# CROSS-COUNTRY FAULT ANALYSIS FOR PROTECTION ENGINEERS

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# Cross-Country Fault (XCF)
# Analysis for Protection Engineers

By

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## 1. Introduction

A fault between 2 different circuits (for example, between 115kV transmission circuit and 12.47kV underbuilt distribution circuit) is generally classified as a **cross-country fault** and it may occur more frequently than anticipated. For example, several cross-country faults between 115kV transmission circuit and 12.47kV distribution circuit caused **surge arrester failures**, **distribution transformer bushing failures**, and **damages to customers' appliances** in the recent past in Northwest.

In general, modern-day microprocessor-based relays are not specifically programmed to detect cross-country faults even though they may operate for cross-country faults, and protection engineers do not consider cross-country faults in calculating relay settings probably because they may not have thorough understanding of cross-country faults and simple analytical tools. No matter which relays are used, protection engineers are responsible for protecting all power system components against short circuit faults, open circuit faults, cross-country faults, other miscellaneous electrical faults, and non-electrical faults in some utilities. Therefore, it is essential for protection engineers to thoroughly understand cross-country faults in addition to typical short-circuit and open-circuit faults.

The author analyzed a number of cross-country faults throughout his electric utility engineering career in Northwest and found the cross-country fault analysis quite intriguing and interesting. This paper presents 4 typical cross-country faults, the author's analytical techniques, and most importantly the author's simplified analytical approaches. Some protection engineers may find the author's simplified analytical approaches very interesting and so the author sincerely wish that protection engineers will accomplish the following by reading this paper:

- Thoroughly understand the unique nature of cross-country faults.
- Learn how to analyze cross-country faults with the conventional short circuit analysis tools.
- Understand the **need for simplified analytical tools** and learn the author's **simplified analytical approaches**.
- Optimize relay settings such that relays can detect cross-country faults reliably if possible.

## 2. Cross-Country Fault Analysis

The cross-country fault analysis has been a very intriguing, challenging task to almost all protection engineers because they may not have adequate analytical tools. One may think that EMTP (Electro-Magnetic Transient Program) can be used to analyze cross-country faults. However, only a handful number of engineers can use it in each utility, small utilities may not have EMTP at all, and using EMTP for cross-country faults is a very time-consuming task. In addition, one may not know the accuracy of his/her case study results without using a simplified approach similar to the author's techniques presented in this paper.

To thoroughly understand cross-country faults and also to meet the previously set objectives, protection engineers generally need the following as minimum requirements in the author's mind.

- **Three (3) Essential Tools** - **Simultaneous fault analysis** using traditional node/loop equations, **symmetrical component analysis**, and **surge arrester operation**.
- **Short Circuit Analysis Program with Simultaneous Fault Analysis Feature** – Since cross-country faults cannot be solved effectively by using the symmetrical component analysis, they are normally solved by the simultaneous fault analysis using positive-sequence node/loop equations and also equations representing transformers. Some commercially available short circuit analysis programs offer both short circuit analysis and simultaneous fault analysis.
- **Symmetrical Component Analysis** – Even though cross-country faults are solved by using the simultaneous fault analysis, protection engineers are practically required to know the symmetrical component analysis because modern-day microprocessor-based relays make operational decisions based on the symmetrical component analysis.
- **Surge Arrester Operation** – Cross-country faults, involving a contact between high-voltage circuit and low-voltage circuit, are followed almost always by low-voltage-side surge arrester operation or insulator flashover. Whether it is surge arrester operation or insulator flashover, the end result always appears to be a short circuit to ground. To understand the surge arrester operation further, protection engineers may want to know the following 4 types of surge arresters:

    - **Gapped Silicone-Carbide Surge Arresters with Isolator** (Ground Lead Disconnector) – Generally, higher discharge voltages than gapped MOV surge arresters. The ground lead isolator removes the ground terminal from the surge arrester in the unlikely event of arrester failures and so the isolation prevents a permanent system fault.
    - **Gapped Silicone-Carbide Surge Arresters without Isolator** – Generally, the arrester failure leads to a permanent system fault.

  - **Gapped MOV (Metal-Oxide-Varistor) Surge Arresters with Isolator** – Generally, MOV surge arresters are conducted above the **MCOV** (Maximum Continuous Operating Voltage) and so they have short **TOV** (Temporary Over-Voltage) characteristics.
  - **Gapped MOV Surge Arresters without Isolator** – Generally, the arrester failure leads to a permanent system fault.

- **Transition from One Type of Cross-Country Fault to Another Type after Surge Arrester Operation –** First, a cross-country fault involving a contact between 115kV circuit and 12.47kV circuit creates a very high voltage to the contacted 12.47kV location. Second, the high voltage triggers surge arrester operation (within approximately one-mile radius) and/or insulator flashover. Finally, the contact between 115kV circuit and 12.47kV circuit becomes a 115kV single-line-to-ground fault as shown later.
- **Simplified Analytical Approach –** The simultaneous fault analysis can solve cross-country faults, but protection engineers may not know the accuracy of their case study results. To verify the accuracy of their results, protection engineers are practically required to know a second, simplified, possibly hand-calculation-based cross-country fault analysis. The author's simplified analytical approaches presented later in this paper may not be the best ones, but they may become **the most useful cross-country fault analysis tools without severely compromising the accuracy**.

# 3. Cross-Country Fault between A-Phase of 115kV Circuit and A-Phase of 12.47kV Circuit (Delta/Wye-Grounded Step-down Power Transformer between 2 Circuits) and Surge Arrester Operation Due to Cross-Country Fault

## 3.1 Actual Fault Case

Referring to Figure 1, there is a step-down power transformer between 115kV transmission circuit and 12.47kV distribution circuit, and the step-down power transformer connection is delta on the 115kV side and wye-grounded on the 12.47kV side. The 115kV side leads the 12.47kV side by 30 degrees. The figure illustrates that A-phase conductor of 115kV transmission circuit made a physical contact with A-phase conductor of 12.47kV distribution circuit.

This type of cross-country faults is very common to 12.47kV distribution circuits built under 115kV transmission circuits. When this type of cross-country faults occurred in the past, 115kV circuit breakers tripped reliably but 12.47kV breakers often times did not operate. For all faults the author investigated in the past, **all distribution-class MOV surge arresters within approximately 1-mile radius were damaged, but no step-down power transformers were damaged**. Interestingly, for at least two faults all distribution-class MOV surge arresters within several-mile radius were damaged, but silicone-carbide surge arresters were not damaged. For some faults, distribution transformers and/or distribution transformer bushings were damaged in addition to surge arrester damages.

## 3.2 Short Circuit Analysis Prior to Surge Arrester Operation

Compared to other types of short circuit faults, this type of cross-country faults display a number of unique characteristics. Referring to Figure 1, some of noteworthy things from this analysis are:

- **A-phase voltage at the fault reached 24.5kV** and this high voltage triggered the surrounding distribution-class MOV surge arresters (typically, a response time of less than several microseconds). Probably, this extremely fast surge arrester operation saved the step-down power transformer and distribution transformers from catastrophic failures.
- The extremely high voltage on the low side of step-down power transformer due to this type of cross-country faults may saturate the step-down power transformer, but no saturation-related step-down power transformer damages were observed for all faults the author investigated in the past.
- **The most significant fault current path** as illustrated is 115kV A-phase conductor – 12.47kV A-phase conductor – step-down power transformer A-phase winding – step-down power transformer neutral – earth – step-up power transformer neutral at generating station – 115kV A-phase conductor.
- **The fault current also can flow through distribution transformers**, but the fault current flow through distribution transformers is generally insignificant and it is very unusual to model distribution transformers for the short circuit analysis. However, if the fault current flow through distribution transformers is significant, then the fault current magnitude may not be the same as what the 12.47kV distribution breaker relays see.
- A small (insignificant) amount of fault current (477 A) flows through the step-down power transformer and it **almost acts as a circulating current** even though it is not a circulating current in a true sense.

## 3.3 Short Circuit Analysis after Surge Arrester Operation

Referring to Figure 2, some of noteworthy things from this analysis are:

- After the surge arrester operation, the cross-country fault **almost appears to be 2 independent faults** {115kV A-to-ground fault at the original contact point (actually, at the nearest distribution-class surge arrester location) and 12.47kV A-to-ground fault at the same point}.
- It appears that the total fault current is a sum of 115kV A-to-ground fault and 12.47kV A-to-ground fault.

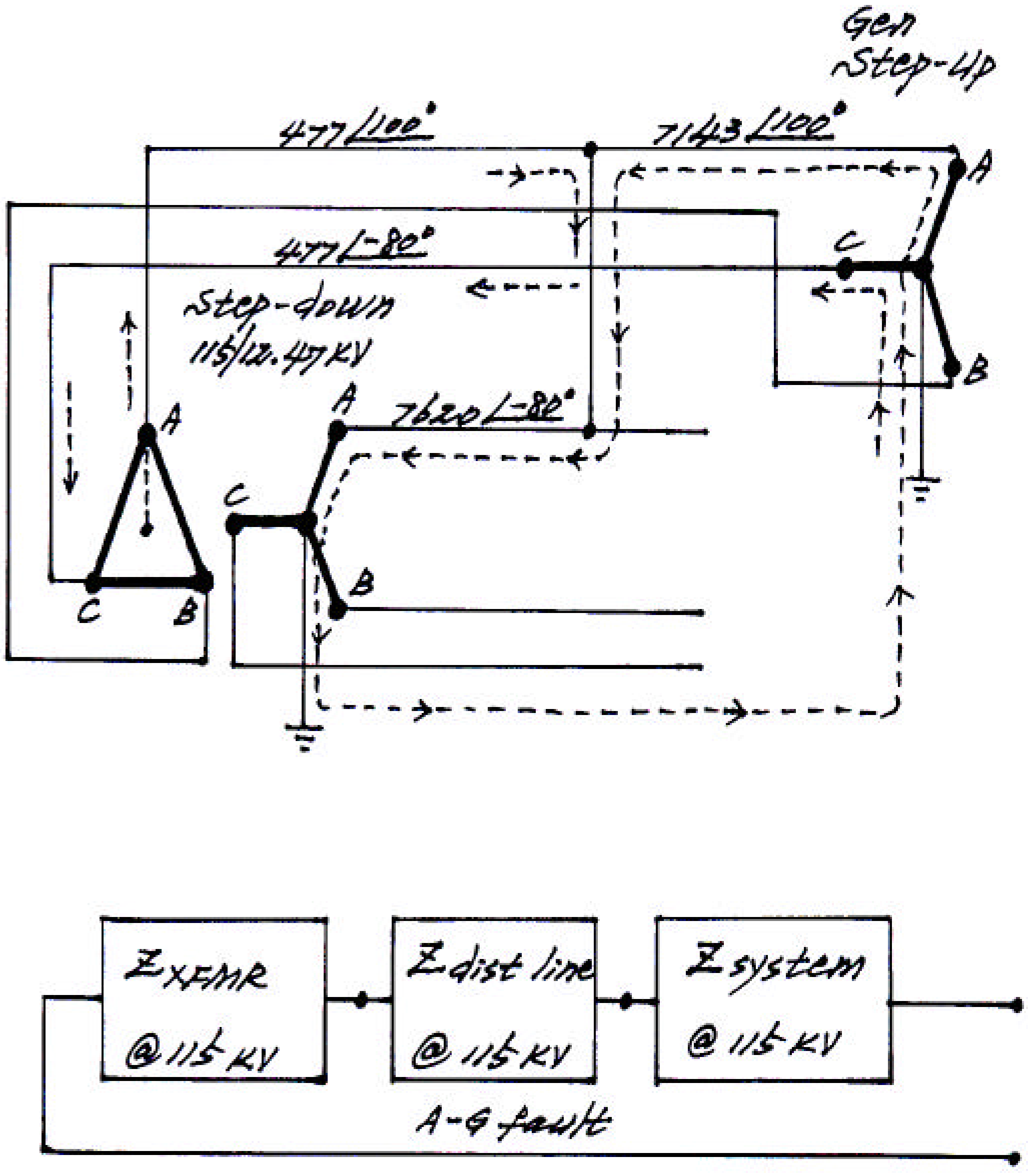

Figure 1. 115kV A-Phase to 12.47kV A-Phase Cross-Country Fault (prior to surge arrester operation)

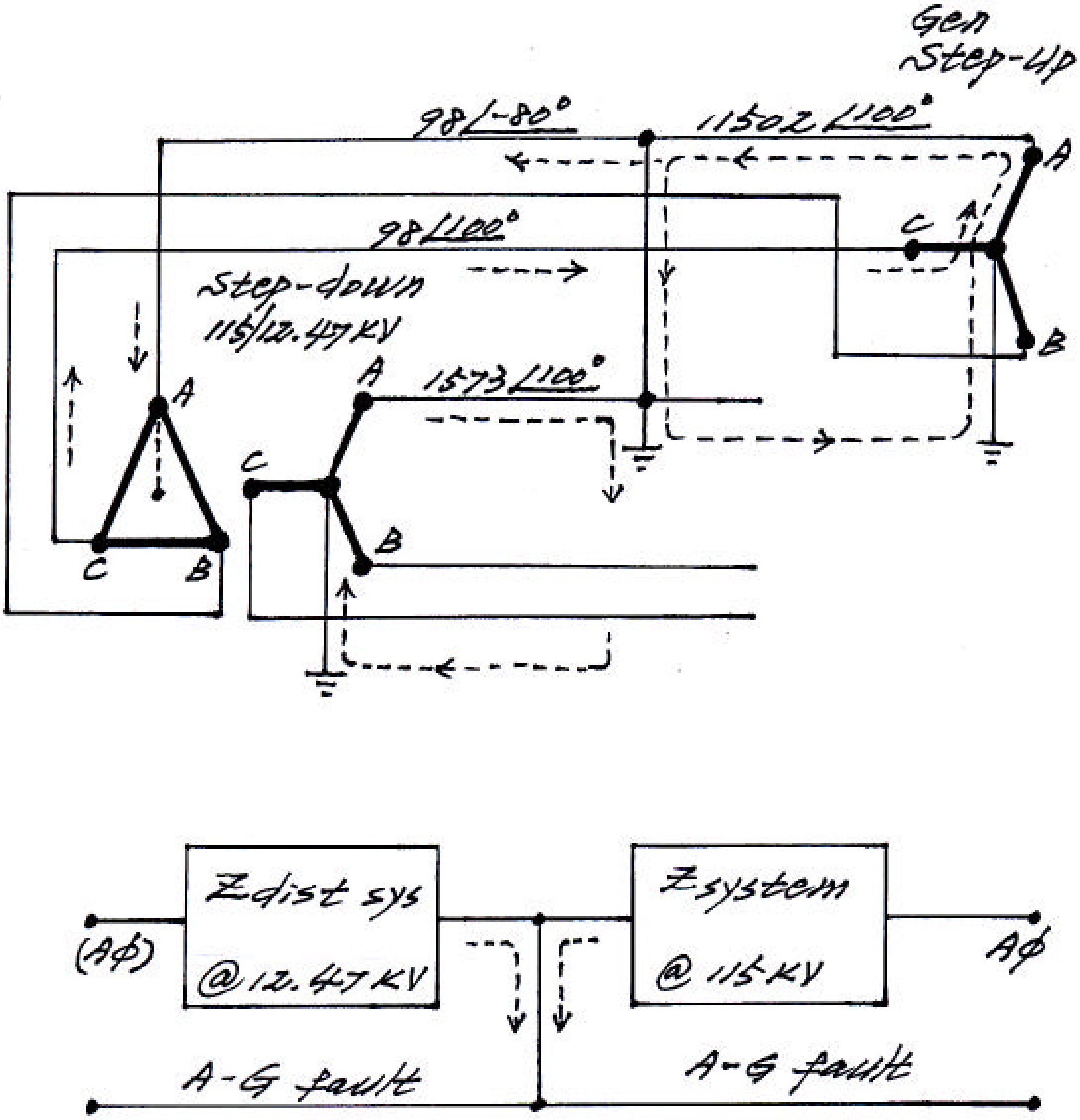

Figure 2. 115kV A-Phase to 12.47kV A-Phase Cross-Country Fault (after surge arrester operation)

## 3.4 Microprocessor-Based Relays' Response

Some of noteworthy things protection engineers may expect to see are:

- Referring to Figure 1, distribution relays supervised or torque-controlled by a directional unit or an under-voltage unit may not operate at all due to high voltage and apparent reverse fault. Generally, simple non-directional ground over-current relays will operate more reliably.
- Generally, transmission relays will operate reliably, but distribution relays may not operate at all due to possible miscoordination between transmission relays and distribution relays.
- Referring to Figure 1, the fault distance(s) determined by transmission relays may not have any significance to operating personnel.

## 3.5 Simplified Analytical Approach for Utility Protection Engineers

Since cross-country faults are normally solved by the simultaneous fault analysis using positive-sequence node/loop equations and also **the fault current path can be easily determined**, it is quite possible to develop a simplified analytical approach as described below without severely compromising the accuracy. Based on the author's past experience, fault current magnitudes and angles calculated by the author's simplified analytical approach are normally very close to those calculated by the simultaneous fault analysis.

- Referring to Figure 1, **the 12.47kV per unit line impedance should be converted to a 115kV per unit line impedance**. For example, 0.45 per unit line impedance at 12.47 kV becomes 0.0053 per unit at 115 kV {(0.45 x 1.56) / 132.25 = 0.0053}. This conversion is necessary because the 12.47kV line is treated as a piece of 115kV line section.
- Referring to Figure 1, the step-down power transformer impedance of 0.55 per unit becomes 0.0065 per unit at 115 kV by using the same conversion process. This conversion is also necessary because the step-down power transformer is treated as a piece of 115kV line section.
- Referring to Figure 1, the 477A fault current flow (theoretically, a burden to the step-down power transformer) should be reflected to the low side of step-down power transformer for the accuracy's sake, but for simplicity the author does not recommend doing it. Another reason for not doing it is that the high-side fault current magnitude is not known prior to any simplification.
- Referring to Figure 1, once all per unit impedance conversion steps have been completed, **the seemingly complex cross-country fault analysis becomes a simple symmetrical component analysis for 115kV A-to-ground fault**.
- Referring to Figure 2, the total fault current at the fault is a sum of contribution from the step-down power transformer (**12.47kV A-to-ground fault**) and contribution from the 115kV system (**115kV A-to-ground fault**).

# 4. Cross-Country Fault between A-Phase of 115kV Circuit and B-Phase of 12.47kV Circuit (Delta/Wye-Grounded Step-down Transformer between 2 Circuits) and Surge Arrester Operation Due to Cross-Country Fault

## 4.1 Actual Fault Case

This particular case is very **similar to the previous cross-country fault case**. The figure illustrates that A-phase conductor of 115kV transmission circuit made a physical contact with B-phase conductor of 12.47kV distribution circuit. This type of cross-country faults is also very common to 12.47kV distribution circuits built under 115kV transmission circuits.

## 4.2 Short Circuit Analysis Prior to Surge Arrester Operation

Referring to Figure 3, some of noteworthy things from this analysis are:

- **B-phase voltage at the fault reached 19.2 kV** and this high voltage triggered the surrounding distribution-class MOV surge arresters (typically, a response time of less than several microseconds). Probably, this extremely fast surge arrester operation saved the step-down power transformer and distribution transformers from catastrophic failures.
- The extremely high voltage on the low side of step-down power transformer due to this type of cross-country faults may saturate the step-down power transformer, but no saturation-related step-down power transformer damages were observed for all faults the author investigated in the past.
- **The most significant fault current path** is 115kV A-phase conductor – 12.47kV B-phase conductor – step-down power transformer B-phase winding – step-down power transformer neutral – earth – step-up power transformer neutral at generating station – 115kV A-phase conductor. **One interesting point here is that the A-phase fault current returns through the B-phase distribution circuit.**
- **The fault current also can flow through distribution transformers**, but the fault current flow through distribution transformers is generally insignificant and it is very unusual to model distribution transformers for the short circuit analysis. However, if the fault current flow through distribution transformers is significant, then the fault current magnitude may not be the same as what the 12.47kV distribution breaker relays see.
- A small (insignificant) amount of fault current (495 A) flows through the step-down power transformer.

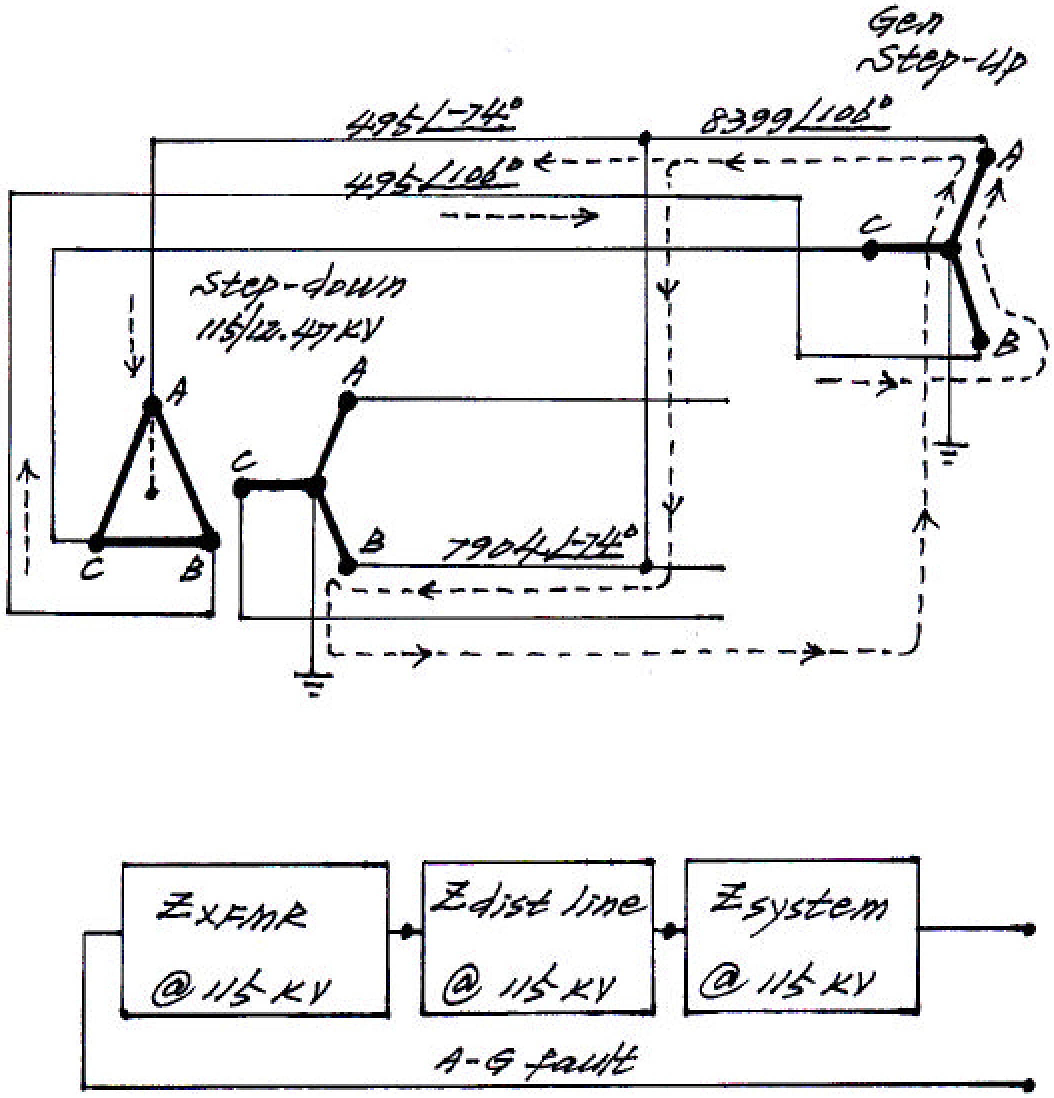

Figure 3. 115kV A-Phase to 12.47kV B-Phase Cross-Country Fault (prior to surge arrester operation)

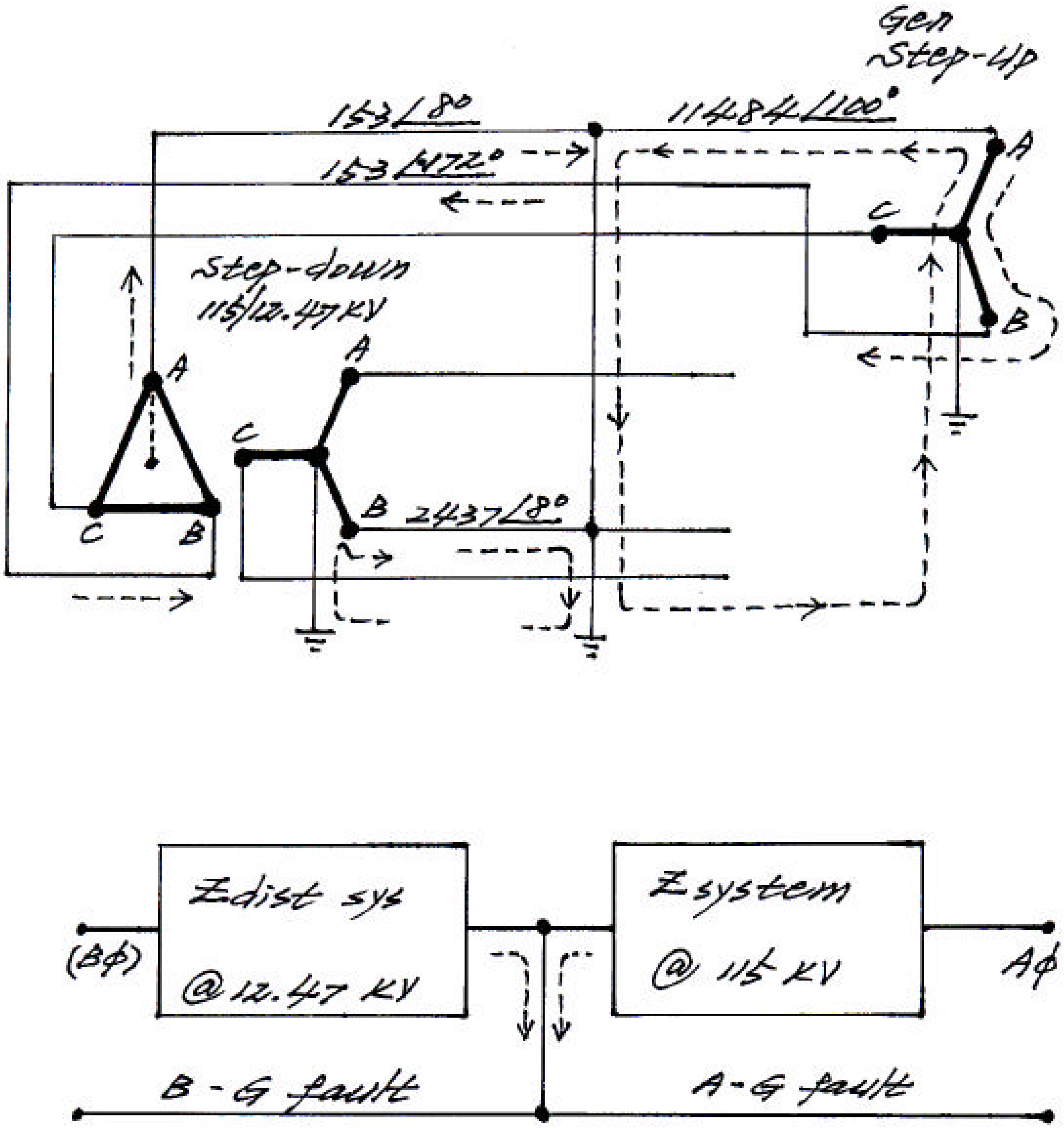

Figure 4. 115kV A-Phase to 12.47kV B-Phase Cross-Country Fault (after surge arrester operation)

## 4.3 Short Circuit Analysis after Surge Arrester Operation

Referring to Figure 4, some of noteworthy things from this analysis are:

- After the surge arrester operation, the cross-country fault **almost appears to be 2 independent faults** {115kV A-to-ground fault at the original contact point (actually, at the nearest distribution-class surge arrester location) and 12.47kV B-to-ground fault at the same point}.
- It appears that the total fault current is a sum of 115kV A-to-ground fault and 12.47kV B-to-ground fault.

## 4.4 Microprocessor-Based Relays' Response

Some of noteworthy things protection engineers may expect to see are:

- Referring to Figure 3, distribution relays supervised or torque-controlled by a directional unit or an under-voltage unit may not operate at all due to high voltage and apparent reverse fault. Generally, simple non-directional ground over-current relays will operate more reliably.
- Generally, transmission relays will operate reliably, but distribution relays may not operate at all due to possible miscoordination between transmission relays and distribution relays.
- Referring to Figure 3, the fault distance(s) determined by transmission relays may not have any significance to operating personnel.

## 4.5 Simplified Analytical Approach for Utility Protection Engineers

Practically, the author's simplified analytical approach for this type of cross-country faults is the same as the previous approach described in Section 3.5.

- Referring to Figure 3, **the 12.47kV per unit line impedance should be converted to a 115kV per unit line impedance**. This conversion is necessary because the 12.47kV line is treated as a piece of 115kV line section.
- Referring to Figure 3, the step-down power transformer impedance of 0.55 per unit becomes 0.0065 per unit at 115 kV by using the same conversion process because the step-down power transformer is also treated as a piece of 115kV line section.
- Referring to Figure 3, the 495A fault current flow (theoretically, a burden to the step-down power transformer) should be reflected to the low side of step-down power transformer for the accuracy's sake, but for simplicity the author does not recommend doing it. Another reason for not doing it is that the high-side fault current magnitude is not known prior to any simplification.
- Referring to Figure 3, once all per unit impedance conversion steps have been completed, **the seemingly complex cross-country fault analysis becomes a simple symmetrical component analysis for 115kV A-to-ground fault.**

- Referring to Figure 4, the total fault current at the fault is a sum of contribution from the step-down power transformer (**12.47kV B-to-ground fault**) and contribution from the 115kV system (**115kV A-to-ground fault**).

# 5. Cross-Country Fault between A-Phase of 115kV Circuit 1 and B-Phase of 115kV Circuit 2

## 5.1 Actual Fault Case

Referring to Figure 5, the figure illustrates that A-phase conductor of 115kV transmission circuit 1 made a physical contact with B-phase conductor of 115kV transmission circuit 2. This type of cross-country faults is not uncommon to 115kV double-circuit construction (2 circuits on each pole or structure).

## 5.2 Short Circuit Analysis

Referring to Figure 5, some of noteworthy things from this analysis are:

- A-phase fault current on 115kV line 1 returns through the B-phase of 115kV line 2.
- It appears that the zero sequence current, $3I_0$, flows from A-phase to B-phase at the 115kV bus, but it is not possible at all as we all know. Nothing is really wrong with the symmetrical component representation, but this apparent discrepancy happens when symmetrical components are mathematically calculated from a short circuit case solved by the simultaneous fault analysis. In other words, **this apparent discrepancy happens when A-phase fault current does not return through B-phase of the same circuit for apparent A-to-B line-to-line fault**.

## 5.3 Microprocessor-Based Relays' Response

Some of noteworthy things protection engineers may expect to see are:

- Since transmission relays on each breaker see the high current flow only on one phase, they generally think that a single-line-to-ground fault occurred instead of a line-to-line fault. Transmission relays on the 115kV circuit-1 breaker will operate reliably because they will see a forward single-line-to-ground fault, but relays on the 115kV circuit-2 breaker may not operate at all because they will see a reverse single-line-to-ground fault. Simple non-directional backup ground over-current relays (or units) will operate more reliably.
- Once the 115kV circuit-1 breaker has opened, transmission relays on the 115kV circuit-2 breaker may not see any fault at all if both transmission lines are radial. However, sensitive non-directional backup ground over-current relays (or units) **may operate due to current imbalance** (higher B-phase loading than other phases).
- The fault distance(s) determined by transmission relays may not have any significance to operating personnel.

## 5.4 Simplified Analytical Approach for Utility Protection Engineers

A simplified analytical approach for this type of cross-country faults was presented by the author at the 25th Western Protective Relay Conference in 1998 ("Application Issues with Modern Distribution Relays"). Since the fault current path can be easily determined, it is quite possible to develop a few simplified analytical approaches as described below without severely compromising the accuracy. Based on the author's past experience, fault current magnitudes and angles calculated by the author's simplified analytical approaches are normally very close to (or equal to) those calculated by the simultaneous fault analysis.

- Referring to Figure 5, one simplified analytical approach is to solve a **A-to-B line-to-line fault at the bus with a fault impedance (Zf)** amounting to a sum of 2 line impedances (115kV circuit-1 A-phase conductor impedance from the bus to the fault and 115kV circuit-2 B-phase conductor impedance from the bus to the fault) by using the simple symmetrical component analysis.
- Referring to Figure 5, another simplified analytical approach (**preferred by the author**) is to solve a **A-to-B line-to-line fault at the calculated impedance** (**Zlines 1&2 avg** amounting to an average of 2 impedances, 115kV circuit-1 A-phase conductor impedance from the bus to the fault and 115kV circuit-2 B-phase conductor impedance from the bus to the fault) **from the bus** by using the simple symmetrical component analysis.

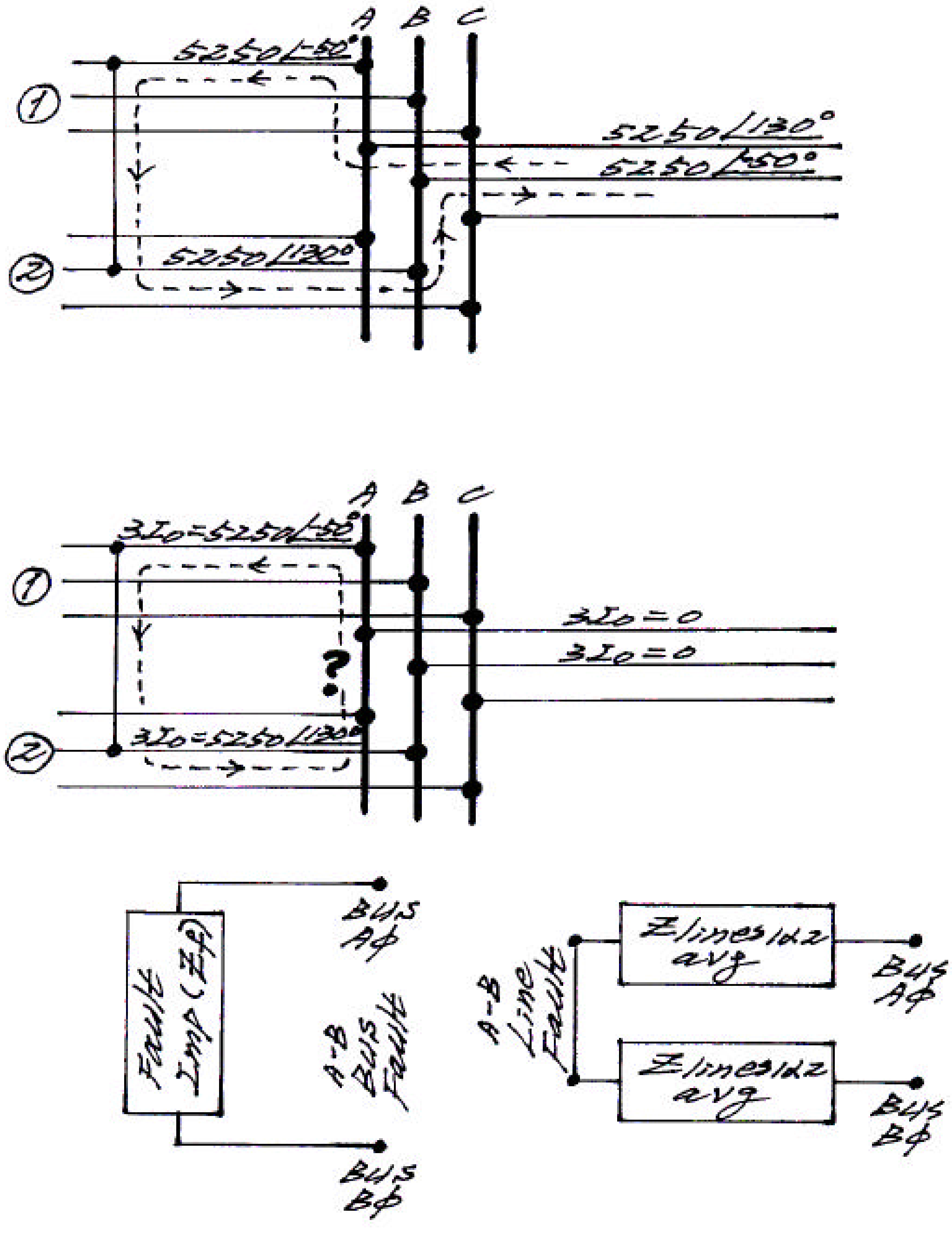

Figure 5. 115kV Circuit 1 A-Phase to 115kV Circuit 2 B-Phase Cross-Country Fault

# 6. Cross-Country Fault between A-Phase of 12.47kV Circuit 1 and B-Phase of 12.47kV Circuit 2 (Circuit 1 from Substation A and Circuit 2 from Substation B)

## 6.1 Actual Fault Case

Referring to Figure 6, there is a step-down power transformer between 115kV transmission circuit and 12.47kV distribution circuit for both substations, and the step-down power transformer connection is delta on the 115kV side and wye-grounded on the 12.47kV side. The 115kV side leads the 12.47kV side by 30 degrees. The figure illustrates that A-phase conductor of 12.47kV distribution circuit 1 from substation A made a physical contact with B-phase conductor of 12.47kV distribution circuit 2 from substation B. This type of cross-country faults is not uncommon to 12.47kV double-source double-circuit construction (2 circuits on each pole, but one circuit from one source and the other circuit from another source).

## 6.2 Short Circuit Analysis

Referring to Figure 6, some of noteworthy things from this analysis are:

- The **fault current path** is circuit-1 A-phase conductor – circuit-2 B-phase conductor – substation-B step-down transformer B-phase winding – substation-B step-down transformer neutral – earth – substation-A step-down transformer neutral – substation-A step-down transformer A-phase winding – circuit-1 A-phase conductor.
- Interestingly, **the line-to-line fault current returns through the earth**.
- Distribution relays on each breaker will see a single-line-to-ground fault instead of a line-to-line fault.

## 6.3 Microprocessor-Based Relays' Response

Some of noteworthy things protection engineers may expect to see are:

- Referring to Figure 6, distribution relays on the circuit-1 breaker will operate reliably, but distribution relays supervised or torque-controlled by a directional unit on the circuit-2 breaker may not operate at all due to apparent reverse fault. Generally, simple non-directional ground over-current relays will operate more reliably.
- Once the circuit-1 breaker has opened, distribution relays on the circuit-2 breaker may not see any fault at all. However, sensitive non-directional backup ground over-current relays (or units) **may operate due to current imbalance** (higher B-phase loading than other phases).

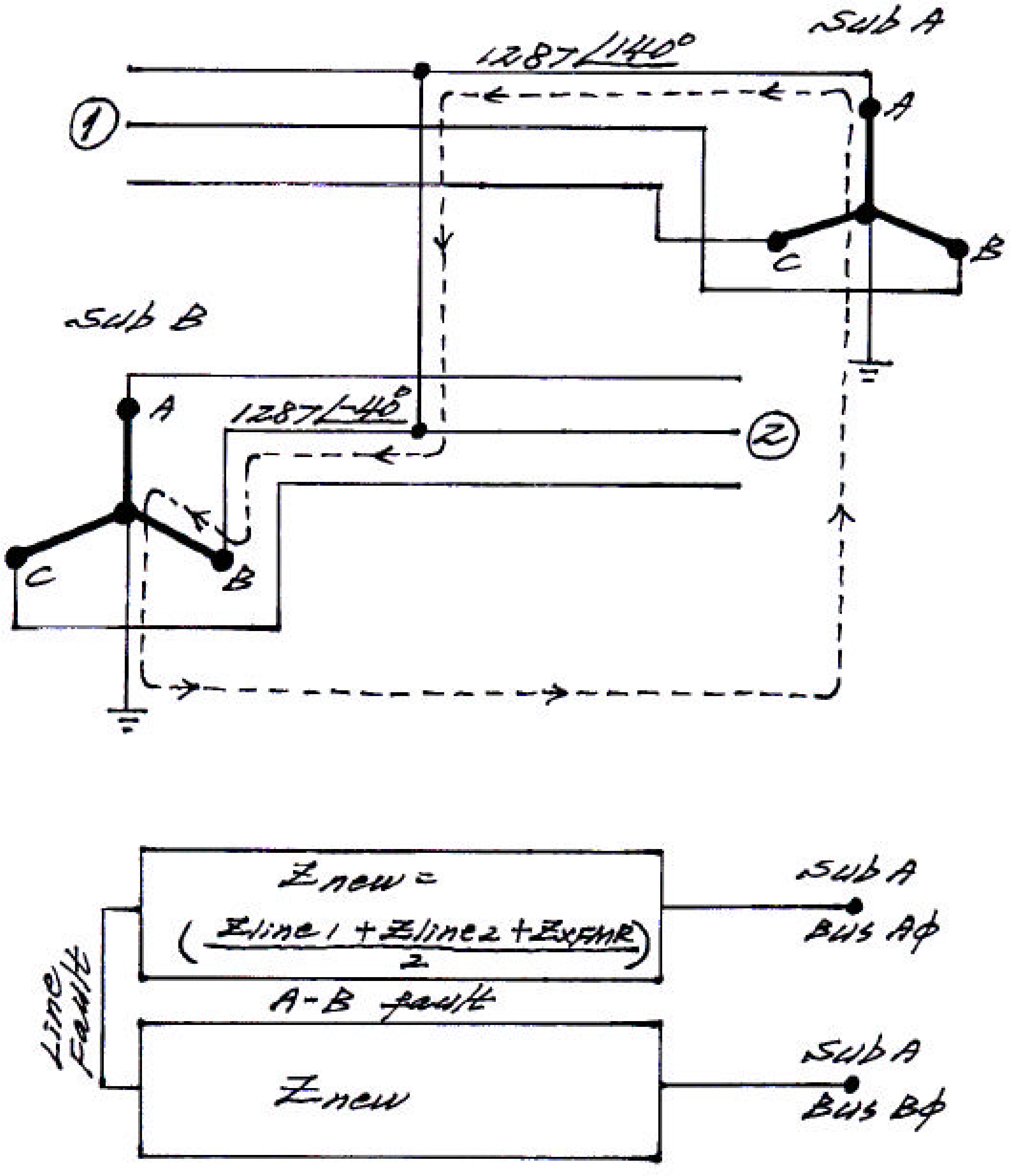

Figure 6. 12.47kV Circuit 1 A-Phase to 12.47kV Circuit 2 B-Phase Cross-Country Fault (circuit 1 from substation A and circuit 2 from substation B)

### 6.4 Simplified Analytical Approach for Utility Protection Engineers

Since this particular cross-country fault is similar to the previous type described in Section 5 and the fault current path can be easily determined, it is quite possible to develop a simplified analytical approach as described below without severely compromising the accuracy. Based on the author's past experience, fault current magnitudes and angles calculated by the author's simplified analytical approach are normally very close to those calculated by the simultaneous fault analysis.

- Referring to Figure 6, one simplified analytical approach is to solve a **A-to-B line-to-line fault at the calculated impedance from the substation A (Znew)**, amounting to one half of a sum of 3 impedances (circuit-1 A-phase conductor impedance from the substation-A bus to the fault, circuit-2 B-phase conductor impedance from the substation-B bus to the fault, and substation-B step-down transformer impedance), by using the simple symmetrical component analysis.

## 7. Conclusion

Short circuit analyses for 4 typical types of cross-country faults have been presented in this paper. As described throughout this paper, cross-country faults are not normally solved by using the conventional symmetrical component analysis, but usually solved by using the simultaneous fault analysis. The author emphasized the need for simplified analytical tools and introduced the author's simplified analytical approaches without severely compromising the accuracy. Based on the author's past experience, fault current magnitudes and angles calculated by the author's simplified analytical approaches are normally very close to those calculated by the simultaneous fault analysis. It is the author's sincere hope that **the simplified analytical approaches** will be **thoroughly understood, refined (if required), and carefully applied by fellow protection engineers** in the future.