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Unfaulted-phase Voltage & Current Rises and Their Impacts to Relaying

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I Introduction

It is well known that single-line-to-ground faults (SLG faults hereafter) occur most frequently in the solidly grounded system and unfaulted-phase voltages & currents may rise significantly in case of SLG faults. Based on the review of damage claims and complaints in the past, the author noticed that the number of damage claims and complaints coming from customers connected to unfaulted phases had been increasing noticeably, and that a primary cause of those damages might have been the **voltage rises up to 140%** in case of SLG faults on distribution feeders. In addition, the author has also noticed that the unfaulted-phase currents in case of transmission SLG faults are noticeably high, based on current waveforms recorded by modern-day digital relays and fault recorders. Surprisingly, it is not uncommon to see the unfaulted-phase currents **as high as 25%** of the faulted phase current and, in fact, one recorded event actually indicated that the **unfaulted-phase currents were higher than the faulted-phase current**.

Referring to Figure 1, Voltage & Current Waveforms for B-Ground SLG Faults, it illustrates the following:

- **Voltage rise due to current flow through the neutral and ground**: Referring to Figure 1.a), the unfaulted-phase voltage (Vc) at a substation approximately 45 miles from a b-g SLG fault location reached **112.4%** of the nominal 66.4kV, which implies 130.6% at the fault location.
- **Current rise due to mutual coupling between phases**: Referring to Figure 1.b), the unfaulted-phase currents (Ia & Ic) 180 degrees out of phase from the faulted-phase current (Ib) reached **13.3%** of the faulted-phase current for a b-g SLG fault on a 115kV transmission line interconnecting two hydro-plants. These currents disappeared upon opening of the remote circuit breaker.
- **Current rise due to mutual coupling between phases and between circuits**: Referring to Figure 1.c), the unfaulted-phase currents (Ia & Ic) 180 degrees out of phase from the faulted-phase current (Ib) reached **16.4%** of the faulted-phase current for a b-g SLG fault on a looped 115kV transmission line.
- **Current rise due to mutual coupling and grounding bank**: Referring to Figure 1.d), the unfaulted-phase currents (Ia & Ic) in phase with the faulted-phase current (Ib) were actually much higher than the faulted-phase current, called "**Current Magnitude Reversal**" in this paper.

The author briefly talked about the unfaulted-phase voltage & current rises at the annual Western Protective Relay Conference in the past[5], but the author feels that not enough serious consideration or attention has been given to this important topic. Therefore, this paper is intended to explain how the unfaulted-phase voltage & current rises might occur and also to explore their potential impacts to relaying.

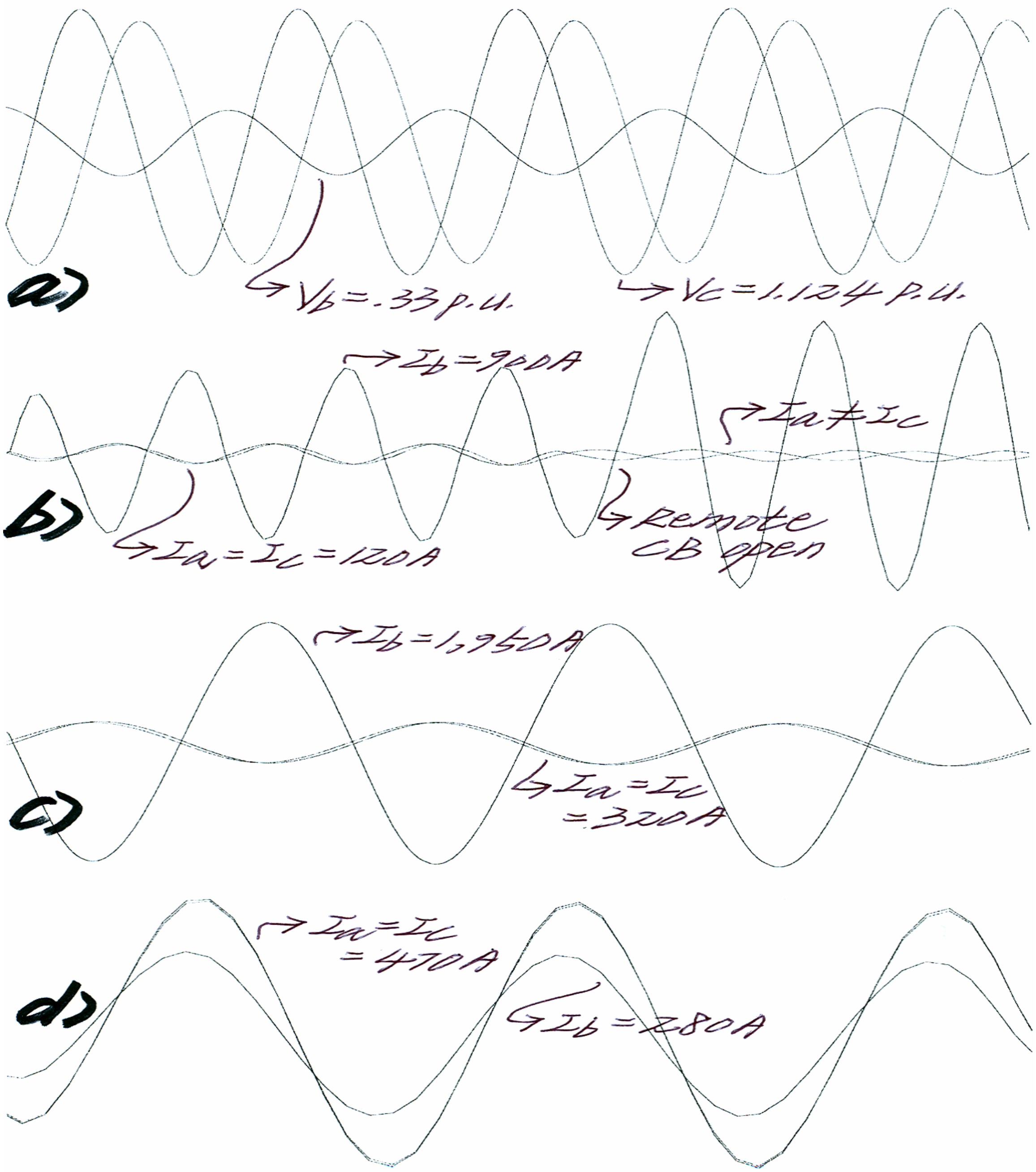

Figure 1. Voltage & Current Waveforms for B-Ground SLG Faults

II Unfaulted-phase Voltage Rise

2.1 Unfaulted-phase Voltage Rise in Radial Distribution Feeders

Referring to Figure 2, Graphical Analysis of Unfaulted-phase Voltage Rise, the unfaulted-phase voltage rise in the solidly grounded systems can be explained easily with a graphical analysis method as illustrated and further detailed below:

- **Voltage rise, due to zero-sequence current flowing through the neutral and ground, seen by the unfaulted-phase equipment connected line to ground**: Referring to Figure 2.b), the fault current (Ia = 3I0) circulates through a-phase stepdown transformer winding, a-phase conductor, fault resistance (Rf), and neutral conductor & ground in parallel. Also, it can be seen that the unfaulted-phase voltage (VbQ) at the a-g fault location (Q) is the vector sum of b-phase line-ground voltage (Eb) and voltage drop due to 3I0 flowing through the neutral and ground.
- **Voltage profile along the distribution feeder**: Referring to Figure 2.c), it can be seen that the unfaulted-phase voltage (Vb) reaches the highest at the a-g fault location (Q) and all b-phase customers beyond Q see the same high voltage.
- **Simple voltage divider circuit**: Referring to Figure 2.d), it can be seen that the voltage drop (Vng) is a simple voltage divider or equal to **{Ea x (K-1)/(K+2)}**.
- **Voltage rise calculation**: Referring to Figure 2.e), it can be seen graphically that the unfaulted-phase voltage (VbQ) at the a-g fault location (Q) is simply **a vector sum of Eb and Vng**. In general, the angle between Eb and Vng is smaller than 60 degrees, so the actual VbQ is likely to be bigger than the calculated as long as the fault resistance Rf is 0.

X0/X1 = K	**Vunfaulted in p.u.** (calculated graphically)	**Vunfaulted in p.u.** (simulated with short circuit analysis)
2	1.146	
3	1.249	
4	1.323	
5	1.378	
2.38 at transmission tap 1		1.19
3.18 at transmission tap 2		1.29
3.9 for distribution feeder 1		1.36
3.1 for distribution feeder 2		1.29

- **Practical maximum unfaulted-phase voltage rise**: The X0/X1 ratio rarely exceeds 5 in both radial distribution and looped transmission and the actual voltage rise is likely to be somewhat higher than the calculated, so the practical maximum unfaulted-phase voltage rise has been determined to be **140%**.

- **Lewis Blackburn's formula**[2]: Referring to Figure 2.f), the formula is included in Symmetrical Components for Power System Engineering authored by Lewis Blackburn and it yields exactly the same results as the graphical method does.
- **Symmetrical component analysis**: For a-g SLG faults, Vb at the fault = a^2 x (Ea – Ia1 x Z1) + a x (- Ia2 x Z2) + (- Ia0 x Z0) in our typical symmetrical component analysis[2,3]. The symmetrical component analysis should yield exactly the same results as the graphical method does.

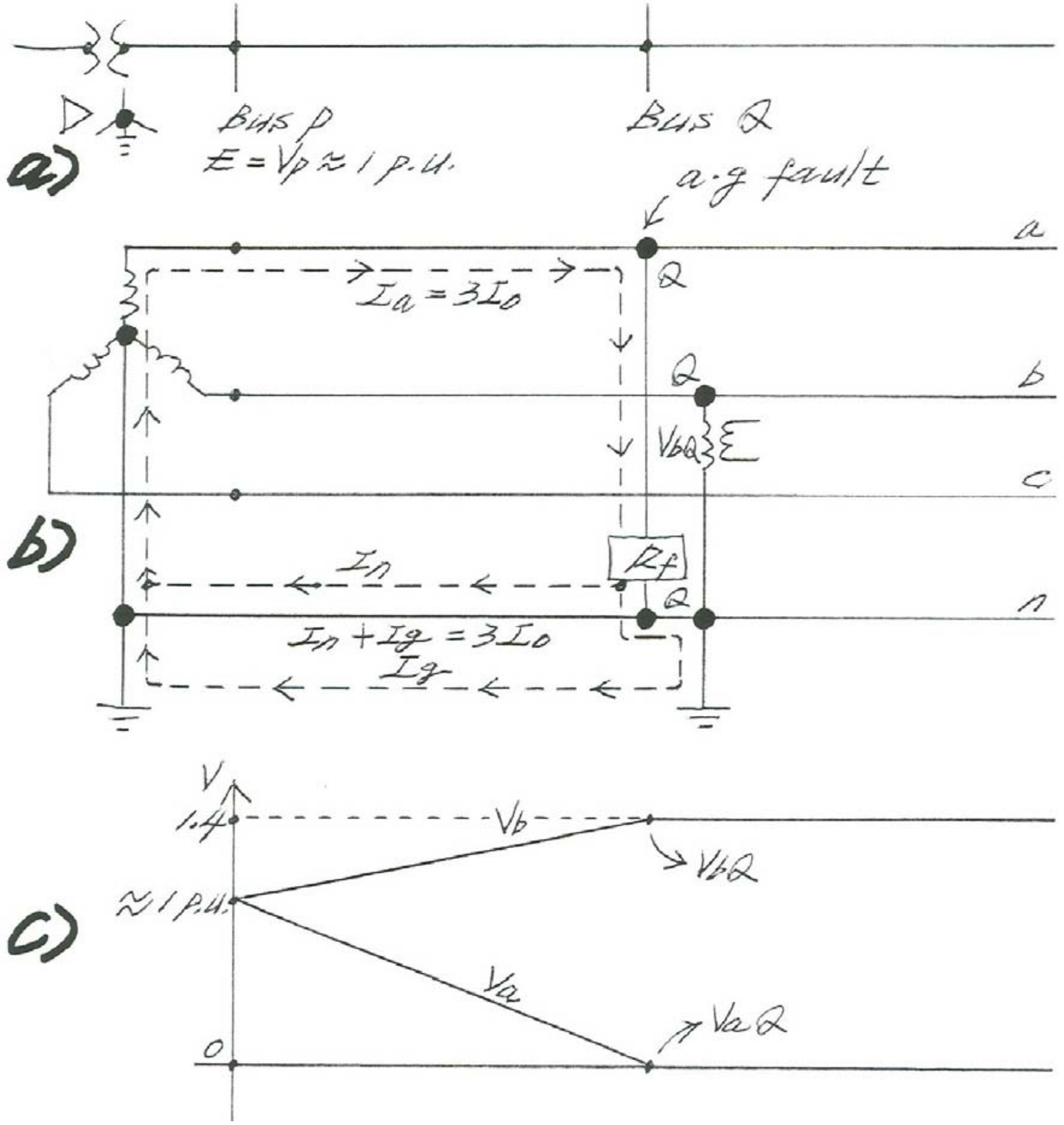

Figure 2. Graphical Analysis of Unfaulted-phase Voltage Rise
(simplified for illustration purposes)

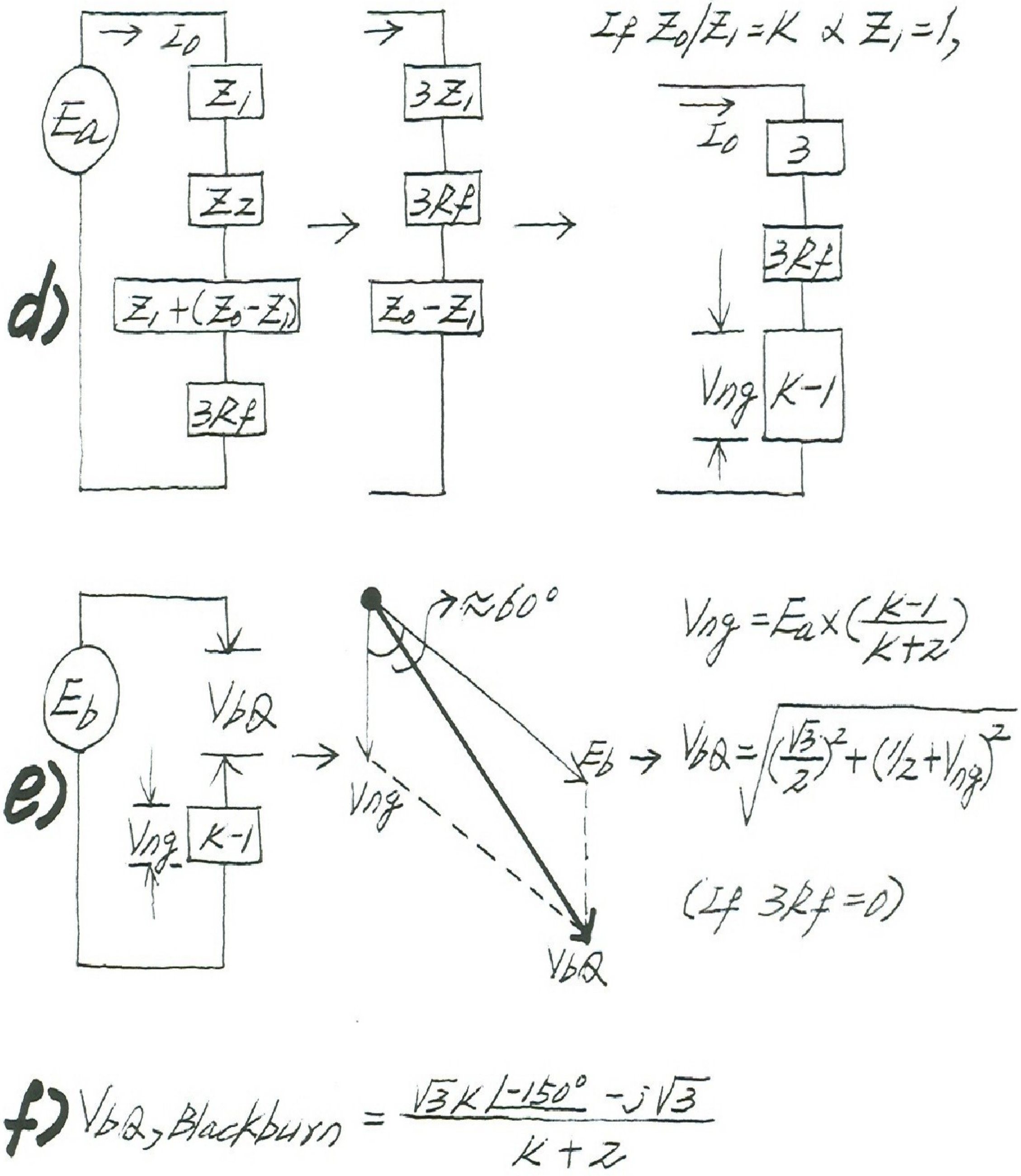

Figure 2. Graphical Analysis of Unfaulted-phase Voltage Rise
(continued from the previous page and simplified for illustration purposes)

2.2 Unfaulted-phase Voltage Rise in Looped Transmission Lines

Theoretically and practically, there is little difference (in the unfaulted-phase voltage rise) between radial distribution feeders and looped transmission lines. In general, there is not any neutral conductor in looped transmission, overhead static wires are installed to protect only switching stations and river crossings, the transmission fault resistance is smaller than the distribution fault resistance, and transmission line conductors are larger than distribution line conductors. Also, there are many auto-transformers, grounding banks, and generator stepup transformers in looped transmission. Therefore, due to somewhat **smaller X0/X1 ratio** of the looped transmission, the unfaulted-phase voltage rise in looped transmission is slightly smaller than that in radial distribution.

2.3 Unfaulted-phase Voltage Rise and Their Impacts to Transmission & Distribution Relaying

At this point, no distribution relays actually calculate or detect the unfaulted-phase voltage rise, 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 nominal. However, it is very clear (at least to the author) that the unfaulted-phase voltage rise may result in premature failure or accelerated aging of transformers over time.

- **Digital electronic equipment lockup and CBEMA curve**: In accordance with the latest CBEMA (Computer and Business Equipment Manufacturer's Association) curve, the maximum tolerable duration at 120% - 140% of the nominal voltage is 3 milliseconds. Therefore, no matter how fast a relay detects a SLG fault and a circuit breaker operates, operation of some digital electronic equipment will be impacted by the unfaulted-phase voltage rise.
- **Surge arresters and their temporary overvoltage characteristics**: 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 for the unfaulted-phase voltage rise reaching up to 140% of the nominal.
- **Transformer over-excitation protection curve**: Based on the General Guide for Permissible Short-time Over-excitation of Power Transformers[4] (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. Therefore, the following transformer over-excitation protection curve developed by the author may be used to protect transformers against the unfaulted-phase voltage rise due to SLG faults.
- **Fuse saving scheme advantage**: Definitely, the fuse saving scheme over the trip saving scheme[6] will be advantageous in preventing transformer damages from the unfaulted-phase voltage rise reaching up to 140% of the nominal voltage. This is due to fast clearing of temporary faults.

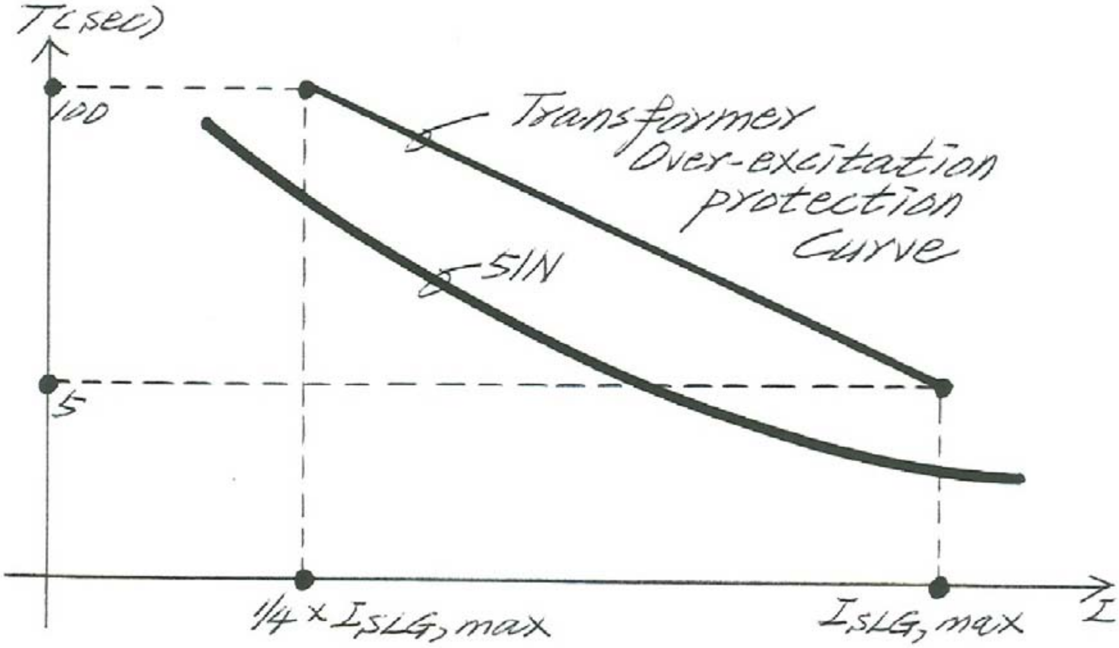

Figure 3. Transformer Over-excitation Protection Curve

III Unfaulted-phase Current Rise

3.1 Unfaulted-phase Current Rise in Looped Transmission Lines

The unfaulted-phase current rise in a solidly grounded system, due to mutual coupling between phases or/and between circuits, is nothing new to relaying professionals. Characteristically, the unfaulted-phase currents due to mutual coupling are either in phase with or 180 degrees out of phase from the faulted-phase current. As illustrated in Figure 1, Voltage & Current Waveforms of B-Ground SLG Faults, it actually occurs quite often. However, the following case of two unfaulted-phase currents being higher than the faulted-phase current (Ib in this particular SLG fault recorded) was quite unexpected to the author and it actually occurred twice in a year. Referring to Figure 4, Case of Unfaulted-phase Currents Higher than Faulted-phase Current, the unfaulted-phase currents (out of Bus T), Ia = Ic = 470A, are much larger than the faulted-phase current, Ib = 280A. This phenomenon is called “**Current Magnitude Reversal**” in this paper.

One may think that the current magnitude reversal can occur only near power plants, but it can occur anywhere with multiple grounding banks or multiple delta-tertiary auto-transformers if the system is configured similar to the one presented in this paper.

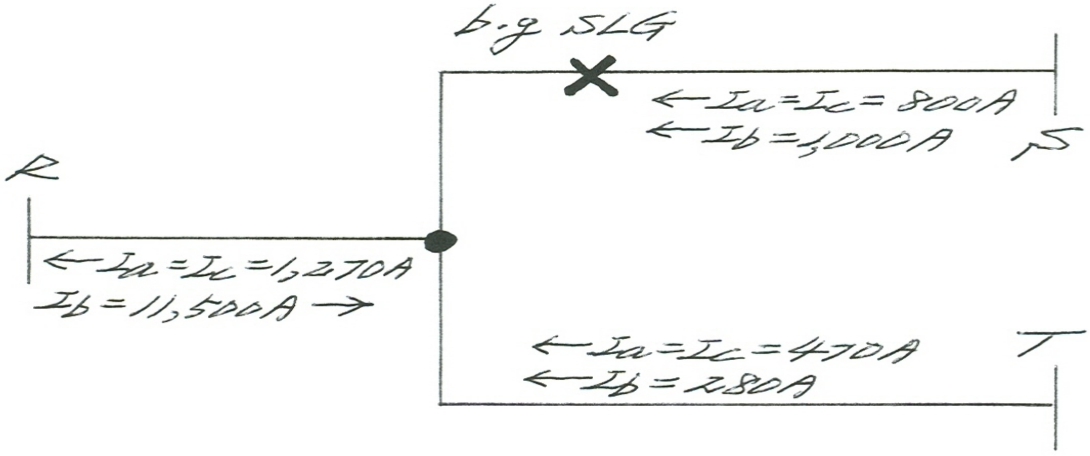

Figure 4. Case of Unfaulted-phase Currents Higher than Faulted-phase Current (simplified for illustration purposes)

The following current magnitude reversal analysis, based on a number of simulation studies, assumes a b-g SLG fault at X. For simplicity and convenience, a superposition method is used to explain how the current magnitude reversal occurs.

The simplified system in Figure 4 above and Figure 5 below consists of 115kV Bus R (electrically strong bus representing the system), 115kV Bus S and 115kV Bus T at a power plant, 72MVA generator stepup transformers S and T (115kV wye-grounded / 13.8kV delta, one on each 115kV bus at a power plant), 13.8kV Bus Tie, 4 23MVA synchronous generators (2 generators connected to the 13.8kV side of each generator stepup transformer), and 1.5MVA synchronous generator connected to the 13.8kV side of generator stepup transformer T.

- **Grounding bank**: Referring to Figure 5.a), acting as a grounding bank (without any generator in service and 13.8kV Bus Tie closed), the generator stepup transformer T supplies 3I0 (I0 = 400A on each phase) for a b-g SLG fault at X. Therefore, Ia,groundingbank = Ib,groundingbank = Ic,groundingbank = I0, all in phase, is 400A.
- **System contribution**: Referring to Figure 5.b), there are two current paths from Bus R (system) to X: one directly to X and the other via 13.8kV Bus Tie. As illustrated, only I1 and I2 can pass through two delta windings. Ib,system (the sum of Ib1 and Ib2) is 180A and Ia,system = Ic,system is 90A. Ia,system = Ic,system is in phase with Ia,groundingbank = Ic,groundingbank, but Ib,system is 180 degrees out of phase from Ib,groundingbank.
- **Small 1.5MVA-generator contribution**: Referring to Figure 5.c), Ib,generator (the sum of Ib1, Ib2, and Ib0) is 75A and Ia,generator = Ic,generator is 30A. Ib,generator is in phase with Ib,groundingbank, but Ia,generator = Ic,generator is 180 degrees out of phase from Ia,groundingbank = Ic,groundingbank.

- **Superposition**: Referring to Figure 5.d), the resultant Ib = Ib,groundingbank + Ib,system + Ib,generator is 295A (= 400A – 180A + 75A) and the resultant Ia = Ia,groundingbank + Ia,system + Ia,generator is 460A (= 400A + 90A – 30A). The resultant Ic is the same as the resultant Ia. Here, the faulted-phase current Ib is much smaller than the unfaulted-phase currents Ia and Ic, resulting in "**Current Magnitude Reversal**."

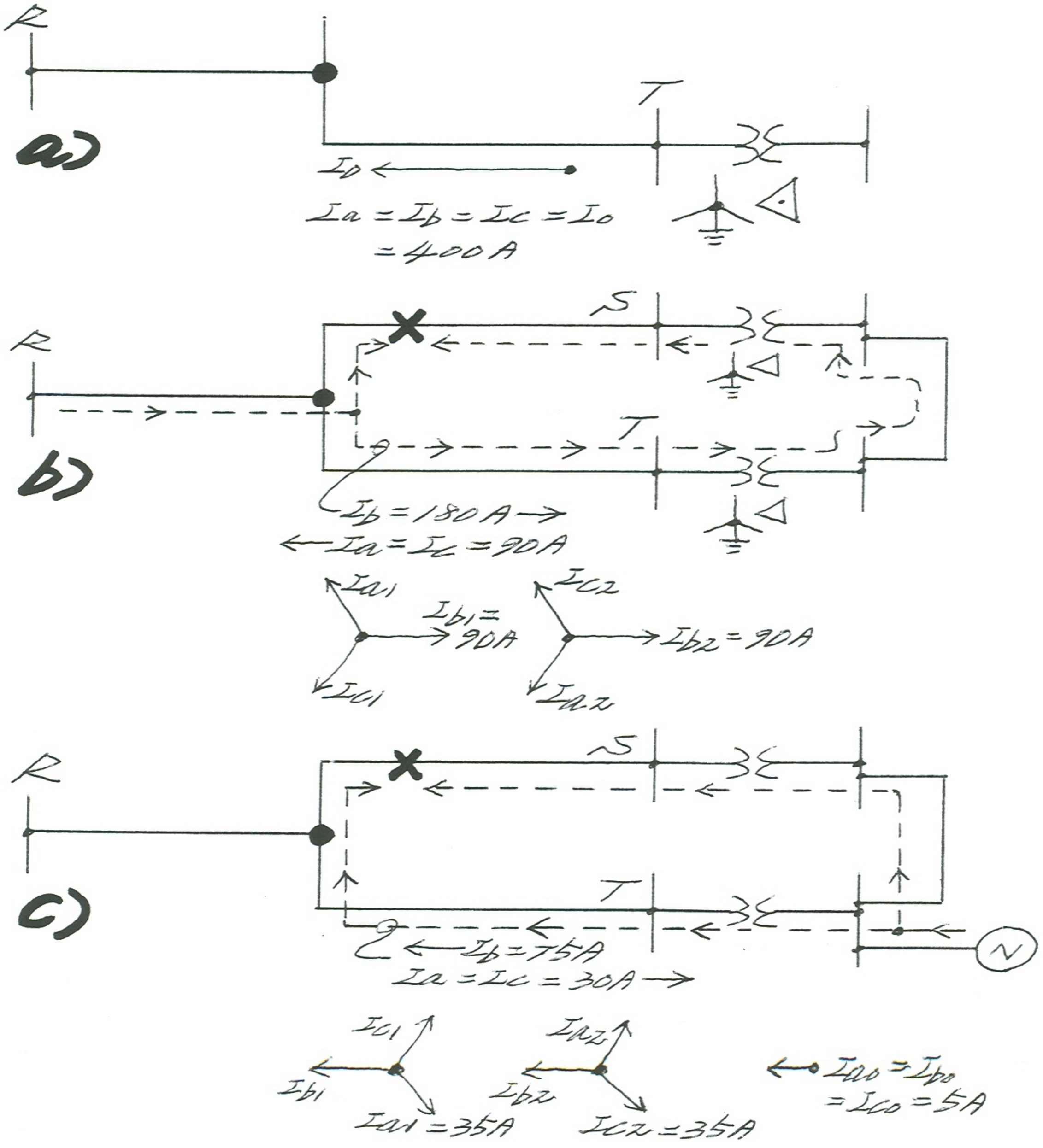

Figure 5. Graphical Analysis of Current Magnitude Reversal (Case of Unfaulted-phase Currents Higher than Faulted-phase Current) (simplified for illustration purposes)

d) $I_b = 400 - 180 + 75 = 295A \leftarrow$

$I_a = I_c = 400 + 90 - 30 = 460A \leftarrow$

$\therefore I_a = I_c > I_b$ for b-g SLG

Figure 5. Graphical Analysis of Current Magnitude Reversal
(continued from the previous page and simplified for illustration purposes)

3.2 Unfaulted-phase Current Rise in Radial Distribution Feeders

Unfaulted-phase current rise is primarily due to **mutual coupling between phases**, **mutual coupling between circuits**, and **grounding bank supplying 3I0**. Characteristically, the unfaulted-phase currents are either in phase with or 180 degrees out of phase from the faulted-phase current. Regardless of looped transmission or radial distribution, the unfaulted-phase current rise can occur as long as the induced or grounding bank-supplied zero-sequence currents can flow. In general, the unfaulted-phase current rise is somewhat insignificant as further detailed below, but could be significant in some distribution systems:

- Due to lack of large 3-phase grounding bank(s), large 3-phase transformer(s) acting as grounding bank(s), and large electrical source(s), the induced zero-sequence currents cannot flow or are very small.
- In typical distribution feeders, each phase has many single-phase line-ground-connected distribution transformers. Theoretically, they can provide paths for the induced zero-sequence currents, but the overall zero-sequence current loop impedance is too high to allow any significant amount of the induced zero-sequence currents.
- Due to the unfaulted-phase voltage rise, the unfaulted-phase lighting currents may increase but are not categorized as unfaulted-phase current rise because such currents are neither in phase with nor 180 degrees out of phase from the faulted-phase current.
- The unfaulted-phase currents for 3-phase motors may increase but are not categorized as unfaulted-phase current rise because such currents are neither in phase with nor 180 degrees out of phase from the faulted-phase current.

3.3 Unfaulted-phase Current Rise and Their Impacts to Transmission & Distribution Relaying

- **Zero-sequence currents in nature:** The unfaulted-phase currents categorized as the unfaulted-phase current rise are either in phase with or 180 degrees out of phase from the faulted-phase current. Characteristically, such unfaulted-phase currents are zero-

sequence currents, so they can be added to or subtracted from the faulted-phase zero-sequence current.
- **Conditional in nature:** Depending on the location of SLG, the unfaulted-phase currents, categorized as the unfaulted-phase current rise, are either in phase with or 180 degrees out of phase from the faulted-phase current. In addition, as shown on Figure 1.b), the unfaulted-phase currents may disappear completely upon opening of the remote circuit breaker. Because of this conditional nature of the unfaulted-phase currents, it is very difficult to develop a relaying application guideline or standard for the unfaulted-phase current rise.
- **Overall relaying impacts:** As shown on Figure 1, if the unfaulted-phase currents are 16.4% of and in phase with the faulted-phase current, the overall 3I0 will be increased by 32.8%. If the same unfaulted-phase currents are 180 degrees out of phase from the faulted-phase current, the overall 3I0 will be decreased by 32.8%. Therefore, the unfaulted-phase current rise may significantly impact the fault detection (no detection, slower or faster), relay reach (under-reaching or over-reaching), relay operating time (slower or faster), fault distance calculation, and fault type determination.
- **Advantage of line differential relaying**: Referring to Figure 4, Case of Unfaulted-phase Currents Higher than Faulted-phase Current, the Current Magnitude Reversal may confuse conventional transmission relays, but a line differential relay will not see any mismatch due to the “passing through” nature of the unfaulted-phase currents or current magnitude reversal.

IV Conclusion

Much attention has been given to the faulted-phase voltages and currents in our relaying education for many good reasons, but almost no attention to the unfaulted-phase current & voltage rises. Presence of the significant unfaulted-phase current & voltage rises may result in significant impacts to protective relaying as described in this paper. Recently, one of those significant current rise cases prompted introduction of a new term “**Current Magnitude Reversal**” in which two unfaulted-phase currents are actually higher than the faulted-phase current in case of frequently-occurring SLG faults. The current magnitude reversal is not a theory but a fact. It occurred twice over the past year. It may happen again in our utility and also other utilities.

As a conclusion, the following is intended as a brief summary of this paper and technical presentation:

- The unfaulted-phase voltage rise can be as high as 140% of the nominal and frequent unfaulted-phase voltage rises may result in premature failure of connected equipment.
- The unfaulted-phase voltage rise can be easily determined by the graphical method presented in this paper.
- The transformer over-excitation protection curve can be used to ensure adequate protection of transformers against the unfaulted-phase voltage rise.

- The unfaulted-phase current rise is primarily due to mutual coupling between phases, mutual coupling between circuits, and grounding bank supplying 3I0.
- Unfaulted-phase current rise can have significant impacts in relaying application, especially in fault detection (no detection, slower or faster), relay reach (under-reaching or over-reaching), relay operating time (slower or faster), fault distance calculation, and fault type determination.
- The Current Magnitude Reversal, in which two unfaulted-phase currents are higher than the faulted-phase current, can occur.
- In the presence of Current Magnitude Reversal, a line differential relay is likely to perform reliably but others may not.
- Due to conditional nature of the unfaulted-phase current rise, it is difficult to develop a relaying application guideline or standard for it.

The author sincerely hopes that this technical paper may be of some value to WPRC attendees and help application engineers understand the significance of unfaulted-phase voltage & current rises in protective relaying application.

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