Grounding Transformers
And Their Impacts on Unfaulted-phase Voltage Rise

Seung Cho

Public Utility District No. 1 of Chelan County
Wenatchee, Washington

Presented at 37th Annual
Western Protective Relay Conference
Spokane, Washington
October 20, 2010

Grounding Transformers
And Their Impacts on Unfaulted-phase Voltage Rise

By
Seung Cho
Public Utility District No. 1 of Chelan County

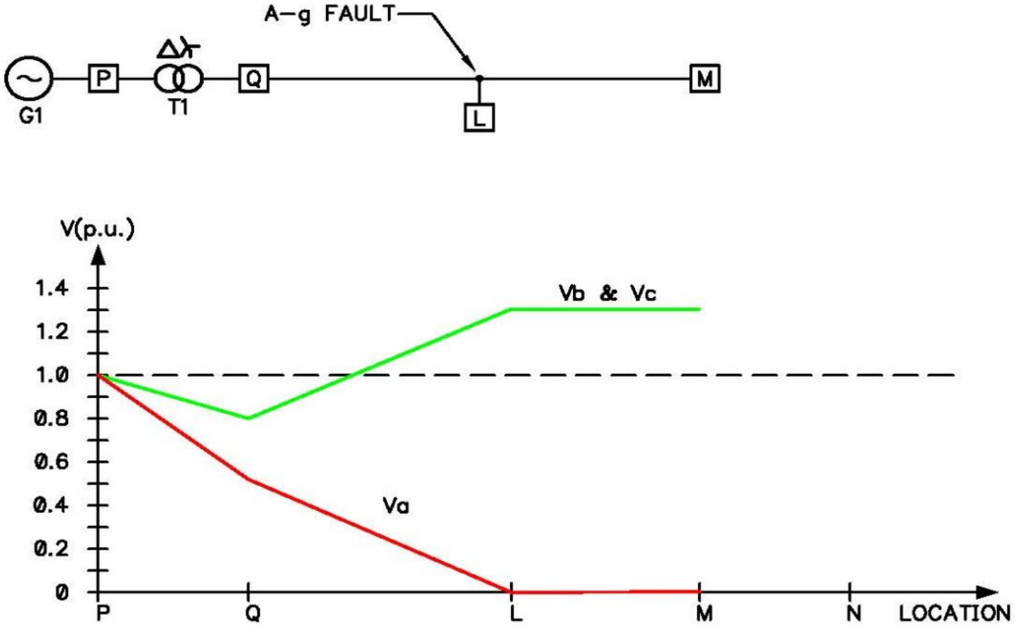
I. Introduction

North American Electric Reliability Corporation (NERC) has drafted PRC-024-1, Generator Frequency and Voltage Protective Relay Settings, to establish voltage ride-through requirements for generating facilities. NERC also requires voltage stability for bulk electric systems. For distribution systems, most of power quality problems are related to under/over-voltages. Therefore, it is more important now than ever for all relaying professionals to pay close attention to voltage variation even though, traditionally, short circuit currents have received more attention.

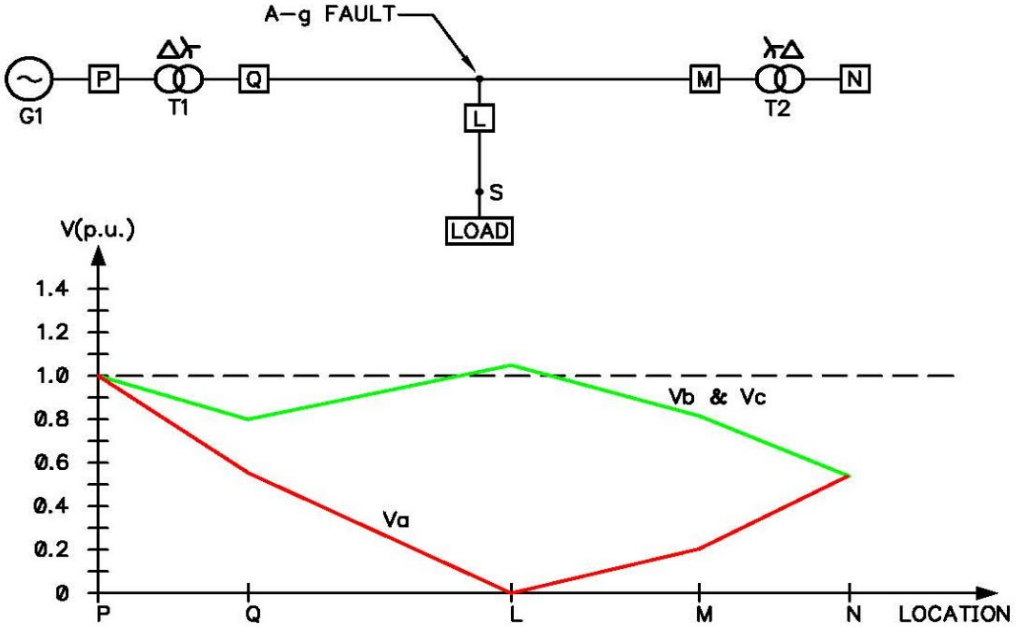
It is well known that single-line-ground (SLG) faults cause unfaulted-phase voltage rise that can reach up to 140% of the rated voltage[2][8]. It is also important to understand that line-line-ground (LLG) faults also cause the unfaulted-phase voltage rise but remote grounding transformers may cause significant unfaulted-phase voltage dip. The unfaulted-phase voltage rise and dip occur not only in distribution systems but also in bulk electric systems as generator step-up transformers become grounding transformers if the connected generators are taken out of service. Clearly, 140% of the rated voltage is not acceptable to most electrical equipment at all if it is sustained for a while, but as of now there is no unfaulted-phase voltage rise protection.

Years ago, an electric customer made a damage claim in which his appliance was damaged due to an electrical surge when a fault occurred near his house, but a utility electrical engineer denied the damage claim on the grounds that the fault occurred on A-phase, the customer's house was being fed from B-phase, and a substation relay recorded a slightly lower than normal voltage on B-phase. The utility electrical engineer's statements sound reasonable, but are they really right? Referring to Figure 1, the author sincerely hopes that this paper will help all relaying professionals clearly understand and recognize importance of the unfaulted-phase voltage rise and dip due to ground faults. Highlights of this paper are:

- NERC voltage ride-through requirements and Computer and Business Equipment Manufacturers' Association (CBEMA) curve
- Unfaulted-phase voltage rise, up to 140% of the rated, due to SLG and LLG faults
- Two formulas for estimating the unfaulted-phase voltage rise
- Unfaulted-phase voltage dip due to remote grounding transformer(s)
- Factors influencing the unfaulted-phase voltage rise and dip



a) Without remote grounding transformer



b) With remote grounding transformer

Figure 1. Voltage profiles with and without remote grounding transformer for A-g fault (*Note: Not scaled for simplicity and illustration purposes*)

II. NERC Voltage Ride-through Requirements

NERC Standard PRC-024-1, Generator Frequency and Voltage Protective Relay Settings, has been drafted and is expected to be a new standard in the near future. The significance of the proposed standard, from the author's engineering standpoint, is:

- Specifically at the point of generation interconnection
- Emphasis on steady-state and dynamic voltage stability
- Philosophical change from "trip as soon as possible" to "stay as long as possible or no trip zone" for bulk electric system reliability
- No specific consideration yet for unfaulted-phase voltage rise
- No consideration yet for distribution customers' power quality, referring to Figure 2 (NERC voltage ride-through "no trip zone" different from CBEMA voltage ride-through characteristics)

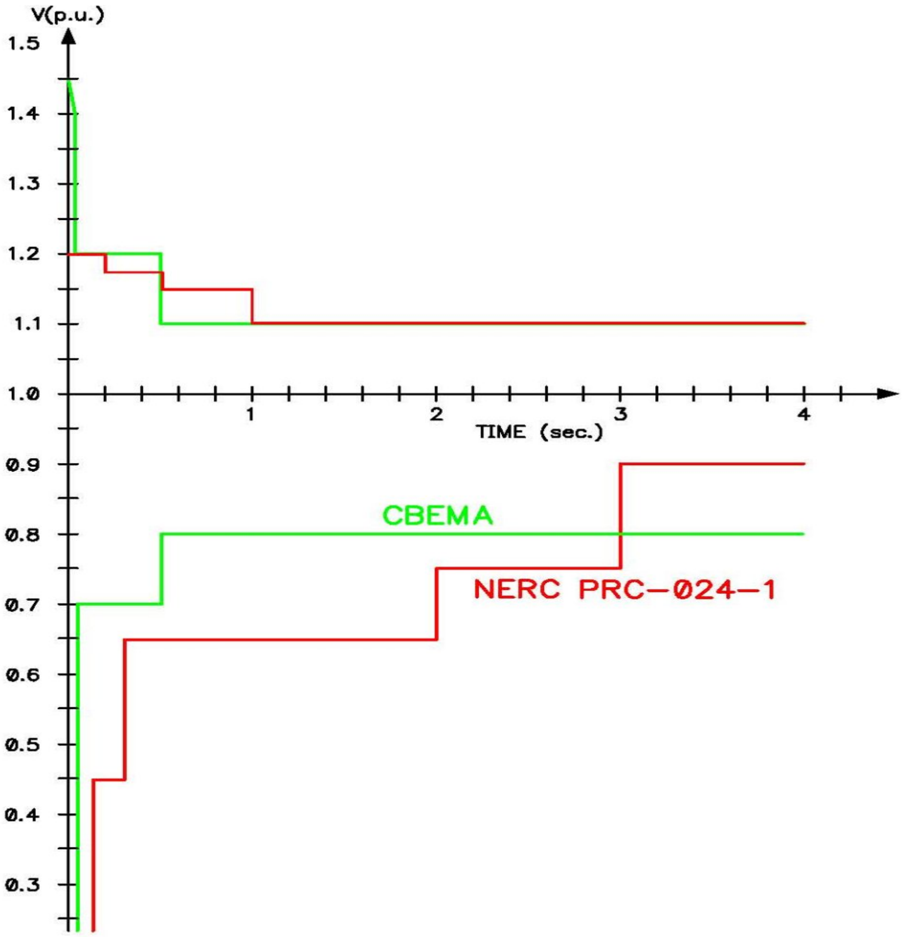


Figure 2. NERC voltage ride-through requirements and CBEMA curve

III. Fundamentals of Grounding Transformer

Grounding transformers are specifically for establishing a grounded neutral for ungrounded systems and supplying only the zero-sequence current $3I_0$ without any positive-sequence current I_1 and negative-sequence current I_2 in case of ground faults, as illustrated in Figure 3, but they are installed sometimes even on grounded systems. It appears that the most common grounding transformer in the Northwest is the delta/Y-ground-connected transformer.

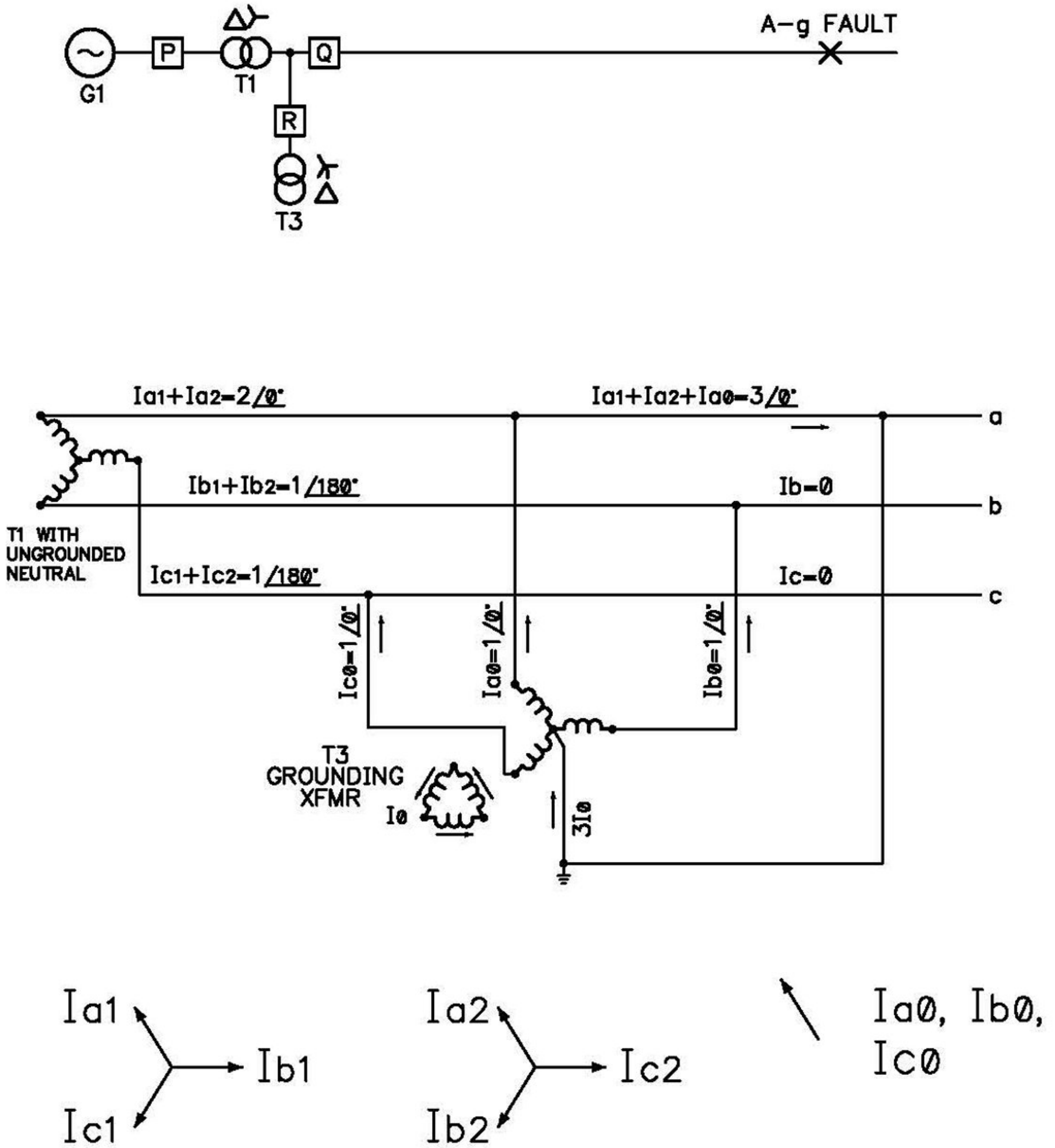


Figure 3. $3I_0$ contribution from grounding transformer

A zig-zag grounding transformer[6][7] is a 3-phase auto-transformer or a bank of 3 single-phase auto-transformers with no secondary winding. Each phase has 2 identical windings, which are wound in opposite directions to give high impedance to normal phase currents. The windings are connected in a Y configuration and the neutral point is connected either directly or through a neutral grounding resistor to ground, as illustrated in Figure 4. It is the most cost-effective means of establishing a grounded neutral and, functionally, it works the same as a typical delta/Y-grounded grounding transformer. To specify a zig-zag or delta/Y-grounded grounding transformer, the line-line voltage of the system, desirable magnitude of the neutral current, duration (typically 10 or 60 seconds) of the neutral current, and system impedance are required.

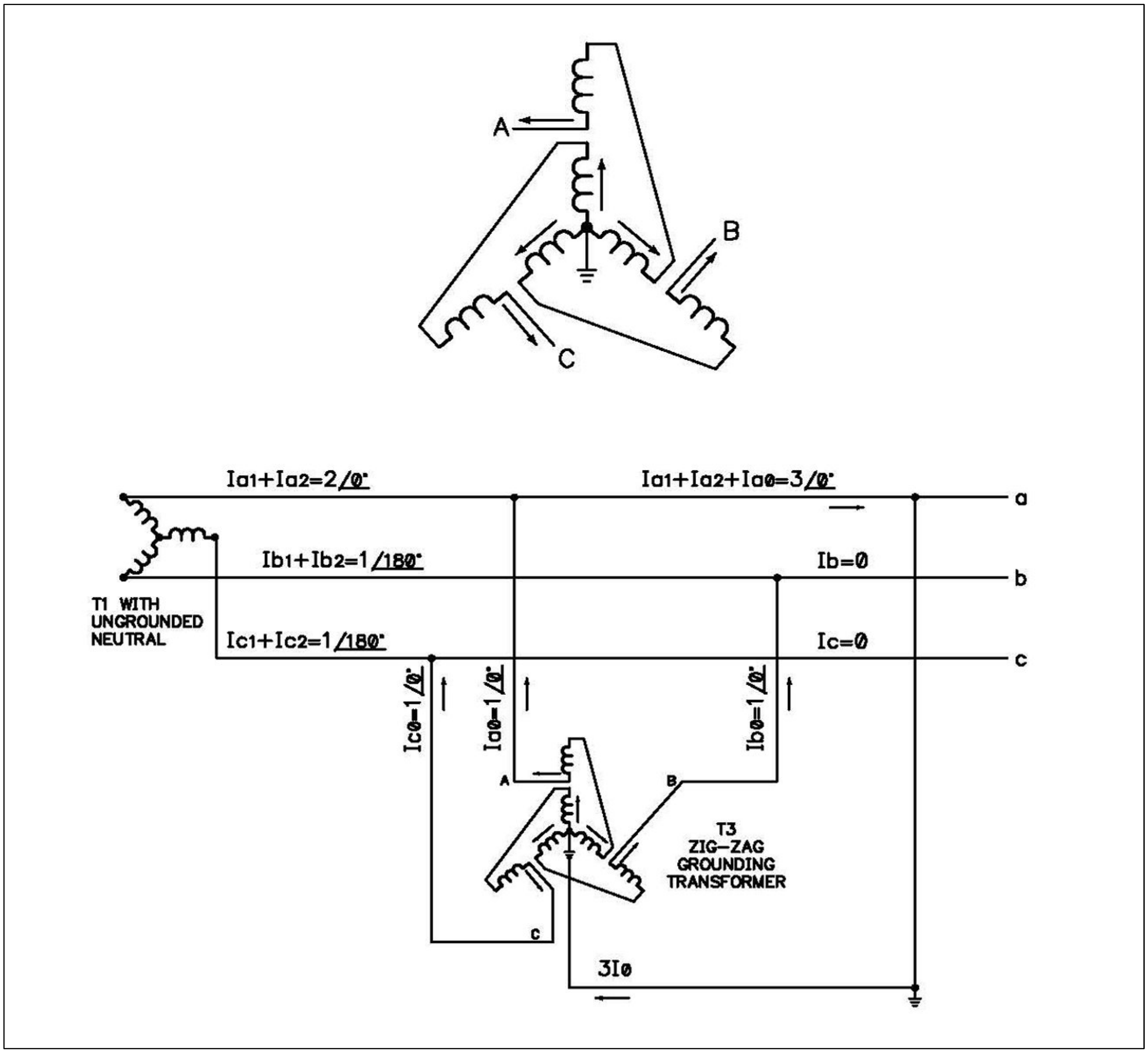


Figure 4. Typical zig-zag grounding transformer connection

Referring to Figure 5, almost all generator stepup transformers, including the independent power producers' stepup transformers, are connected in delta on the generator side and Y-grounded on the line side. Those generator stepup transformers connected in delta/Y-ground are not typically considered as grounding transformers, but they are grounding transformers if the connected generators are taken out of service. In addition, theoretically and conceptually, a delta/Y-grounded transformer is the same as a delta/Y transformer plus a delta/Y-grounded grounding transformer (or a zig-zag grounding transformer).

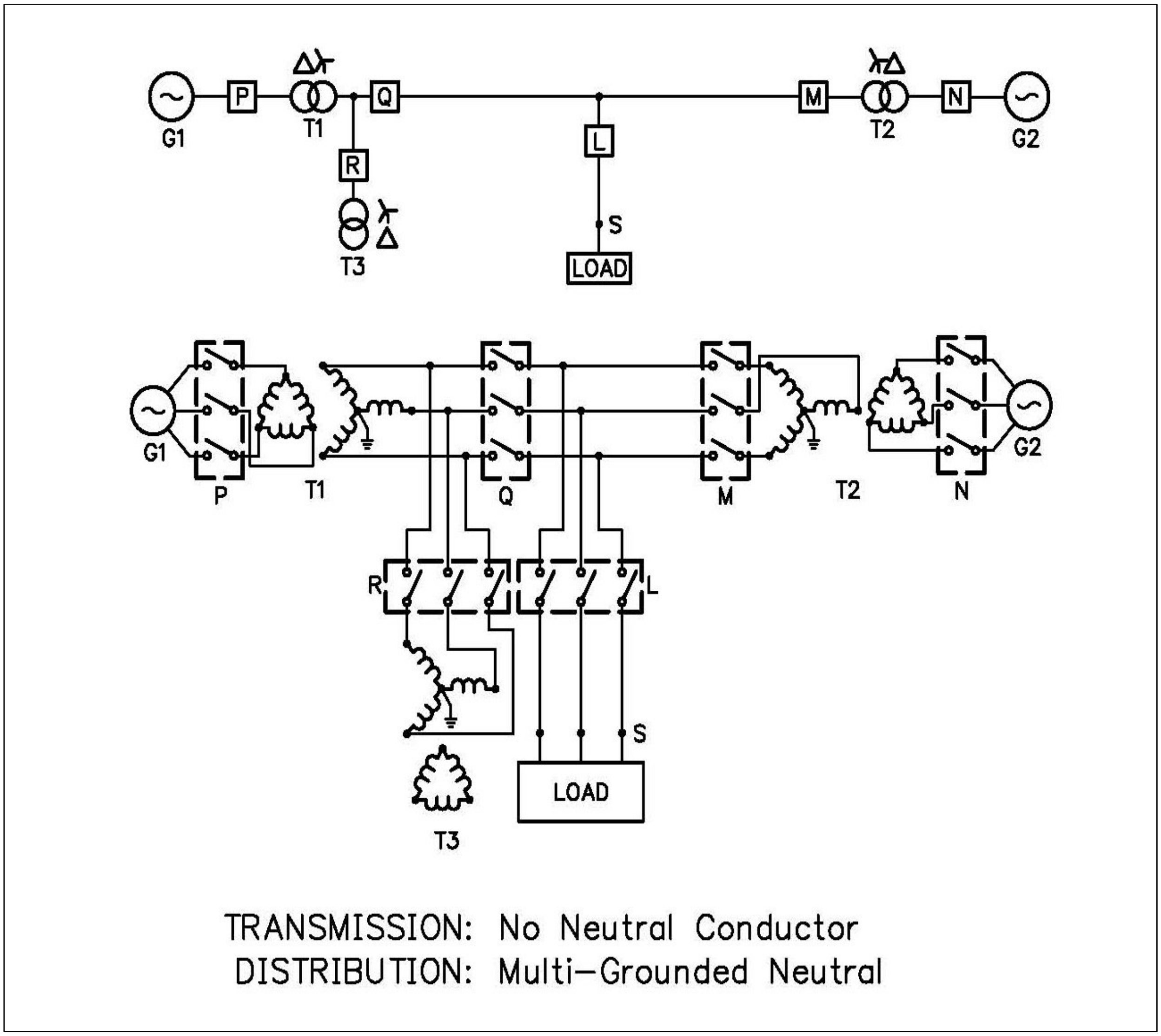


Figure 5. Simplified, typical electrical system

IV. Unfaulted-phase Voltage Rise

In general, it appears that the unfaulted-phase voltage rise due to neutral shift in case of ungrounded systems is intuitive, but the unfaulted-phase voltage rise due to ground faults in case of grounded systems is much less intuitive. The best way to develop such intuition is to understand not necessarily mathematical formulas but rather concepts, so the author’s primary approach will be more graphical than mathematical in this section and throughout this paper (*Note: A technical paper on this topic was presented by the author at 2006 Western Protective Relay Conference*[8].).

4.1 Unfaulted-phase Voltage Rise in Case of SLG Fault

Referring to Figure 6, the unfaulted-phase voltage rise in case of SLG faults in the solidly grounded systems can be explained easily with a graphical analysis method as illustrated and further detailed below:

- **Voltage drop V_{ng} across the neutral and ground:** It can be very significant and can be larger than the line voltage drop V_{line} in the following equations:

$$Va = Ea - Vline - Vng = 0.$$

$$\dot{Vb} = \dot{Eb} + \dot{Vng}$$

- If $Z_1 = Z_2$, $3R_f = 0$, $\mathbf{Z_0 \equiv Z_1 + (Z_0 - Z_1)}$, $\mathbf{Z_0 > Z_1}$, $Z_0 / Z_1 \equiv K$, and $Z_1 = 1$ p.u., then

$$Vng = Ea\,\frac{K-1}{K+2}$$

- If X >> R and no load (*Note:* $Ea\,\frac{K-1}{K+2}$ *is not a vector in the following equation.*), then

$$Vb \approx \sqrt{0.75 + (0.5 + Ea\,\frac{K-1}{K+2})^2}$$

- If Ea = 1 p.u., then

$$\boldsymbol{Vb \approx \sqrt{0.75 + (0.5 + \frac{K-1}{K+2})^2}}$$

- **Practical maximum unfaulted-phase voltage rise of 140%**: The Z_0/Z_1 ratio rarely exceeds 5 in electrical utility transmission and distribution systems. For $Z_0/Z_1 = 5$, the calculated unfaulted-phase voltage rise is 138% and so the practical maximum unfaulted-phase voltage rise in case of SLG faults is determined to be 140%.

- **Typically, Vb > Vc**: For simplicity, Figure 6 assumes Vb = Vc, but in reality Vb is typically greater than Vc, due to lagging power factor and presence of the resistive element.

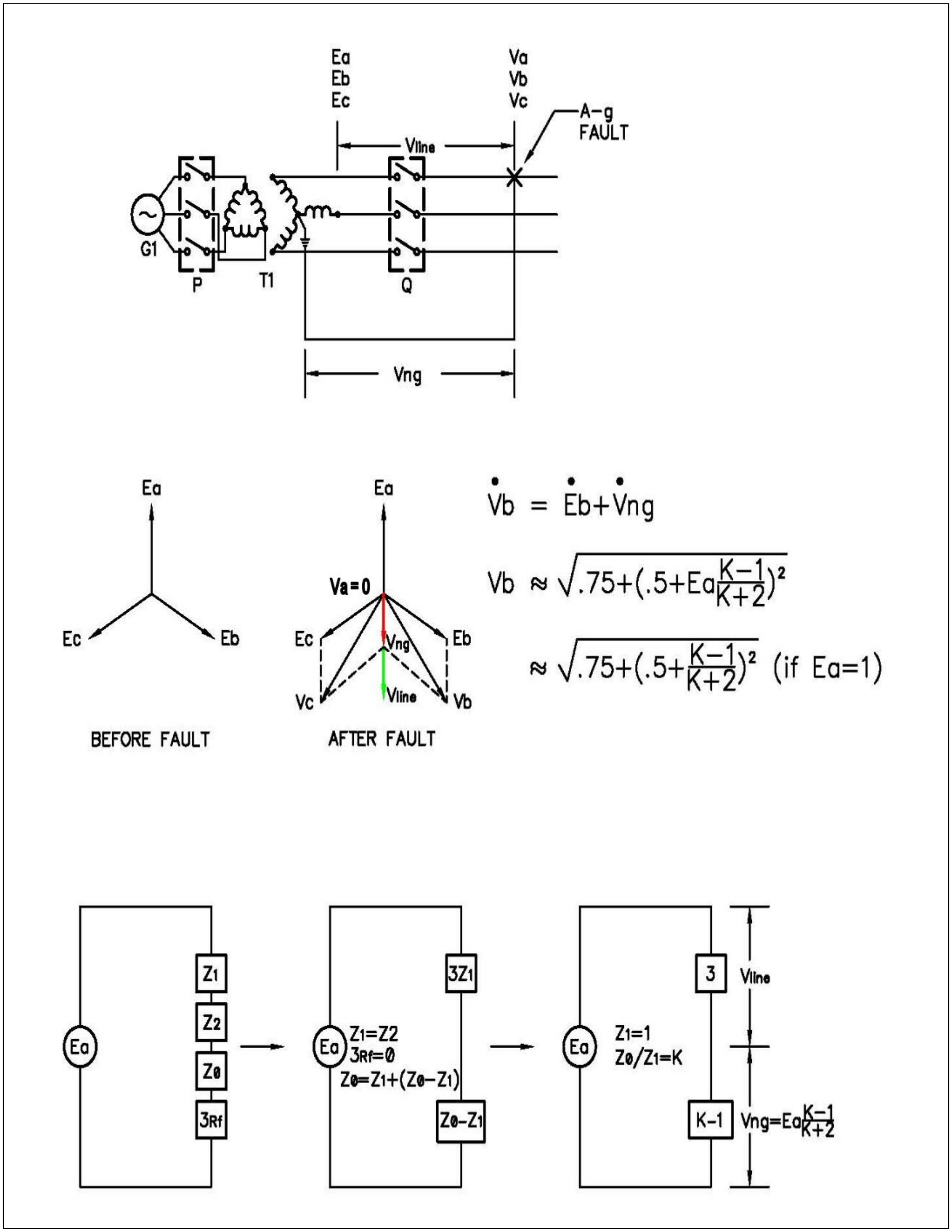


Figure 6. Unfaulted-phase voltage rise in case of SLG fault

4.2 Unfaulted-phase Voltage Rise in Case of LLG Fault

Referring to Figure 7 (*Note: It is customary to use A-phase for sequence network construction as shown in Applied Protective Relaying[3], but the author uses B-phase in this paper simply because it is easier to visualize the fault current flow and develop the unfaulted-phase voltage rise formula. The author sincerely hopes that it is not too confusing to readers of this paper.*), derivation of the unfaulted-phase voltage rise in case of LLG faults is very similar to that for SLG faults except a few details as shown below:

- If $Z_1 = Z_2$, $3R_f = 0$, $\mathbf{Z_0 \equiv Z_1 + (Z_0 - Z_1)}$, $\mathbf{Z_0 > Z_1}$**,** $Z_0 / Z_1 \equiv K$, and $Z_1 = 1$ p.u., then V_{ng} in phase with the unfaulted-phase voltage Ea can be calculated easily as:

$$Vng \approx Eb\,(\frac{K-1}{2K+1})$$

- The unfaulted-phase voltage Va can be calculated as (*Note:* $Eb\,(\frac{K-1}{2K+1})$ *is not a vector in the following equation.*):

$$Va \approx Ea + Vng = Ea + Eb\,(\frac{K-1}{2K+1})$$

- If Ea = Eb = 1 p.u., then:

$$\boldsymbol{Va \approx \frac{3K}{2K+1}}$$

- **Practical maximum unfaulted-phase voltage rise of 140%**: The Z_0/Z_1 ratio rarely exceeds 5 in electrical utility transmission and distribution systems. For $Z_0/Z_1 = 5$, the calculated unfaulted-phase voltage rise is 136% and so the practical maximum unfaulted-phase voltage rise in case of LLG faults is determined to be also 140%.

4.3 Formula Application Notes

All formulas should be applied correctly and each formula may have a set of conditions and assumptions for accuracy and validity. As always, any use beyond those conditions and assumptions may result in an inaccurate and/or erroneous answer. Two formulas developed and presented by the author in this paper are very simple but powerful tools all relaying professionals can use to estimate the unfaulted-phase voltage rise due to ground faults for SLG and LLG faults. They are not for estimating the unfaulted-phase voltage dip but specifically for estimating the unfaulted-phase voltage rise. One important application condition is that $\mathbf{Z_0}$ **should be greater than** $\mathbf{Z_1}$ because "$Z_0 < Z_1$" typically means "no unfaulted-phase voltage rise."

The formula, Va = {3K / (2K + 1)}, has not been presented yet anywhere else, but its validity and accuracy have been verified through a series of simulation studies and also by comparing simulated results with real-life digital fault recorder recordings.

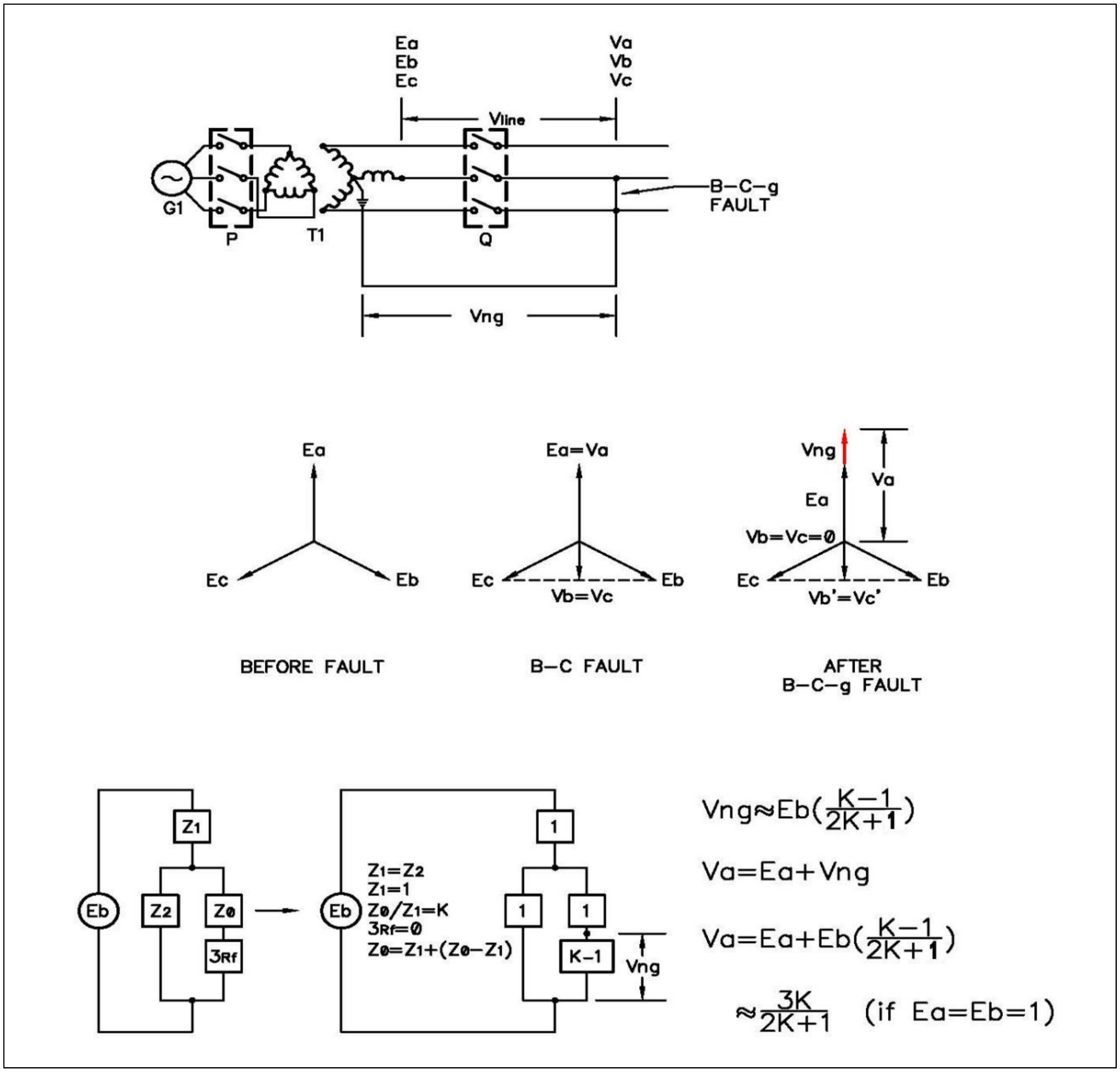


Figure 7. Unfaulted-phase voltage rise in case of LLG fault

V. Unfaulted-phase Voltage Dip

In the previous section the unfaulted-phase voltage rise has been a main focus because that is a more common occurrence in electrical utility distribution systems, typically radial. However, a system with a remote grounding transformer or a generator stepup transformer with the connected generator(s) out of service, as shown in Figures 8 and 9, may experience a voltage dip on the unfaulted-phase(s) instead of the typical voltage rise. A primary objective of this section is to make the unfaulted-phase voltage dip intuitive to all relaying professionals.

5.1 Unfaulted-phase Voltage Dip in Case of SLG Fault

Referring to Figure 8, the simplest and best approach to understand the unfaulted-phase voltage dip, from the author's viewpoint, is to think that a single 3-phase source feeds the same fault in two different ways as:

- Primary source Ea feeds the A-g fault ($3I_0$ to the fault) and Va at the fault is zero.
- Secondary sources, Eb and Ec, excite the remote 3-phase grounding transformer and then the grounding transformer feeds the same A-g fault (*Note:* ***Vng is 180 degrees out of phase from Vng,*** $_{T2}$***. Vng causes the voltage rise but Vng,*** $_{T2}$ ***causes the voltage dip***.).

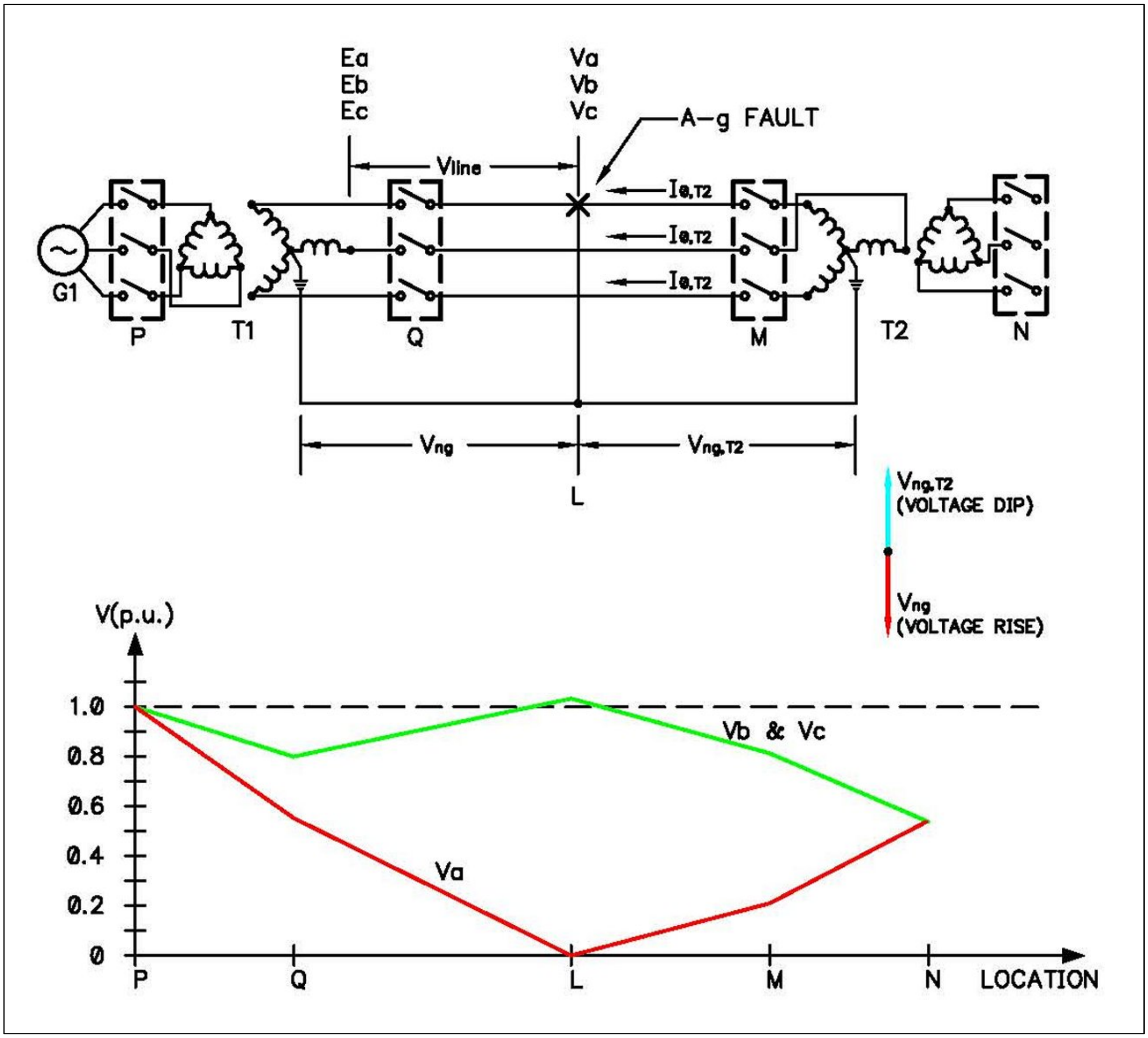


Figure 8. Unfaulted-phase voltage dip due to grounding transformer in case of SLG fault (*Note: Not scaled for simplicity and illustration purposes*)

5.2 Unfaulted-phase Voltage Dip in Case of LLG Fault

Referring to Figure 9, the simplest and best approach, again, is to think that a single 3-phase source feeds the same fault in two different ways as:

- Primary sources, Eb and Ec, feed the B-C-g fault and Vb and Vc at the fault are zero.
- Secondary source, Ea, excites the remote 3-phase grounding transformer and then the grounding transformer feeds the same B-C-g fault (*Note:* ***Vng is 180 degrees out of phase from Vng,T2. Vng causes the voltage rise but Vng,T2 causes the voltage dip***.).

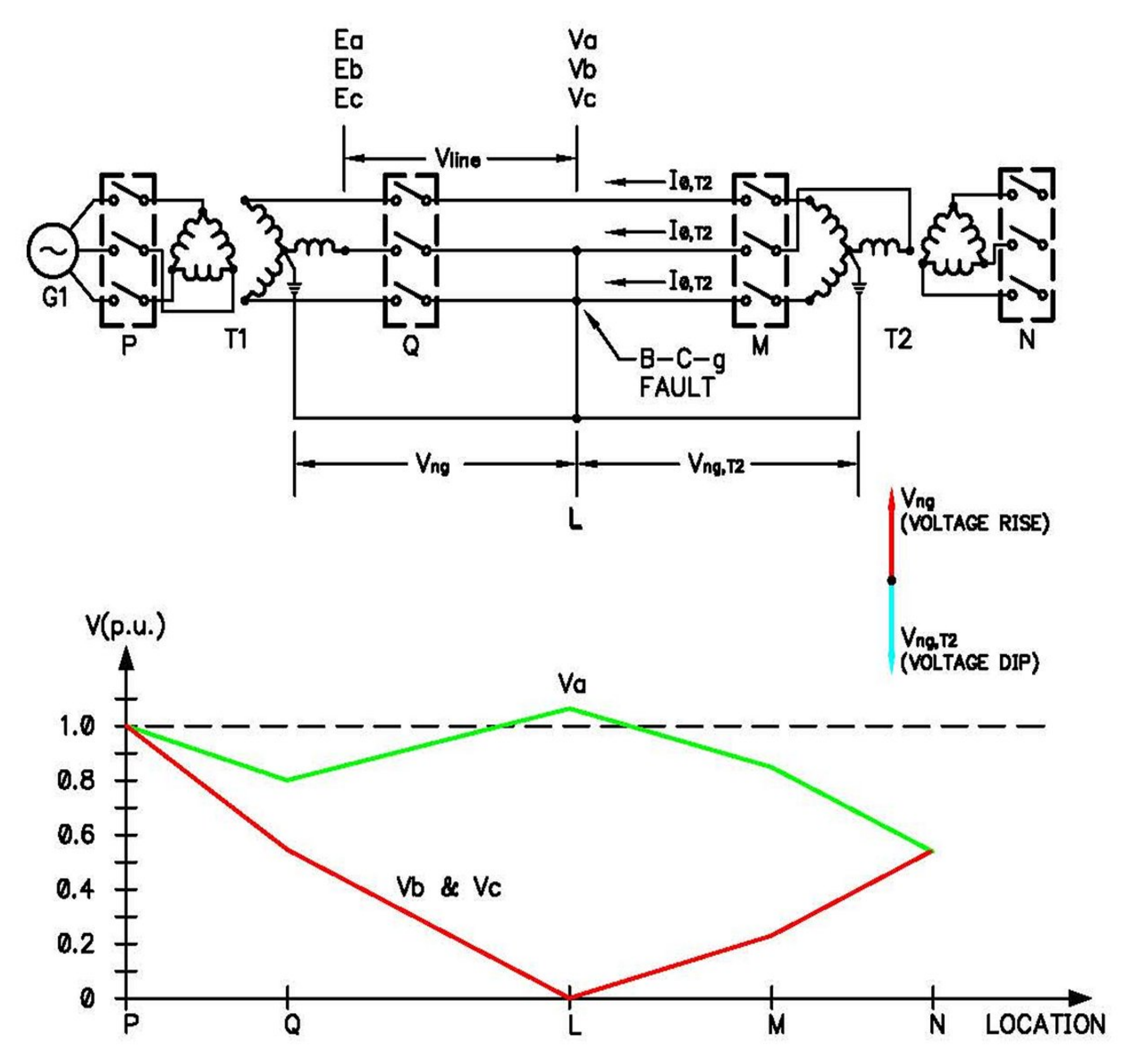


Figure 9. Unfaulted-phase voltage dip due to grounding transformer in case of LLG fault (*Note: Not scaled for simplicity and illustration purposes*)

VI. Protective Relaying Consideration of Unfaulted-phase Voltage Variation, Rise or Dip

6.1 Factors Affecting Unfaulted-phase Voltage

Referring to Figure 10, the following factors influence the unfaulted-phase voltage variation, rise or dip:

- Grounding transformer location: local or remote
- Circuit type: radial or loop
- Z_0/Z_1 ratio (i.e., $K \equiv Z_0/Z_1$):
  - Circuit type: overhead or underground
  - Ground current return path type: neutral conductor or no neutral conductor
- Generator stepup transformer: with or without the connected generator(s) in service
- Independent power producer's generator stepup transformer: with or without the connected generator(s) in service
- Fault type: SLG or LLG
- Fault location
- Fault resistance
- Loading: single-phase or three-phase
- Load size and location
- Customer location
- System configuration: normal or abnormal

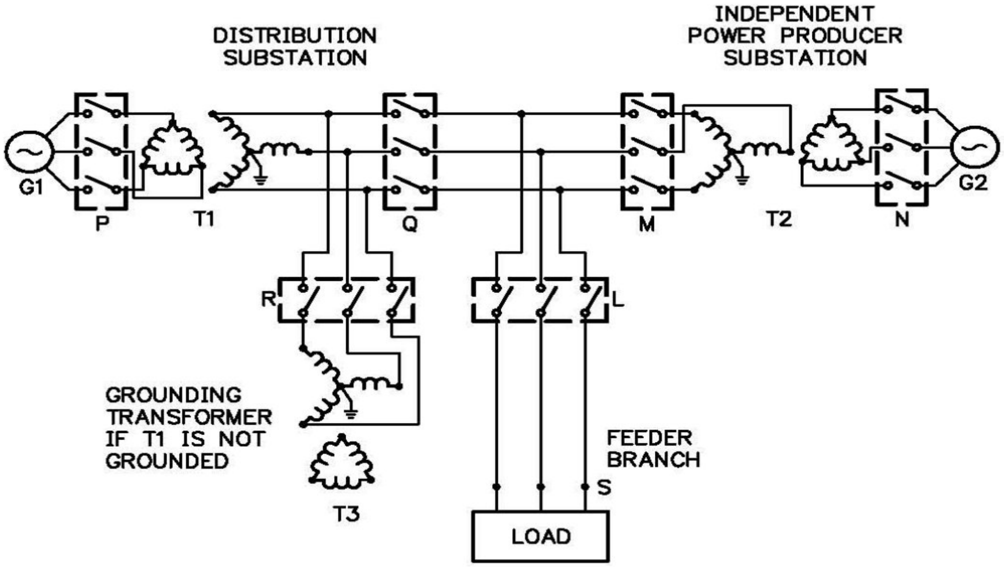


Figure 10. Typical distribution system

6.2 Protective Relaying Issues

At this point, no protective relays actually calculate or detect the unfaulted-phase voltage rise or dip at the fault, so it is not customary for utilities or relay manufacturers to be seriously concerned about the unfaulted-phase voltage rise reaching up to 140% of the rated or the unfaulted-phase voltage dip due to presence of remote grounding transformer(s). However, it is very clear to the author that the unfaulted-phase voltage rise may result in premature failure or accelerated aging of transformers and other equipment over time and so it is desirable to have an unfaulted-phase voltage rise protection. Some potential relaying implementation issues are:

- Inadequate understanding of the unfaulted-phase voltage rise and dip
- Difficult for substation relays to estimate the unfaulted-phase voltage rise and dip at the fault
- Modern digital relays without the inverse voltage-time characteristic
- No direct relationship between the faulted-phase short circuit current and the unfaulted-phase voltage at the fault
- Surge arresters manufactured in accordance with ANSI/IEEE C62.11 should be able to withstand 140% of the nominal voltage indefinitely. Therefore, surge arresters will not do anything when the unfaulted-phase voltage rise reaches up to 140% of the nominal.
- In accordance with the latest CBEMA curve, the maximum tolerable duration at 140% of the nominal voltage is 3 milliseconds. Therefore, no matter how fast a fault is cleared, operation of some digital electronic equipment will be impacted by the unfaulted-phase voltage rise.
- Switching from the fuse-saving scheme to the trip-saving scheme
- Based on the General Guide for Permissible Short-time Over-excitation of Power Transformers (*Note: Not readily available for distribution transformers, but distribution transformers are also built in accordance with ANSI/IEEE C57.12.*), the permissible duration at 140% of the nominal voltage is approximately 10 seconds. It is not difficult for a relay to clear a fault in 10 seconds, but there is not any relay designed specifically for unfaulted-phase voltage rise protection.

VII. Conclusion

The unfaulted-phase voltage rise (overvoltage) due to ground faults in case of ungrounded systems is intuitive, but the unfaulted-phase voltage rise due to ground faults in case of grounded systems is much less intuitive. However, the unfaulted-phase overvoltage due to ground faults can seriously damage electrical equipment as the faulted-phase overcurrent can. The author's primary objective was to help all relaying professionals develop intuition for the unfaulted-phase voltage rise and also the unfaulted-phase voltage dip due to presence of remote grounding transformer(s). As a summary, the following conclusions are presented:

- For grounded systems, ground faults, both SLG and LLG, cause not only the faulted-phase voltage dip (undervoltage) and short circuit current flow but also the unfaulted-phase voltage rise (overvoltage). Therefore, the **unfaulted-phase voltage rise is as important as the faulted-phase short circuit current** or voltage dip.

- The **unfaulted-phase voltage rise in case of SLG faults** can be estimated with a simple formula, where K is defined as Z_0/Z_1 ratio:

$$V_{\text{unfaulted-phase}} = \sqrt{\mathbf{0.75} + \left(\mathbf{0.5} + \frac{\boldsymbol{K} - \mathbf{1}}{\boldsymbol{K} + \mathbf{2}}\right)^{\mathbf{2}}} \quad \boldsymbol{in\ p.u.}$$

- The **unfaulted-phase voltage rise in case of LLG faults** can be estimated with a simple formula, where K is defined as Z_0/Z_1 ratio:

$$V_{\text{unfaulted-phase}} = \frac{\mathbf{3}\boldsymbol{K}}{\mathbf{2}\boldsymbol{K} + \mathbf{1}} \quad \boldsymbol{in\ p.u.}$$

- For overhead conductor circuits ($K < 5$) and all practical purposes, the unfaulted-phase voltage can be high but should be less than **140%** of the rated voltage for both SLG and LLG faults. For underground cable circuits ($K < 3$), the unfaulted-phase voltage can be high but should be less than **130%** of the rated voltage.
- A remote grounding transformer can reduce the unfaulted-phase voltage rise and, in fact, can also cause the **unfaulted-phase voltage dip**.
- **Unfaulted-phase voltage rise protection** for grounded systems should be considered, as needed, in the near future.

The author sincerely hopes that this technical paper may be of some value to the 37th Western Protective Relay Conference attendees and may help all relaying professionals develop intuition for the unfaulted-phase voltage rise and also the unfaulted-phase voltage dip due to remote grounding transformer(s).

References:

1. J. Lewis Blackburn, Protective Relaying Principles and Applications, published by Marcel Dekker, Inc.
2. J. Lewis Blackburn, Symmetrical Components for Power System Engineering, published by Marcel Dekker, Inc.
3. Westinghouse, Applied Protective Relaying, published by Westinghouse Electric Corporation
4. R.L. Bean, N. Chackan, Jr., H.R. Moore, and E.C. Wentz, Transformers for the Electric Power Industry, published by Westinghouse Electric Corporation
5. L.F. Blume, Transformer Engineering: A treatise on the theory, operation, and application of transformers, published by John Wiley and Sons
6. General Electric, GET-2J Transformer Connections including Autotransformer Connections
7. A.C. Franklin and D.P. Franklin, J and P Transformer Book, published by Butterworths
8. Seung Cho, Unfaulted-phase Voltage & Current Rises and Their Impacts to Relaying, presented at 33rd Western Protective Relay Conference in 2006