{1}{X_{40}} + \frac{1}{X_{41}} + \frac{1}{X_{42}} = \frac{1}{0.1735} + \frac{1}{0.1735} + \frac{1}{0.1735} = 17.30$$

$$X_{H-L} = 0.0578$$

Right Branch L-T

$$\frac{1}{X_{L-T}} = \frac{1}{X_{40}} + \frac{1}{X_{41}} + \frac{1}{X_{42}} = \frac{1}{0.1117} + \frac{1}{0.1117} + \frac{1}{0.1117} = 26.85$$

$$X_{L-T} = 0.037$$

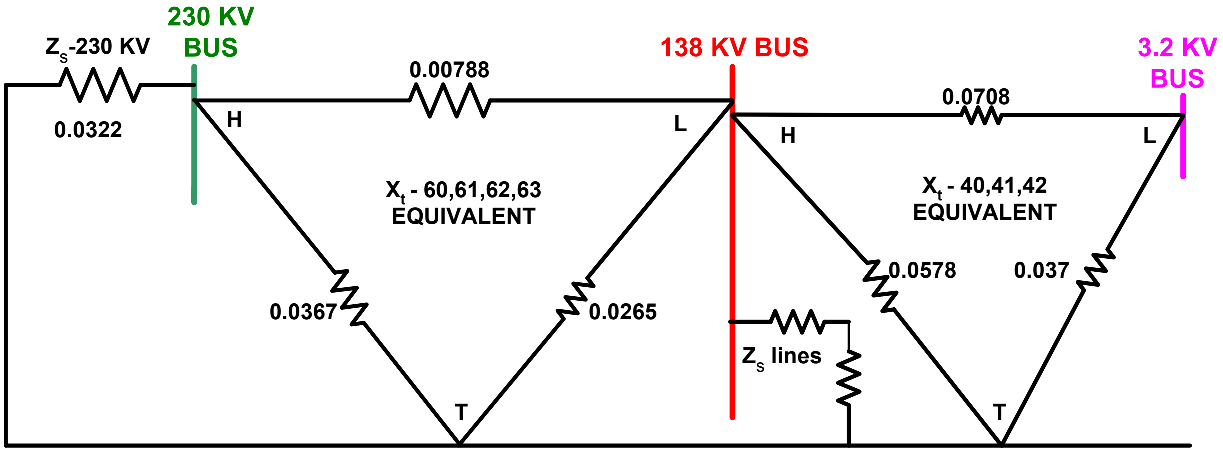


Figure 5. Zero-Sequence Reduction

The equations used to transform a "Delta" to a "T" model are covered in many power system textbooks and are also repeated here. See Appendices D and E for zero-sequence connection.

230/138 KV TRANSFORMATION

$$X_H = \left[\frac{X_{H-L} + X_{H-T} - X_{L-T}}{2}\right] = \left[\frac{0.00788 + 0.0367 - 0.0265}{2}\right] = 0.009\ P.U.$$

$$X_L = \left[\frac{X_{H-L} + X_{L-T} - X_{H-T}}{2}\right] = \left[\frac{0.00788 + 0.0265 - 0.0367}{2}\right] = -0.00116\ P.U.$$

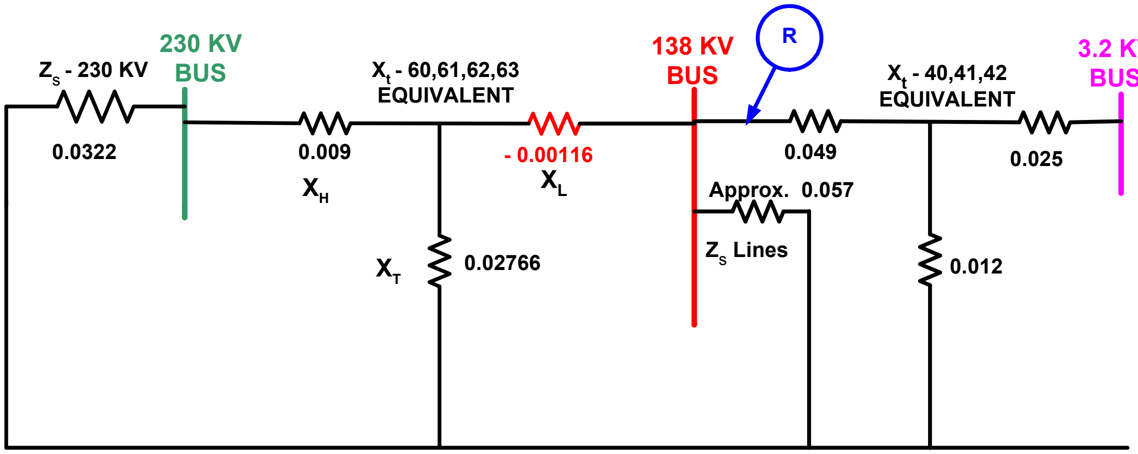
$$X_T = \left[\frac{X_{H-T} + X_{L-T} - X_{H-L}}{2}\right] = \left[\frac{0.0367 + 0.0265 - 0.00788}{2}\right] = 0.02766\ P.U.$$

138/3.2 KV TRANSFORMATION

$$X_H = \left[\frac{X_{H-L} + X_{H-T} - X_{L-T}}{2}\right] = \left[\frac{0.0708 + 0.0578 - 0.037}{2}\right] = 0.049\ P.U.$$

$$X_L = \left[\frac{X_{H-L} + X_{L-T} - X_{H-T}}{2}\right] = \left[\frac{0.0708 + 0.037 - 0.0578}{2}\right] = 0.025\ P.U.$$

$$X_T = \left[\frac{X_{H-T} + X_{L-T} - X_{H-L}}{2}\right] = \left[\frac{0.0578 + 0.037 - 0.0708}{2}\right] = 0.012\ P.U.$$



Note: The negative reactance for the 230/138 kV "T" model X_L.

Figure 6. Zero-Sequence "T" Equivalent

POSITIVE- AND NEGATIVE-SEQUENCE REDUCTION

The positive and negative sequence can be combined and reduced to an equivalent reactance for both 230 kV and 138 kV systems with a voltage source as shown in Figures 7 through 9.

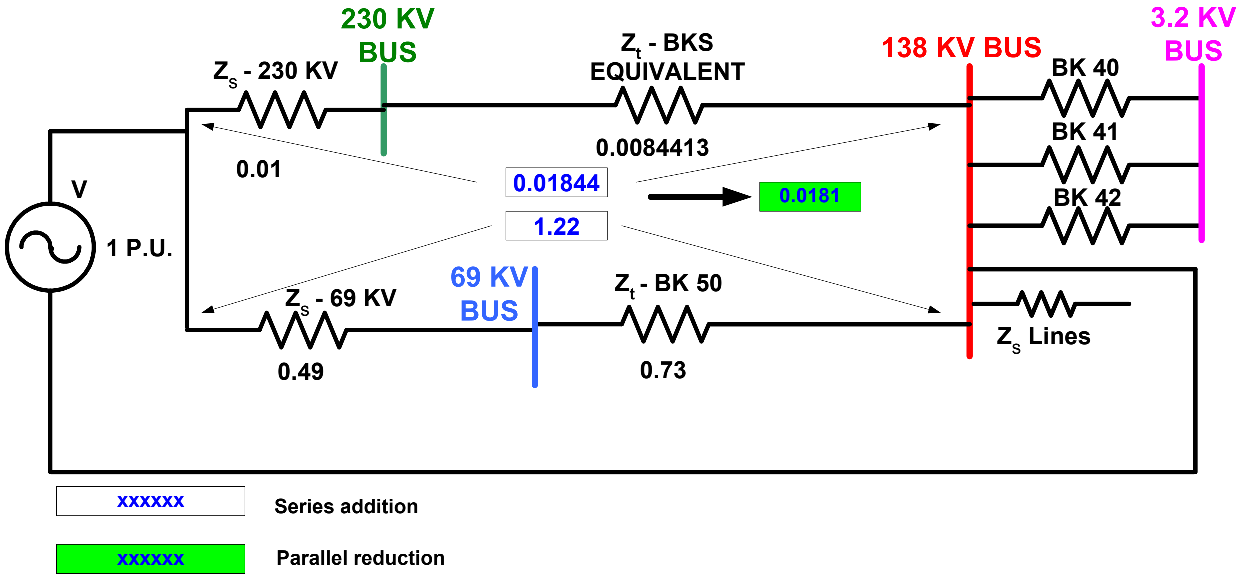


Figure 7. Positive and Negative Sequence Combined

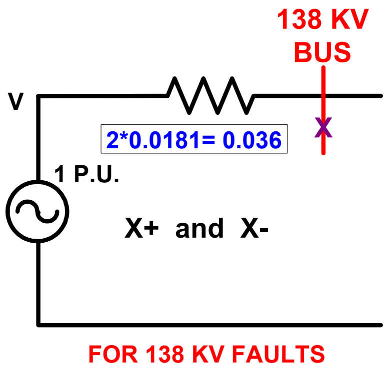


Figure 8. Positive and Negative Sequence for 138 kV Faults

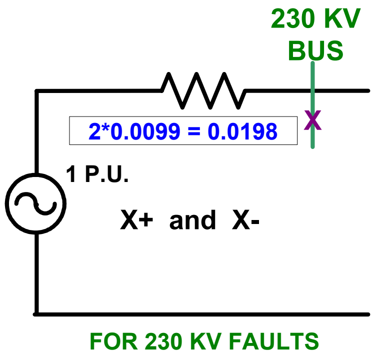


Figure 9. Positive and Negative Sequence for 230 kV Faults

ZERO-SEQUENCE FAULT CALCULATION

The idea now is to connect the networks for a line-to-ground fault on the 138 kV bus first, and then on the 230 kV bus, and then to compare the currents seen by each relay on the 138 kV bus as shown in Figures 10 and 11.

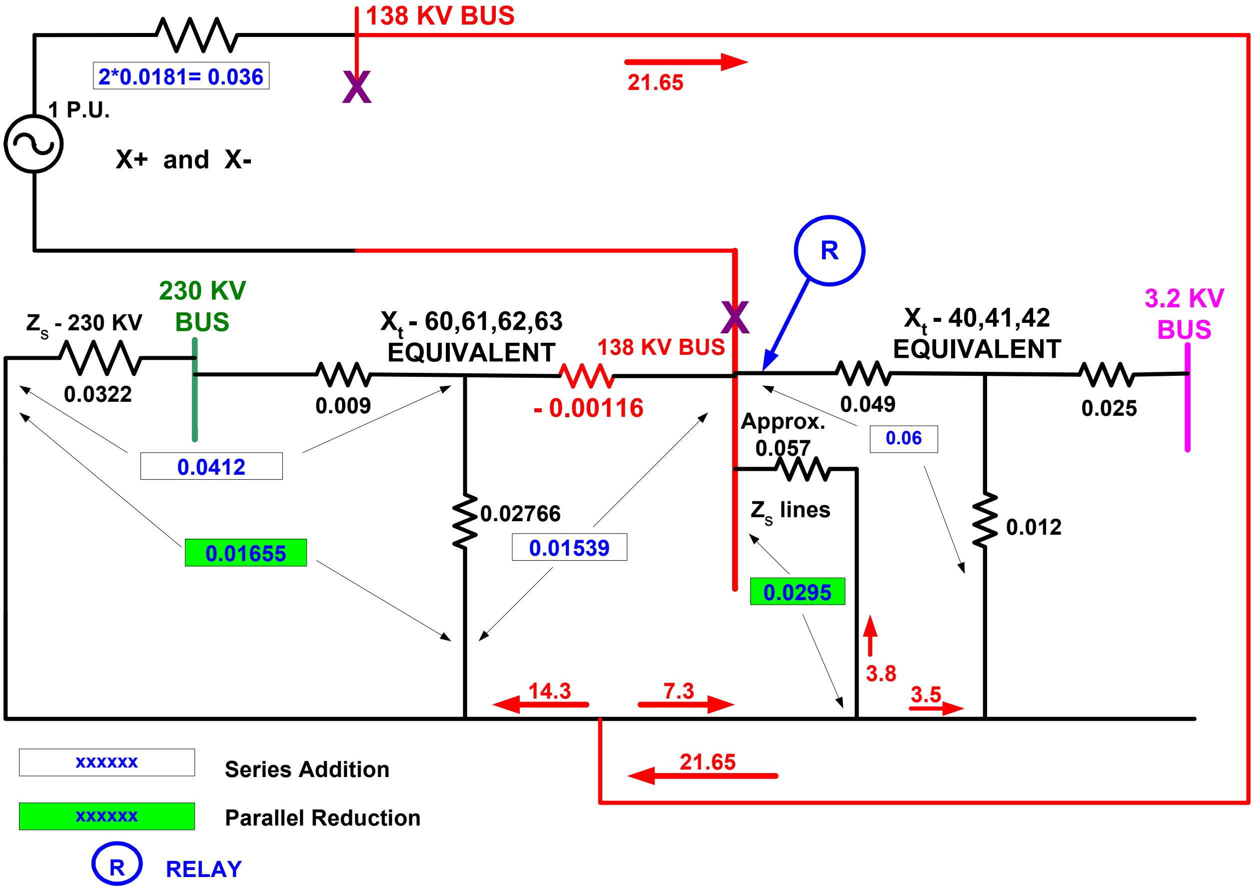


Figure 10. 138 kV Bus Fault

$$I_1 = I_2 = I_0 = \frac{1}{0.046} = 21.65\ P.U.\ current$$

For the 138 kV bus fault, $3I_0$ of approximately **3.5 *3 = 10.5 P.U**. Amperes will flow up the neutral of Banks 40, 41, and 42, or **3.5 P.U.** from each 138 kV transformer. The short-circuit program in Appendix C shows **3.7 P.U.,** which compares very closely to the hand calculation.

Total bus fault will be **$3I_0$ = 3*21.65 = 64.95 P.U. Amperes,** which compares to the short-circuit program of **64.25 P.U** in Appendix **C.**

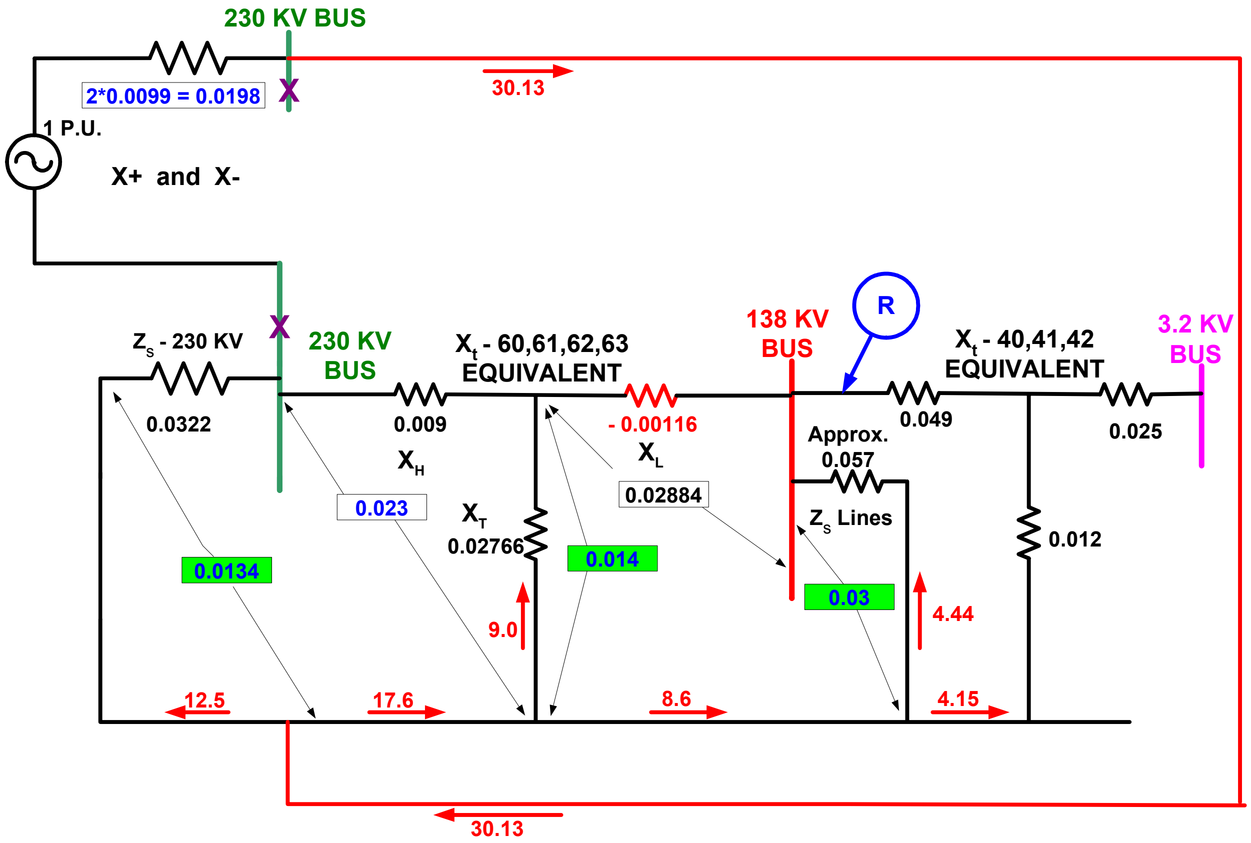


Figure 11. 230 kV Bus Fault

If you compare the P.U. currents flowing up the neutral of Banks 40, 41, and 42 for the 230 kV bus fault, you will see that the magnitudes are higher than the 138 kV bus fault. For the 138 kV bus fault, $3I_0$ of approximately **4.15 * 3 = 12.45 P.U**. Amperes will flow up the neutral of Banks 40, 41, and 42, or **4.15 P.U** from each of the 138 kV transformers. The short-circuit program in Appendix **B** shows **4.3 P.U.,** which compares very closely to the hand calculation.

The total bus fault will be **3Io = 3*30.13 = 90.4 P.U** Amperes and compares to the short-circuit program of **89.46 P.U.**

CONCLUSIONS

The analysis shows that the ground fault current near the 138 kV relays is less for a 138 kV bus fault than for a 230 kV fault further away from the relay. The traditional method of looking for highest fault current must be altered when strong coupling exists in the zero-sequence network with a major reduction in the positive and negative sequence impedances. There may be other cases where unexpected high, or even low currents, occur due to the complication of the system connections.

Comparing the currents up the neutrals of Banks 40, 41, and 42 for the 138 kV bus fault of 3.5 P.U. to the fault current for the 230 kV bus fault of 4.15 P.U. shows that a greater magnitude of current can flow for the 230 kV fault, which is further away.

It is important that protection engineers know where the maximum fault current can be generated so that proper relay settings can be applied for a specific protection zone. Having a good knowledge of the symmetrical component theory will help to easily discover these unusual conditions before a relay misoperation occurs. This paper provides protection engineers with insights and knowledge of an actual relay misoperation for an external fault that could have been prevented, if the fault simulation during relay settings had taken into account autotransformers with low-series impedance coupling in the zero-sequence network.

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BIOGRAPHY

Girolamo (Gerry) Rosselli received his B.S. degree in Electrical Engineering from the University of Illinois in 1978. Upon graduation, he was hired by Commonwealth Edison Company, where he worked on the planning side of the 12 kV overhead and underground distribution systems, as well as electrical planning for high-rise buildings in central Chicago.

He joined San Diego Gas & Electric as a Substation Engineer in 1981. In 1985, he joined the System Protection group, where he is now a Principal Relay and Protection Engineer. One of his major accomplishments was the coordination of the transmission and subtransmission systems of the Island of Guam. He has written an article on 500 kV Series Capacitors for T&D Magazine (1987). He was one of the speakers at the 30th Western Protective Relay Conference held in Spokane, Washington, and also the 57th Annual Protective Relaying Conference at Georgia Tech, in Atlanta, Georgia. The presentation, and published paper, was titled Transformer Test to Calculate Z0 For Interconnected Winding Transformers. He also presented the paper to the IEEE Transformer Committee and it has been accepted for implementation into the IEEE Standards. He is a member and former Chairman of IEEE/PES Society San Diego Chapter, and a Registered Professional Engineer in the State of California.

APPENDIX A

NETWORK DATA (In Per Unit 100 MVA)

Transformer No.	**Voltage (kV)**	**MVA**	**Positive Sequence Reactance P.U.**	**Zero Sequence Reactance P.U. X_{ps}, X_{pt}, X_{st}**	**Connection**
60	230/138	150/168	0.059	0.0593, 0.2586, 0.1826	AUTO
61	230/138	210/350/392	0.0237	0.0203, 0.0876, 0.0595	AUTO
62	230/138	150	0.0613	0.069, 0.25, 0.175	AUTO
63	230/138	210/350/392	0.0233	0.02219, 0.1264, 0.1023	AUTO
50	138/69	15/20/25	0.73	X_0 = 0.734	D-Y
40	138/3.2	33/44/55	0.17	0.2125, 0.1735, 0.1117	Y-D-Y
41	138/3.2	33/44/55	0.1678	0.2125, 0.1735, 0.1117	Y-D-Y
42	138/3.2	33/44/55	0.1678	0.2125, 0.1735, 0.1117	Y-D-Y

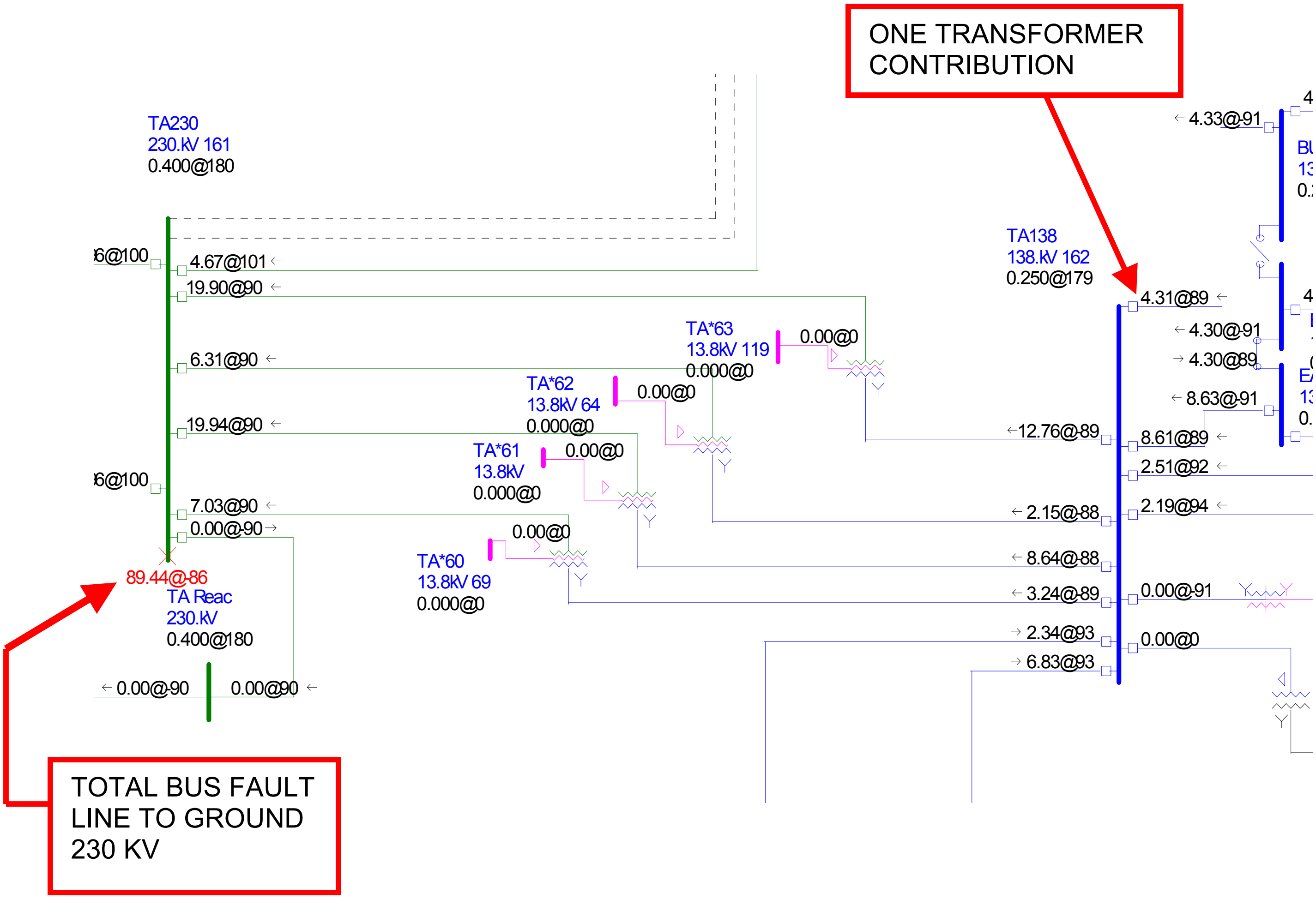
Source Impedances

230 kV X_s positive and negative = **0.01** X_0 = **0.0322**

69 kV X_s positive and negative = **0.49** X_0 = infinite, delta winding on 138 kV side

APPENDIX B

SHORT-CIRCUIT PROGRAM 230 KV BUS FAULT
(In Per Unit 100 MVA)

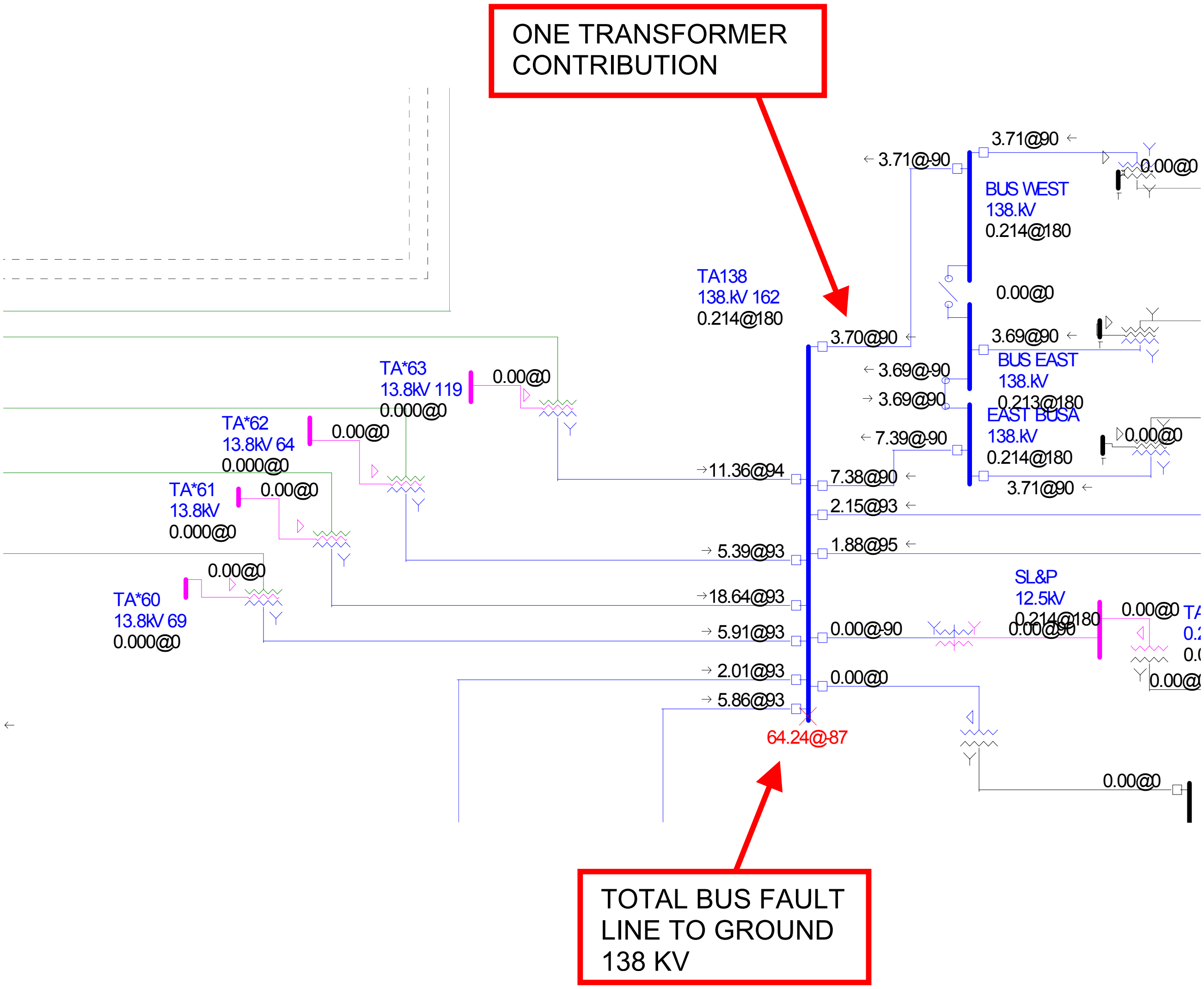


ONE TRANSFORMER CONTRIBUTION

TOTAL BUS FAULT LINE TO GROUND 230 KV

APPENDIX C

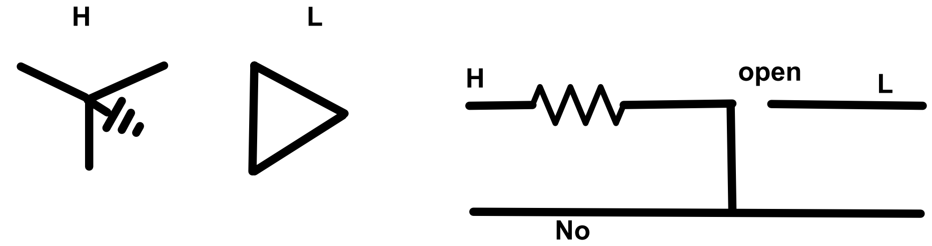
SHORT-CIRCUIT PROGRAM 138 KV BUS FAULT
(In Per Unit 100 MVA)

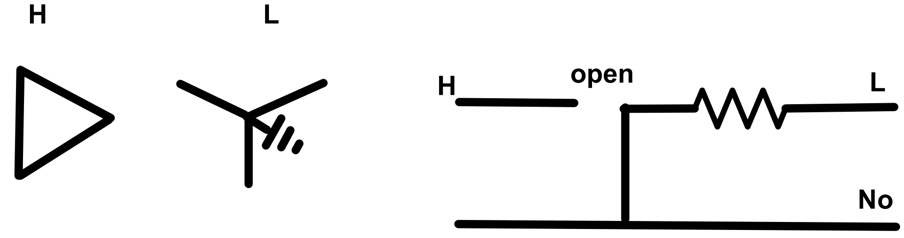

ONE TRANSFORMER CONTRIBUTION

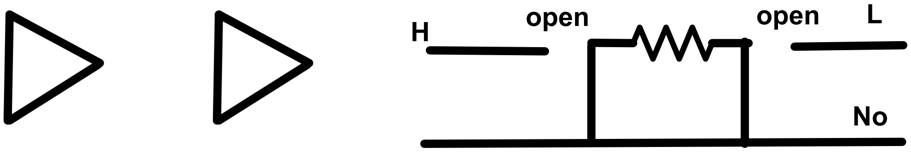
TOTAL BUS FAULT LINE TO GROUND 138 KV

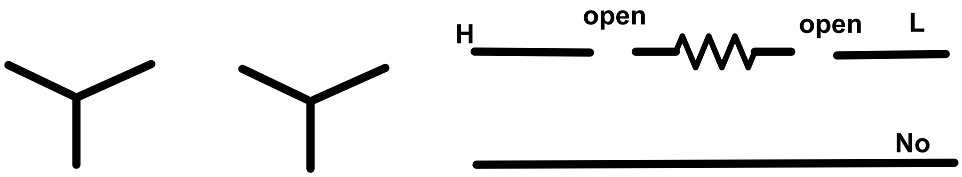
APPENDIX D

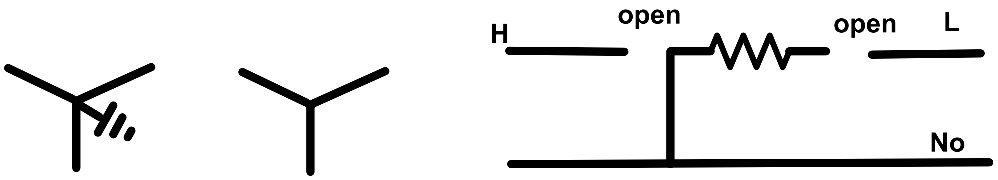
TRANSFORMERS CONNECTION WITH ISOLATION IN THE ZERO-SEQUENCE NETWORK





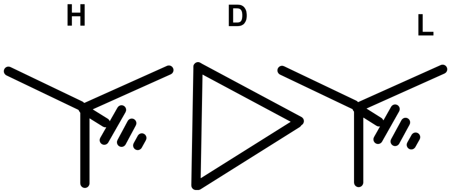


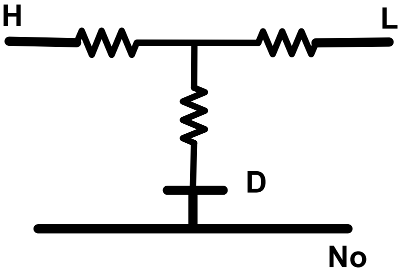


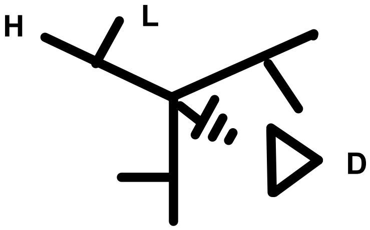


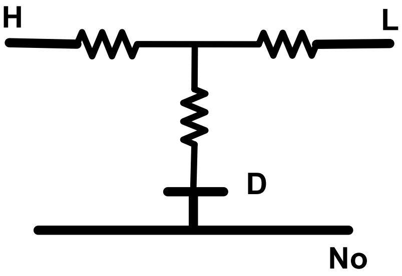
APPENDIX E

TRANSFORMERS CONNECTION WITHOUT ISOLATION IN THE ZERO-SEQUENCE NETWORK









Back to Table of Contents