

Methods for Analyzing and Detecting an Open Phase Condition of a Power Circuit to a Nuclear Plant Station Service or Startup Transformer

Power System Relaying and Control Committee Report of Working Group K11 of the Substation Protection Subcommittee

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CONTENTS

1. INTRODUCTION.....	1
1.1 Assignment.....	1
The report presents approaches used to detect open phase conditions that occur in the three phase, high voltage power supply to primary windings of grid connected station auxiliary transformers that provide energy to nuclear power plants.	1
1.2 Summary	1
1.3 Purpose	1
1.4 Definitions.....	3
1.5 Key Abbreviations and Acronyms	4
2. Detection methods and location of protection	4
2.1 Current Based Detection Schemes	4
2.1.1 Current differential.....	5
2.1.2 Phase current unbalance	5
2.1.3 Phase Comparison.....	6
2.1.4 Sequence Quantities.....	7
2.1.5 Hybrid Scheme	7
2.1.6 Sequence Voltage and Current Comparison	8
2.1.6.1 Type 1 Sequence Voltage and Current Magnitude - Phase Comparison Setpoints	9
2.1.6.2 Type 2 Sequence Voltage and Current Magnitude - Phase Comparison Setpoints	10
2.2 Voltage Based Open Phase Detection Methods	11
2.2.1 Undervoltage Detection.....	11
2.2.2 Overvoltage Detection.....	11
2.2.3 Degraded Voltage Relays	11
2.3 Negative Sequence Relays.....	12
2.3.1 Negative Sequence Differential Voltage Detection	12
2.4 Impedance Based Detection	13
2.4.1 Impedance relay characteristics	13
2.5 Harmonic Frequency Based Detection.....	13
2.6 Location of protection.....	14
2.6.1 Sequence Voltage and Current Comparison Scheme	14
2.6.2 Other Schemes	14

2.7	Communication aided schemes	15
2.7.1	Ethernet based detection schemes	15
2.8	Current transformers.....	15
2.8.1	Optical CTs	15
2.8.2	Rogowski Coils	17
2.8.3	Traditional iron core current transformers.....	18
2.9	Open Phase Detection Based on Active Neutral Signal Injection Combined with Passive Neutral Overcurrent Detection.....	18
2.9.1	Active Neutral Detection Method Response to a Single Open Phase on Primary of Transformer	18
2.9.2	Realization of the Active Neutral Detection Method.....	20
2.10	Transformer loading conditions	21
2.11	Anti-islanding technology Feasibility of Active Schemes	23
2.11.1	Introduction	23
2.11.2	Local Injection & Impedance Measurement.....	23
2.11.3	Remote Injection and Local Measurement Method.....	29
2.12	Open Phase Detection Methods Using Analog-to-Digital Converter Behavior	32
2.13	Power Transformer Open Phase Detection by Current Transformer Open Circuiting	32
2.14	Power Transformer Open Phase Detection using specially designed window- type current sensors	32
3.	Security and Dependability concerns.....	33
3.1	Load Bus Transfers	34
3.2	Emergency Generator Load Testing	34
3.3	Motor Starting and Acceleration.....	34
3.4	Fault Cases	35
3.5	Transmission Grid Disturbances	35
4.	Transformer data.....	36
4.1	Core-Type wye-primary transformers.....	36
4.2	Delta-primary transformers	37
4.3	Shell-type transformers.....	37
5.	Conclusion	37
APPENDIX A	Bibliography	39
A.1	NRC IN 2012-03: Design Vulnerability in Electric Power System, March 1, 2012	39
A.2	EPRI Report 1025772: Analysis of Station Auxiliary Transformer Response to Open Phase Conditions, Technical Update June 2012.....	39

A.3 EPRI Report 3002000764: Nuclear Maintenance Application Center: Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers, Final report May 2013.....	39
A.4 EPRI Report 1026484: Development and Analysis of an Open-Phase Detection Scheme, Technical Update, September 2012.....	40
A.5 Single phase diagram, Gary Kobet presentation at January 2013, IEEE PSRC meeting	40
A.6 Texas A&M University Relay Conference Paper: Open Phase Conditions in Transformers Analysis and Protection Algorithm, Amir Norouzi, GE Digital Energy, April 2013	42
A.7 Texas A&M University Relay Conference Paper: Effect of Transformer Connection and Construction on Single Phasing Detection, Gerald Johnson & Randy Hamilton, Basler Electric Company, Sudhir Thakur, Exelon Corporation, April 2013.....	42
A.8 Practical Guide for Detecting Single-Phasing on a Three-Phase Power System, John Horak and Gerald Johnson, Basler Electric Company, Presented at the Western Protective Relay Conference October 2002.....	42
A.9 EPRI Report 3002004432: Interim Report: EPRI Open-Phase Detection Method, October 2014.....	42
A.10 NEI Reports	43
A.11 Open-Phase Detection for Station Auxiliary Transformers, Dwayne Cox, Exelon Generation Company, Ahmed Abd-Elkader, and Harish Chaluvadi, Schweitzer Engineering Laboratories, Presented at the Western Protective Relay Conference October 2018.....	43
APPENDIX B Symmetrical Component Model of Phase Open Line	44
B.1 Symmetrical Component Overview	44
B.1.1 Symmetrical Component Networks	45
B.1.2 Symmetrical Component Networks for Open Phase Conditions	48
B.1.3 Symmetrical Component Network Connections for Open Phase Conditions	51
B.1.4 Simplified Symmetrical Component Analysis.....	57
B.1.5 Discussion of Symmetrical Component Analysis of Open Phase Conditions	58
APPENDIX C Optical CT	60
C.1 System components	61
C.2 Dual stream data processing	61
C.3 Redundant VT frequency reference	62
C.4 Relay logic description	62
C.5 Redundancy	63
APPENDIX D Rogowski Coils.....	65
APPENDIX E Open Phase Detection Methods Using Microprocessor Relays	67

E.1	Difference Between The Ratio Of The Second-Harmonic To Fundamental Currents	67
E.2	Digital Filters	68
E.3	Zero-Crossings Measurements	69
E.4	Zero-Sequence To Positive-Sequence Currents Ratio	70
E.5	Negative-Sequence To Positive-Sequence Currents Ratio	70
APPENDIX F Power Transformer Open Phase Detection by Current Transformer Open Circuiting		71
F.1	Introduction	71
F.2	Scheme Description	71
F.2.1	Configuration	72
F.2.2	Scheme Operation	72
F.2.3	Lab Testing	73
F.2.4	Field Testing	77
F.2.5	Scheme Improvement	79
F.3	Conclusions	80
APPENDIX G Power Transformer Open Phase Detection using specially designed window-type current sensors		81
Fig. 1	Open phase with ground location	3
Fig. 2	Hybrid Scheme simplified logic	8
Fig. 3	CT, VT, and Microprocessor Based Relay Connections	14
Fig. 4	Sequence network connections for a single open phase on the primary of a wye-grounded transformer	20
Fig. 5	Reduced sequence network for a single open phase on the primary of a wye-grounded transformer	20
Fig. 6	Realization of the active neutral injection method	21
Fig. 7	Delta-Wye Transformer with an Open Phase on the Wye Winding	23
Fig. 8	Dynamic System Simulation Model	24
Fig. 9	Impedance Plot	25
Fig. 10	Dynamic System Simulation model with Transmission line	26
Fig. 11	Impedance Plot	27
Fig. 12	Stray Capacitance in a Three Winding Transformer	28
Fig. 13	Short Circuit Impedance versus Frequency	29
Fig. 14	Schematic Diagram	30
Fig. 15	Signal Generation	31
Fig. 16	Signal Recovery	31
Fig. A-1	Present open phase condition protection scheme	41
Fig. A-2	Preferred open phase condition protection scheme	41
Fig. B-1	Nuclear Power Plant Electrical System One Line Diagram	46
Fig. B-2	Positive Sequence Diagram for Fig. B-1	47

Fig. B-3. Negative Sequence Diagram for Fig. B-1	47
Fig. B-4. Zero Sequence Diagram for Fig. B-1	48
Fig. B-5. Nuclear Power Plant Electrical System One Line Diagram--Open Phase Condition.....	49
Fig. B-6. Open Phase Positive Sequence Diagram for Fig. B-5.....	50
Fig. B-7. Open Phase Negative Sequence Diagram for Fig. B-5	50
Fig. B-8. Open Phase Zero Sequence Diagram for Fig. B-5	51
Fig. B-9. Symmetrical Component Network Connections for Open Phase Conditions shown in Fig. B-5.....	52
Fig. B-10. Simplified Component Network Connections for Open Phase Conditions shown in Fig. B-5.....	53
Fig. C-1. OPTICAL CT	60
Fig. C-2. Open Phase Detection Architecture.....	61
Fig. C-3. Test of Normally Connected Power Transformer, Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current	64
Fig. C-4. Test of Faulty Connected Power Transformer (Phase B Open), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current	64
Fig. C-5. Test of Faulty Connected Power Transformer (Phase B Grounded), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current	64
Fig. D-1. Examples of Rogowski Coil Designs.....	66
Fig. D-2. Examples of Rogowski Coil Installations	66
Fig. E-1. Difference Between The Ratio Of The Second-Harmonic To Fundamental Currents.....	68
Fig. E-2. Open Phase Event Involving Long Cables	68
Fig. E-3. IIR Filter Response	69
Fig. E-4. Zero-Crossings Open Phase detection logic	70
Fig. F-1. Three legged core transformer.	71
Fig. F-2. Basic scheme design.	72
Fig. F-3. Magnetizing test current applied to current transformer primary.	73
Fig. F-4. Voltage measured across current transformer secondary when open circuited (primary test current 1 A peak).	74
Fig. F-5. Voltage measured across current transformer secondary when open circuited (primary test current 2 A peak).	74
Fig. F-6. Voltage measured across current transformer secondary when open circuited (primary test current 3 A peak).	75
Fig. F-7. Voltage measured across current transformer secondary when open circuited (primary test current 5 A peak).	75
Fig. F-8. Voltage measured across current transformer secondary when open circuited (primary test current 10 A peak).	76
Fig. F-9. Voltage measured across current transformer secondary when open circuited (primary test current 20 A peak).	76
Fig. F-10. Harmonic content of the waveform of Fig. F-9.	76
Fig. F-11. Protection one-line drawing of power transformer on which the scheme was tested.	78

Fig. F-12. Voltage measured across A-phase current transformer secondary when open circuited.....	79
Fig. F-13. Raw voltages measured by test relay when A-phase CT open circuited. Scale by $\sqrt{2}$ to see actual waveform amplitude.	79
Fig. G-1. System Layout Drawing.....	82
Fig. G-2. Field data on 345kV transformer exciting current (3 ϕ avg.).....	82
Fig. G-3. Lab data from “A”-phase open test case.	83
Table 1: Impact of Transformer Parameters’ ’	2
Table B1. Typical Light Load Impedance Values, Normal Operation.....	54
Table B2. Typical Light Load Impedance Values, Accelerating Motors	55
Table B3. Typical Load Impedance Values, Significant Load	56
Table B4. Typical Load Impedance Values, Significant Load, Accelerating Motors	57
Table F1. Summary of Test Results.....	73
Table F2. Estimated Base Rating of 230kV Transformer.....	76

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1. INTRODUCTION

1.1 Assignment

The report presents approaches used to detect open phase conditions that occur in the three phase, high voltage power supply to primary windings of grid connected station auxiliary transformers that provide energy to nuclear power plants.

The report addresses:

1. The effect of an open phase condition on transformer types (shell/core) and winding configurations
2. Schemes that can detect open phase conditions
3. Location of the detection schemes
4. Discussion of open phase consequences

1.2 Summary

In 2012, the Nuclear Regulatory Commission issued NRC Information Notice 2012-03. This notice was a call to action to the owners and operators of nuclear generating stations to review their procedures and protection schemes as to their ability to detect the loss of a phase of an offsite power circuit. The NEI (Nuclear Energy Institute) is developing a response for the industry. This IEEE PES PSRCC report is meant to discuss state of the art detection methods.

Schemes that are being implemented:

1. Active injection
2. Phase current unbalance

1.3 Purpose

This Institute of Electrical and Electronics Engineers (IEEE) Power System Relaying and Control Committee (PSRCC) report provides insights into open phase detection schemes brought to the attention of this working group. The report discusses the difficulty in detecting such an anomaly with conventional detection and/or protection schemes depending on the type and loading condition of certain transformers.

The response to an open-conductor condition depends on transformer construction. Table 1, below, shows the voltage response of unloaded and/or lightly loaded transformers for various transformer winding and core configurations to an open phase (A) on the primary. As can be seen in the table, under no-load conditions delta connected primaries and wye primary transformers that do not have a delta connection on their

secondary/tertiary or are not a core-form transformer result in low voltages on their primary and secondary. Whereas, the wye connected primaries that have a delta connection on their secondary/tertiary or are core-form transformers, recreate the voltage to 1 pu in the open phase. This illustrates the fact that certain transformer configurations may not require the same protection needed for those transformers that recreate the voltage.

The addition of motor loads, which alter these voltage responses, need to be studied for each transformer configuration. The addition of motor loads may balance the voltages somewhat due to the backfeed from the motors.

Table 1: Impact of Transformer Parameters^{1, 2, 3}

	Primary Voltage (pu)			Secondary Voltage (pu)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Wye-Wye (Shell Core)	0	1.0	1.0	0	1.0	1.0
Wye-Wye* (5-Legged Core)	0.54	1.0	1.0	0.54	1.0	1.0
Delta-Wye (3-Legged Core)	0.5	1.0	0.5	0.5	1.0	0.5
Wye-Wye (3-Single Phase Cores)	0	1.0	1.0	0	1.0	1.0
Wye-Delta (3-Legged Core)	1.0	1.0	1.0	1.0	1.0	1.0
Wye-Wye (3-Legged Core)	1.0	1.0	1.0	1.0	1.0	1.0
Wye-Wye (Shell Core with	1.0	1.0	1.0	1.0	1.0	1.0

¹ Analysis of Station Auxiliary Transformer Response to Open Phase Conditions, EPRI, Palo Alto, CA: 2012, EPRI Report 1025772.

² Development and Analysis of an Open-Phase Detection Scheme. EPRI, Palo Alto, CA: 2012, EPRI Report 1026484.

³ Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers, EPRI, Palo Alto, CA: 2012, EPRI Report 3002000764.

Buried Delta)						
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*An open in Phase B (inner leg) of the transformer, the voltage on Phase B becomes 0.43 pu.

Based on the results of Table 1, there are generally two categories of station auxiliary transformers:

- those that can use conventional detection
- those that need unconventional detection

The transformers in the shaded section of Table 1 are the transformers that require unconventional detection. If a site has one of these types of transformers and they are unloaded or lightly loaded, then a review of the open phase detection schemes presented in this report could be beneficial for possible application as needed.

1.4 Definitions

The open phase condition is a break in a power conductor such that current cannot flow into a conductor at a source terminal. An open phase can also occur due to equipment malfunction such as breaker pole discordance. Open phase conditions could involve two phases in practical application.

An open conductor can be isolated from ground or in contact with ground, depending on the location of the discontinuity and the length of conductor between support structures.

For open phase conditions addressed in this Special Report, one of three phase conductors is assumed to be open.

Throughout this report there will be references to an open with a ground. Fig. 1 shows a very simple drawing indicating the location of the ground. Note that it is on the transformer side of the open. A ground on the source side would normally be detected by conventional line relay protection.

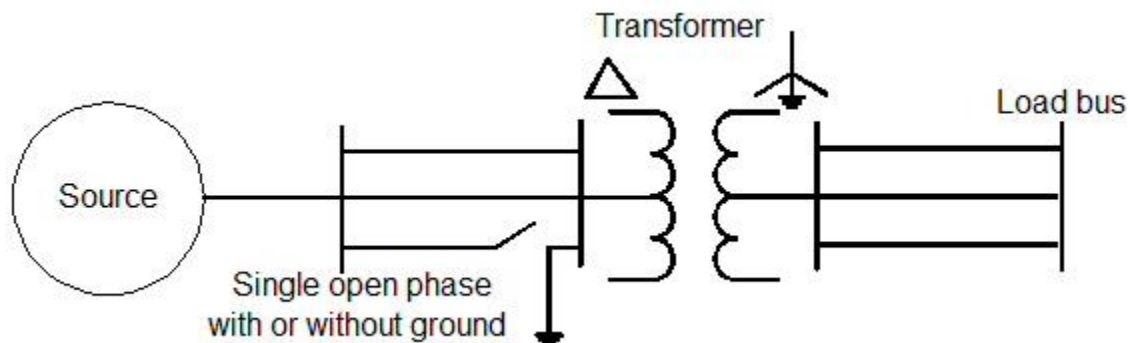


Fig. 1 Open phase with ground location

1.5 Key Abbreviations and Acronyms

AUX	Auxiliary
Class 1E	Special term that describes safety-related electrical equipment
CSST	Common Station Service Transformer
CT	Current Transformer
EMTP	Electromagnetic Transients Program
EPRI	Electric Power Research Institute
ESF	Engineered Safety Feature
FIDVR	Fault Induced Delayed Voltage Recovery
Gen.	Generator
GSU	Generator Main Step Up Transformer
IEEE	Institute of Electrical and Electronics Engineers
IN	Information Notice
LV	Low Voltage – less than 1000 volts
MV	Medium Voltage more than 1000 volts, less than 35,000 volts
NEI	Nuclear Energy Institute
NEMA	National Electrical Manufacturers Association
N.O.	Normally Open (circuit breaker)
Neg Seq	Negative Sequence
NRC	Nuclear Regulatory Commission
OPC	Open Phase Condition
OpenDSS	Distribution System Simulator (EPRI developed frequency-domain open-source software simulator)
PES	Power & Energy Society
Pos Seq	Positive Sequence
PSRCC	Power System Relaying and Control Committee
RCP	Reactor Coolant Pump
Ref Bus	Reference Bus
SAT	Station Auxiliary Transformer
SCRAM	Emergency Shutdown of a Nuclear Reactor
Tr.	Transformer
VY	Voltage Transformer
Zero Seq	Zero Sequence

2. Detection methods and location of protection

This clause discusses various detection methods for identifying open phase conditions. Active and passive detection schemes are presented. For each specific scheme, an explanation is presented as to how it works and whether an open phase can actually be determined using such a scheme. Additionally there is some discussion on various sensors that have been employed to detect an open phase.

2.1 Current Based Detection Schemes

The following current based schemes are discussed in the section:

- current differential

- phase current unbalance
- phase comparison
- sequence quantities

Very low current values (i.e., magnetizing current that are typically in the mA primary range) at high voltages (the kV levels) are difficult to measure. Thus, most current based methods have difficulty in effectively detecting open phase conditions on transformer types that are susceptible to voltage recreation under open phase conditions.

2.1.1 Current differential

Current differential relays measure the true differential between relay input currents. There are several basic types of current differential relays such as those meant for transformers, motors, generators, busses, pilot wires, and transmission lines.

Each of these schemes measures the current on an individual phase basis and thus can easily detect most fault conditions within the protection zone. The transmission line difference in current seen by each terminal is the result of the mismatch of CTs, line charging current, unaccounted for tapped load, and of course short circuits. To allow for any mismatch that is not fault related, these relays may have a minimum threshold or slope setting that relates an operate quantity to a restraint quantity that is to be met before the relay declares a fault condition. The problem is that for an open phase with no fault, the particular phase in question may show either no current or very little which is below threshold, in the no trip slope region, or appears to sum to zero. As a result, to the differential current relay, there is no mismatch.

Given the setting constraints for this type of relay, it would not appear to be dependable to trip for open phase conditions. If a simultaneous fault also occurred, then the differential relay would have a higher probability of operation.

2.1.2 Phase current unbalance

The most intuitive method for open phase detection is phase current unbalance. If one phase is less than a setpoint, while the two remaining phases are greater than a setpoint, this could be indicative of an open conductor. This method requires a detectable current level on the two healthy phases, which, given the inaccuracies in CTs, is typically significantly above the transformer magnetizing current. Therefore, some load is required on the transformer in order to produce enough current to detect the difference while not tripping the transformer under light loading. This scheme will not work in cases of an open phase which is grounded (Fig. 1), if the CTs are located downstream of the grounded phase. In this situation, the magnitude of the current on the grounded phase will remain relatively high, and may even be equal to the current on the healthy phases.

High current on two phases with one phase low is also indicative of a line to line or a double line to ground fault. Therefore, it is necessary that the open phase detection scheme coordinate with existing fault detection relays. This may require monitoring of

additional quantities, such as sequence quantities, in order to prevent tripping the open phase detection due to an unbalanced fault downstream of the transformer.

A drawback of the phase current unbalance scheme is the difficulty in differentiating between an open phase and grid unbalances due to transients or steady-state unbalances caused by non-transposed lines, unbalanced loading, etc. It is possible that a high zero sequence component on the transmission grid can result in a load current which is 180 degrees out of phase with one of the phase currents. As a result, the magnitude of the current on that phase would be significantly reduced due to cancellation with the zero sequence component, resulting in a possible false-detection. The use of this scheme requires a loading which is greater than the maximum zero sequence component of the load current which could flow as a result of a grid unbalance.

2.1.3 Phase Comparison

A form of line current differential protection that has been employed for many years for fault detection is phase comparison. This communication based scheme has numerous basic forms with names such as: static-phase-comparison, straight-phase comparison-blocking-mode, straight-phase-comparison-permissive-mode, single-phase-comparison blocking, dual-phase-comparison blocking, dual-phase-comparison transfer trip, segregated phase comparison, and non-segregated phase comparison. All of these schemes are based on comparing the phase angle between primary line currents at the ends of the protected section. If the line currents are essentially 180° out of phase, then there is no fault between terminals within the protected section. If the line currents are in phase, then there is an internal fault within the protected section.⁴ There are two basic schemes employed for doing the actual comparison; Segregated and Non-Segregated.

A Segregated version of phase comparison uses 3 individual phases (and perhaps $3I_0$); and thus would need 3 or 4 communication channels per terminal rather than one that is used for non-segregated schemes to send the phase information to the remote terminal. The segregated version has been developed to be especially useful for series compensated lines. Since the open phase has zero current (or very low), there would be nothing to compare for that phase. The assumption would be that the other 2 phases are good and have "normal" power flow, so they would not operate either for an open phase. Thus a segregated phase comparison relay could be considered inherently blind to open phase conditions.

Non-Segregated schemes tend to have two fault detector levels; FD1 (typically set above load and starts the comparison) and FD2 (based on available fault current and used for tripping) and make use of a composite signal that has removed knowledge as to the actual faulted phase. For an open phase condition, the composite signal would indicate a non-fault condition since the composite current would appear to go in one terminal and out the other. Thus the non-segregated phase comparison relay could also be considered inherently blind to open phase comparison.

⁴ GE Multilin publication GER-2681B, "Phase Comparison Relaying"

2.1.4 Sequence Quantities

The open phase on the high side of a wye-primary transformer will cause a circulating current in any delta windings of the transformer or in the tank for transformers without delta windings. As a result, high zero sequence current is expected, especially when the open phase is grounded (Fig. 1). This current can typically be detected with metering-class CTs. High levels of zero sequence current can be observed under fault conditions, however, so it is necessary to verify coordination with existing fault detection relays.

A drawback of this scheme is the difficulty in differentiating between an open phase and grid unbalances due to transients or steady-state unbalances caused by non-transposed lines, unbalanced loading, etc. The sequence current based detection scheme may need to be set greater than any expected sequence quantities present due to grid unbalances.

2.1.5 Hybrid Scheme

Part of the difficulty in addressing open phase protection is the wide range in severity for possible open phase events. A single open phase on an unloaded wye-primary transformer may produce very little disruption, to the extent that the condition is very nearly indistinguishable from normal operation. Whereas, an open phase in contact with grounded equipment (on the transformer side, Fig. 1) may cause severe unbalance resulting in immediate trips of all downstream loads. While it may be critical to trip/isolate severe open phase events immediately, in less severe events, it is preferable to avoid immediate trips in order to allow plant operators time to assess the situation and make informed decisions on how best to address the situation with minimal disruption to safety and non-safety systems.

In response to these concerns, the hybrid scheme has been implemented at numerous nuclear stations. The scheme consists of open phase detection on the high side of the transformer (i.e. Optical CT, neutral injection (see clause 2.9 for an explanation), or other similar schemes), combined with open phase protection on the low side of the transformer (based on negative sequence voltage or undervoltage relays), which will trip whenever the voltage on the downstream buses is sufficiently unbalanced as to cause adverse conditions (i.e. damage or tripping of any safety-related equipment). This scheme has typically been implemented with the high side open phase detection relay in alarm-only mode, so that the operator will be alerted whenever there is a potential open phase condition, but the scheme will only trip when necessary to prevent damage or tripping of equipment.

Design of this scheme and determination of setpoints requires that all safety-related equipment be evaluated (typically motor-by-motor) in order to determine how quickly it will be either damaged or tripped due to varying voltage conditions at the bus level (typically an exhaustive set, varying negative sequence voltage and total phase magnitude, has been considered). Settings for the negative sequence voltage protection are then determined by the allowable time to reach an adverse condition at varying levels of negative sequence voltage. Typically, two or more negative sequence voltage relays

(sensitive setting with a long time delay, combined with a high setting and a short time delay) are used in order to provide protection and eliminate spurious trips.

Settings for the high side open phase detection are then determined by ensuring that all open phase events are detected. In some cases, these more sensitive settings may result in the potential for spurious indication under non-open phase conditions. However, with a relay implemented in alarm-only mode, the undesirable outcomes for possible insecure indications are mitigated.

Fig. 2 below shows a simplified alarm and tripping scheme.

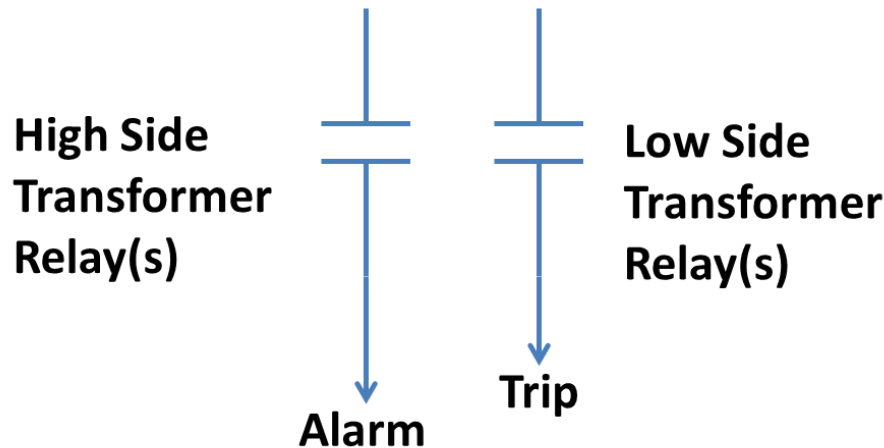


Fig. 2. Hybrid Scheme simplified logic

2.1.6 Sequence Voltage and Current Comparison

Using the simplified component network shown in Fig. B-10 (see the very simplified relay connections in Fig. 3) and impedance values listed in Table B1, Table B2, Table B3, and Table B4 (see Appendix B) reveals that comparison of positive (I1), negative (I2), and zero (I0) sequence current magnitudes in conjunction with phase angle relationships between positive sequence voltage (V1) and current (I1) and negative sequence voltage (V2) and current (I2) may be an effective method to detect open phase conditions.

Under normal conditions, positive sequence voltage leads positive sequence current by 25 degrees and negative sequence current and zero sequence current are zero.

Under open phase conditions, with motors rotating, positive sequence voltage leads positive sequence current by more than 25 degrees and negative sequence current and zero sequence current are not zero.

Under open phase conditions, with motors accelerating, positive sequence voltage leads positive sequence current by 75 degrees and negative sequence current and zero sequence current are not zero.

To be effective, multi-step, timed, sequence magnitude and phase comparisons are needed. At light load levels, a 10 second delay before protective relay schemes actuate in response to open phase conditions can be acceptable. During acceleration of a significant number of motors, a 2 second delay will be preferred.

Sequence voltage and current magnitude - phase comparison schemes can utilize positive sequence voltage and current from existing medium voltage VTs and CTs (connected to the transformer secondary) and negative sequence current as a primary indicator of open phase conditions.

With relaying class CTs and microprocessor based protective relays, sequence voltage and current magnitude/phase comparison schemes should be able to quickly and securely detect open phase conditions. Relaying class CTs are designed to be 3% accurate at rated current and at rated burden and 10% at 20 times rated current at rated burden.⁵

The next two sub-clauses describe settings for two types of system grounding. Type 1 discusses a system that would have a resulting zero sequence impedance network that has either an open or has a high impedance; such as from a delta or ungrounded wye or perhaps a high impedance neutral wye connection. Type 2 discusses a system that would have the resulting zero sequence network, that is has zero or low impedance, such as from a solidly grounded or low impedance neutral wye connection.

2.1.6.1 Type 1 Sequence Voltage and Current Magnitude - Phase Comparison Setpoints

(Type 1: Open Circuit Zero Sequence Network)

For the system shown in Fig. B-5, with 2000/5 CTs and 4.16 kV / 120 V VTs on the secondary of Station Tr. 2, typical settings for systems with an open or high impedance zero sequence network would be:

If $I_1 > 20$ amps and $I_2 > 40\% I_1$ and V1 leads I_1 by 40 degrees, alarm and trip in 10 seconds.

If $I_1 > 40$ amps and $I_2 > 40\% I_1$ and V1 leads I_1 by 40 degrees, alarm and trip in 5 seconds.

If $I_1 > 40$ amps and $I_2 > 40\% I_1$ and V1 leads I_1 by 70 degrees, alarm and trip in 2 seconds.

⁵ IEEE Standard Requirements for Instrument Transformers, IEEE Standard C57.13-2016, June 2016.

If $I_1 > 120$ amps and $I_2 > 40\%$ I_1 and V_1 leads I_1 by 40 degrees, alarm and trip in 10 seconds.

If $I_1 > 120$ amps and $I_2 > 40\%$ I_1 and V_1 leads I_1 by 70 degrees, alarm and trip in 2 seconds.

If $I_1 > 600$ amps and $I_2 > 40\%$ I_1 and V_1 leads I_1 by 40 degrees, alarm and trip in 10 seconds.

If $I_1 > 600$ amps and $I_2 > 40\%$ I_1 and V_1 leads I_1 by 70 degrees, alarm and trip in 1.0 second.

At 4.16 kV busses with induction motors rotating, 20 amps is equivalent to 150 hp; 40 amps is equal to 300 hp; 120 amps is equal to 900 hp and 600 amps is equal to 4,500 hp.

At 4.16 kV busses with induction motors accelerating, 20 amps is equivalent to 50 hp; 40 amps is equal to 100 hp; 120 amps is equal to 300 hp and 600 amps is equal to 1,500 hp as motor current is a function of slip.

Note that $I_2 > 40\%$ I_1 is somewhat arbitrary, that is, I_2 values between 10% and 40% of I_1 will be acceptable.

2.1.6.2 Type 2 Sequence Voltage and Current Magnitude - Phase Comparison Setpoints

(Type 2: Low Impedance Circuit Zero Sequence Network)

For the system shown in Fig. B-5, with 2000/5 CTs on the secondary of Station Tr. 2, typical settings for systems with a low impedance zero sequence network would be:

If $I_1 > 40$ amps and $I_2 > 10\%$ I_1 alarm in 10 seconds and trip in 10 minutes.

If $I_1 > 120$ amps and $I_2 > 10\%$ I_1 alarm in 10 seconds and trip in 5 minutes.

If $I_1 > 240$ amps and $I_2 > 10\%$ I_1 alarm in 10 seconds and trip in 1 minute.

If $I_1 > 600$ amps and $I_2 > 10\%$ I_1 alarm and trip in 2.0 seconds.

Note that $I_2 > 10\%$ I_1 is somewhat arbitrary, that is, I_2 values greater than 10% of I_1 may be acceptable. The significant consideration is that the low zero sequence impedance shunts the negative sequence impedance and significantly reduces negative sequence voltage which in turn reduces negative sequence heating of the motor.

The preceding setpoints are based on typical load conditions that are biased to actuate quicker when motor stalling or acceleration is detected. V_1 , I_1 , and I_2 are being used.

Angular differences need to be calculated for specific categories of motors and motor designs. Small angular differences are typical of load current. Large angular differences indicate motor locked rotor current. Negative sequence current and larger than expected

angular differences are indicators of open phase conditions. Delay on tripping needs to be based on open phase, reduced speed, motor heating calculations.

Determination of actual setpoints for a specific nuclear power plant requires detailed analysis of specific transformer winding configurations, actual load conditions, etc. Positive sequence voltage and current as well as negative sequence current can be detected at any location downstream of the open phase as sequence voltage and current comparisons are primarily functions of load.

2.2 Voltage Based Open Phase Detection Methods

Voltage based open phase detection needs to include transformer core configuration and winding connections as design inputs. For Wye-primary transformers with a three-legged core, when there is an open phase on the primary winding, the coupling between the phases will tend to reproduce the lost voltage on the low side of the transformer. For an open phase where the open conductor does not short to ground, and under light transformer loading, the change in voltage on the low side of the transformer may be undetectable with simple voltage based detection.

2.2.1 Undervoltage Detection

Undervoltage detection may introduce additional concerns. Short circuits at remote locations along with FIDVR (Fault Induced Delayed Voltage Recovery) will need to be studied and evaluated as the power grid evolves.) This is to assure that open phase detection undervoltage schemes do not actuate inadvertently.

2.2.2 Overvoltage Detection

Overvoltage detection may introduce additional concerns. Short circuits at remote locations and transmission system recovery voltage at nuclear generating stations during upset conditions (such as loss of offsite power, turbine trips, faults on the secondary steam side, gas blower failure) will need to be studied and evaluated as the power grid evolves. This is to assure that open phase detection overvoltage schemes do not actuate inadvertently.

2.2.3 Degraded Voltage Relays

Degraded voltage relays are employed to ensure that adequate voltage is available to operate all Class 1E loads at all voltage distribution levels. Should the voltage drop below the setpoint of the degraded voltage relay, the Class 1E power system is disconnected from its supply and resequenced onto the diesel generators in order to restore system voltages to acceptable levels.

Degraded voltage relays are not able to detect an open phase in most cases. For Wye-primary transformers, the phase voltages on the low side remain relatively normal, depending on the transformer loading, and unless there is significant load, the phase voltages are not expected to drop below a degraded voltage setpoint (typically undervoltage is set at 95% and overvoltage is set at 105%). Under heavy load, protective

relays applied for motor protection may actuate faster than the typical actuation time delay for degraded voltage relays, making it likely that voltage will recover to near normal before degraded voltage relays actuate.

Under intermediate loading scenarios, if the motors do not stall, the motors will tend to balance voltage on medium voltage buses and mask the effect of the open phase. This is especially true for delta-primary transformers, where the voltages on the secondary of the transformers drop to 50% under no load, but can easily increase to above the typical degraded voltage setpoints when there is significant motor load on the transformers. In this case, evaluating heavy and light loading cases may not be bounding, and it is necessary to run intermediate loading cases. The most difficult case to detect will be the maximum possible motor load before the motors stall during the open phase.

2.3 Negative Sequence Relays

Depending on transformer construction and winding connections, open phase events can be characterized by either negative sequence current, or zero sequence current. If sufficient load is on the low voltage side of the transformer, there may be a significant negative sequence voltage component. However, an open phase detection relay needs to coordinate with the existing fault detection relays so as to minimize having any misoperations. A high impedance line-to-line fault that is just below the pickup of the fault detection relay will produce significant negative sequence voltage. The open phase detection relay will have to be set above the negative sequence voltage that is produced by this type of fault. As a result, the necessary load in order to detect the open phase may be higher than the typical load that is carried by the transformer. The solution which has been proposed to do this is to use a negative sequence current restraint. In the event of a fault which produces high negative sequence current on the low side of the transformer, the relay will be blocked from operating.

A negative sequence voltage relay placed on the high side of the transformer, depending on the location, may detect very little negative sequence voltage due to the open phase. Additionally, negative sequence voltages tend to be detectable (less than 3% of positive sequence voltage) in the transmission grid due to normal grid unbalances. Historical information regarding the level of unbalanced voltage in the transmission grid is scarce, and typically, any data will only consist of voltage magnitudes, making it impossible to determine sequence component data. Furthermore, it is impossible to predict the expected grid voltages over the expected life of the relay. Therefore, it is difficult to determine an open phase detection setpoint which is above the expected grid contribution.

2.3.1 Negative Sequence Differential Voltage Detection

One drawback of the negative sequence voltage detection approach is that it is impossible to predict the negative sequence voltages which will be present on the transmission grid. Differentiating between an open phase in the switchyard and a grid disturbance needs to be taken into account when determining setpoints. In order to account for the unknown grid unbalance, a differential voltage scheme has been proposed. The scheme monitors

the difference in negative sequence voltage between the point of interconnection with the transmission grid, and the low side of the transformer. It has been proposed to connect auxiliary VTs between the high and low sides of the transformer such that the negative sequence differential voltage can be observed directly from the VT connections. However, this scheme does introduce the potential for voltage feedback through the VT circuit when the transformer breakers are open. To reduce this possible feedback issue, the high and low side VTs (and thus avoiding the use of auxiliary VTs in the differential circuit) could be connected directly to a microprocessor-based relay, which would then calculate the negative sequence component of the differential voltage through programming.

This scheme provides robustness against disturbances in the transmission grid, and when combined with negative sequence current restraint to prevent tripping due to unbalanced faults on the low side of the transformer, it can result in a secure scheme. The drawback of this scheme is the complexity, requiring many CTs and VTs, as well as requiring a microprocessor relay with many inputs. Additionally, significant load may be required, especially when the transformer has a delta winding, as the winding tends to balance the differential voltages.

2.4 Impedance Based Detection

Impedance relays measure system voltages and currents and compare the ratio of input voltage divided by input current to a threshold (setpoint) value.

2.4.1 Impedance relay characteristics

Impedance relays determine power circuit impedance and operate if the measured circuit impedance drops below predetermined limits. Also known as distance relays, they are typically classified according to the shape of their zone of operation. Thus, the basic types include Impedance, Mho, Offset Mho, Self-polarized Mho, Reactance, Quadrilateral, and Lenticular. Both single-phase and poly-phase types are available.

All distance relays operate using the same basic principle; the relays measure some version of the voltage to current ratio; $Z = \frac{V}{I}$. If the voltage goes low and the current goes high, then it is likely a fault has occurred. In the case of an open phase condition, the voltage may remain essentially unchanged from the pre-open condition and the current may remain very low (perhaps even zero) or might even be the load current. Thus, it would appear that an impedance relay may not see an open phase condition.

2.5 Harmonic Frequency Based Detection

Open phase conditions are not expected to result in deviations to the frequency of 60 Hz power systems. Some special scenarios, such as an open conductor that is arcing to ground, may result in detectable harmonics as the total current will be asymmetrical. But, the low probability of detectable harmonics reduces the efficacy of harmonic detection.

2.6 Location of protection

2.6.1 Sequence Voltage and Current Comparison Scheme

CTs and VTs for the Sequence Voltage and Current Comparison scheme discussed in Section 2.1.6 are shown in Fig. 3 below. Protective relays applied to detect open phase conditions need to be connected to VTs and CTs that monitor motor current as motors need to either be operating or accelerating for open phase conditions to be detectable.

Ideally, open phase protection would be provided for each three phase motor. As this is not feasible in a power generating station, open phase protection could be applied on a bus basis utilizing VTs connected to the bus and CTs associated with each incoming power supply. CTs and VTs for the Sequence Voltage and Current Comparison scheme discussed in Section 2.1.6 scheme would be installed at the 4.16 kV bus in Fig. B-1. The induction motor shown in the following figure can be a 4.16 kV motor, several 480 volt motors or an equivalent motor.

The sensitivity of the open phase scheme is a function of the location of the CTs, bus voltage and CT ratio. For a given threshold current, such as 0.05 relay amps, with 2000/5 CTs, at least 150 hp of motors need to be rotating in order to detect an open phase condition at a 4.16 kV bus. When bus voltage is increased to 13.8 kV, at least 500 hp of motors need to be rotating in order to detect an open phase condition.

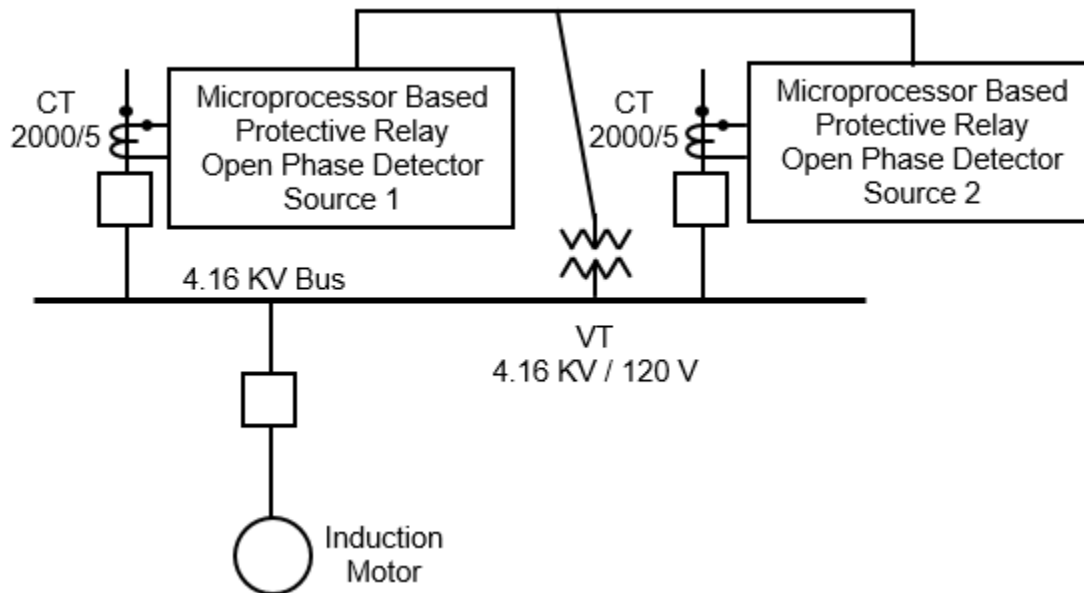


Fig. 3. CT, VT, and Microprocessor Based Relay Connections

2.6.2 Other Schemes

The location of CTs and VTs for other schemes would be similar to the location of CTs and VTs shown in Fig. 3.

2.7 Communication aided schemes

2.7.1 Ethernet based detection schemes

The development of IEC 61850 (the International Standard Communication Networks and Systems in Substations), DNP3 (the Distributed Network Protocol IEEE STD 1815-2010), and many other standards for IEDs that are Ethernet related, have led to creation of all manner of protection and control logic that can be used to implement a detection scheme. Without the need to have extensive wiring and through the use of the substation Ethernet connections, protection functions can be enhanced in addition to all of the other control functions.

For example, it could be that the motor protection will be the best way to determine that a line has an open phase. Thus, using something like IEC 61850 to communicate amongst relays, it is possible to determine if it is a single motor or multiple motors that have detected an unbalance. If multiple motors detect something simultaneously, then it is probably not an individual motor circuit problem and thus is more likely a system problem. Should multiple motors detect an issue, then standby generators could be started and operators alerted to investigate further.

Additionally, it would be possible to have the generating station's line, bus, and transformer relays send to a host computer the voltages and currents measured. IEC 61850 can easily perform this task. The host computer could then execute calculations to determine if there is an open phase condition and issue appropriate trip and control signals.

2.8 Current transformers

2.8.1 Optical CTs

Optical current sensors (CTs) have been successfully tested at one utility for the detection of open (or grounded) phase conditions (OPC) on unloaded and loaded power transformers. Passive fiber optic current sensors are placed in aluminum rings which are installed by slipping over the bushings of the high side of each phase. The VT triggered optical CTs are able to measure the magnetization (plus capacitive) currents flowing into each phase of the transformer from the high side while the low side is unloaded. Currents flowing into the high side of the power transformer with unloaded secondary are on the order of 50 mA to 1 A depending on the type of transformer.

In the open phase condition, the current on that phase significantly drops. The optical CT easily measures this drop, as it has a measurement noise floor of a few mA. The optical CT measures small currents with excellent stability. The centering of the ring around the current carrying conductor is not important. Since both the measurement principle and the data transmission are optical, the CT is immune to electromagnetic pickup.

A relay with IEC 61850-9-2LE Process Bus capability reads the currents coming from the 3-phase CT electronics chassis, and is programmed to detect open phase conditions, including grounded phase and high impedance grounded phase conditions. This relay can

be set with 2 mA resolution down to 0 mA. The communications between the CT electronics chassis and the relay is via optical Ethernet. The relay logic employs the measurement of the individual phase currents together with a zero sequence check for the case of an unloaded transformer, and a negative sequence check for the case of a loaded transformer. In the case of long incoming lines, where there can be significant charging of an open phase line, the unloaded transformer case can also be monitored using a negative sequence check.

Optical Current Sensor And Features

Fiber optic current sensors have been in commercial development for applications in the electric power grid for over 30 years.^{6, 7, 8, 9, 10, 11, 12, 13, 14, 15} Current flow is detected through combining the Faraday Effect with Ampere's law. The total rotation angle of linearly polarized light or (equivalently) the excess phase shift of circularly polarized light in a fiber encircling a conductor is linearly proportional to the current flowing in that conductor. Ampere's law guarantees that as long as the sensor encircles the conductor, its sensitivity does not depend on its positioning relative to the conductor, and it is insensitive to all externally flowing currents and magnetic fields. Optical current sensors provide several key advantages over wire wound CTs for the measurement of small currents in the substation environment. These advantages include:

- i) Wide linear dynamic range (1 mA to >100 kA, allowing for one sensor to easily cover both the loaded and unloaded transformer cases),

⁶ Rose, A. H., Day, G. W., "Optical Fiber Current and Voltage Sensors for the Electric Power Industry," chapter 27, Handbook of Optical Fibre Sensing Technology, ed. Jose Miguel Lopez-Higuera, Wiley & Sons, Ltd., West Sussex, England, 569-618 (2002).

⁷ Bohnert, K., Gabus, P., Nehrign, J., Brandle, H., Brunzel, M. G., "Fiber-Optic Current Sensor for Electrowinning of Metals," J. of Lightwave Tech., Vol. 25, No. 11, 3602-3609, (2007).

⁸ Bosselmann, T., "Innovative applications of fiber-optic sensors in energy and transportation," Proc. SPIE 5855, 188-193 (2005).

⁹ Masao, T., Sasaki, K., Terai, K., "Optical Current Sensor for DC Measurement," Proc. T&D Conf. 2002: Asia Pacific IEEE/PES, 440-443 (2002).

¹⁰ Rose, A. H., Blake, J. N., "Free Form Factor Optical Current Sensor for AC and DC Commercial Power Applications," Proc. 18th International Conference on Optical Fiber Sensors, Cancun, Mexico, Oct., 1-4 (2006).

¹¹ Blake, J. N., Rose, A. H., "Interfacing Optical CTs and VTs to Relays and Meters," Proc. 2005/2006 IEEE PES T&D meeting, Dallas, TX, May, 1-4 (2006).

¹² Blake, J. N., Rose, A. H., "Fiber-Optic Current Transducer Optimized for Power Metering Applications," Proceedings of the IEEE T&D meeting, Dallas, TX, Sept., 1-4 (2003).

¹³ Blake, J. N., Rose, A. H., "Precision Fiber-Optic Current Sensor as a Check-Standard," Proc. IEEE PES summer meeting, Chicago, IL, Jul., 1-5 (2002).

¹⁴ Blake, J., Rose, A., Glasow, C., Bergh, R. A., "An Optical Current Transducer having Linearity Better than 0.4% from 4 to 108,000 A," Proc. 15th Optical Fiber Sensors Conference, Portland, OR, May, 545-548 (2002).

¹⁵ Sanders, G. A., Blake, J. N., Rose, A. H., Rahmatian, F., Heardman, C., "Commercialization of Fiber-Optic Current and Voltage Sensors at NxtPhase," Proc. 15th Optical Fiber Sensors Conference, Portland, OR, May, 31-34 (2002).

- ii) Ability to arbitrarily increase the measurement sensitivity to low currents by increasing the number of fiber sensing turns in the sensing head (40 sensing turns yields good results for the open phase application),
- iii) Ability to size the sensing head to any diameter (aluminum ring housing large enough to slip over the high side transformer bushing contains the wraps of sensing fiber),
- iv) Immunity to electromagnetic pickup (allowing for robust measurement of mA currents in the substation environment),
- v) Ability to transmit the data a long distance via optical fiber (allowing the CT electronics and relay to be located inside a distant control room),
- vi) Digital communications (allowing for reliable data transfer via optical Ethernet).

Appendix C has a more detailed description of the optical CT system.

2.8.2 Rogowski Coils

Rogowski coils operate based on a principle similar to conventional iron-core current transformers. The major difference is that the Rogowski coil secondary is wound over a non-magnetic core, which provides linear volt-current relationship. This is an important characteristic for a current sensor. However, because of the non-magnetic core that supports the secondary winding, mutual coupling between the primary conductor and the secondary winding is weak. To obtain quality current sensors, the Rogowski coil manufacturing process needs to be precise to satisfy required design criteria. When design criteria are met, Rogowski coils may achieve high accuracy (up to 0.1%). The same sensor can be used for both protection and metering^{16, 17}. Rogowski coils are low-power current sensors and generate low-voltage output signals during operation. Standard IEC 61869-10 defines requirements for Rogowski coil applications for metering and protection.¹⁸ Unlike CTs that produce secondary current proportional to the primary current, Rogowski coils produce an output voltage that is a scaled time derivative $di(t)/dt$ of the primary current and require microprocessor-based equipment to accept these types of signals. Standards IEEE C37.92-2005, IEC 61869-10, and IEC 61850 define the interface between low-power sensors and protective relays or other substation intelligent electronic devices.^{19, 20, 21} IEEE Standard C37.235-2007 provides guidelines for the application of Rogowski coils used for protective relaying purposes.²²

¹⁶ Lj. A. Kojovic, "Innovative Non-conventional Current Transformers for Advanced Substation Designs and Improved Power System Performance", 42nd CIGRE Session 2008, Paris, France, 2008.

¹⁷ A. dos Santos, J. Lourenço, J. F. Martins, P. Monteiro, J. Fitch, T. Rahman, Lj. A. Kojovic, "Relay Protection Solutions based on Non-Conventional Current Sensors in Actual Industrial/Utility Applications", CIGRE Study Committee B5 Colloquium, Belo Horizonte, Brazil, August 25-31, 2013.

¹⁸ IEC Standard 61869-10-2017, Instrument transformers - Part 10: Additional requirements for low-power passive current transformers

¹⁹ IEEE Standard C37.92-2005, Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers.

Appendix D Rogowski Coils has more details on Rogowski Coils.

2.8.3 Traditional iron core current transformers

Traditional iron core current sensors (CTs) have been used with conventional relays to detect open phase conditions. In order to use traditional CTs the user needs to understand the limitation of the CT and the available current fed to the protective relays. This could especially be an issue when the operating current is very low. Thus the protection scheme might have trouble deciding whether the low current seen is an open circuit or just low operating current. Modern IEDs with their improved sensitivity compared to conventional relays might be able to function with traditional iron core CTs and correctly operate for open phases. It will up to the user to determine if a traditional iron core CT will operate correctly. This report is not going to explain the physics of iron core CTs.

2.9 Open Phase Detection Based on Active Neutral Signal Injection Combined with Passive Neutral Overcurrent Detection

The Active Neutral Signal Injection method for open phase detection is specifically designed to detect open phase conditions on industry-recognized types of transformers where an open phase under no-load or lightly-loaded conditions is undetectable by traditional voltage or current measurements. The active neutral injection method combined with passive neutral overcurrent detection can detect open phase conditions from no-load to fully-loaded transformer conditions.

This detection method takes advantage of the known characteristics of the transformer that occur during single and double open phase conditions with or without a ground fault (of any impedance) during all loading conditions.²³ In essence, the active neutral injection scheme monitors the zero-sequence mode of the transformer and detects the change in this mode that occurs during an open-phase condition.

2.9.1 Active Neutral Detection Method Response to a Single Open Phase on Primary of Transformer

Consider a transformer with primary windings connected wye-grounded, secondary windings connected wye-grounded through resistance, and tertiary windings connected delta. The sequence network connections for a single open phase on the primary of this transformer are shown in Fig. 4. The simplified network is shown in

Fig. 5, where V_{inj} represents the injection source. Referring to Fig. 4, without the open phase condition the impedance seen by the neutral injection source is practically the

²⁰ IEC Standard 61869-10-2017, Instrument transformers - Part 10: Additional requirements for low-power passive current transformers

²¹ IEC Standard 61850-2004, Communication networks and systems in substations.

²² IEEE Document C37.235-2007, Guide for the Application of Rogowski Coils used for Protective Relaying Purposes

²³ Interim Report– EPRI Open Phase Detection Method. EPRI, Palo Alto, CA: 2014. 3002004432.

series combination of X_{0Sys} , X_{0H} , and X_{0T} , neglecting the branch in parallel with X_{0T} since it will typically be much greater than X_{0T} . However, with the open phase, the impedance detected by the injection source increases by the addition of the positive and negative sequence impedances as shown in Fig. 1. The amount by which the impedance increases depends on the transformer loading conditions and whether or not the open phase is grounded (Fig. 1). An ungrounded open phase on an unloaded transformer will result in a drastic increase in zero sequence impedance as seen from the transformer neutral, whereas a ground on the transformer side of the open phase may not result in an increase in zero sequence impedance as seen from the transformer neutral, but this type of ground would result in an increase in the power frequency neutral current in the transformer. A ground on the source side of the open phase is essentially a bus fault and should be detected by other relaying; even so, an open phase with a ground on the source side of the open phase would result in a change in zero sequence impedance detectable by the active neutral detection method. Thus the active neutral injection, along with the addition of a passive neutral overcurrent relay in the primary neutral, can detect any open phase condition on the primary of the transformer, including an open phase that is solidly grounded at the transformer primary with the ground on the transformer side of the open phase or on the source side of the open phase.

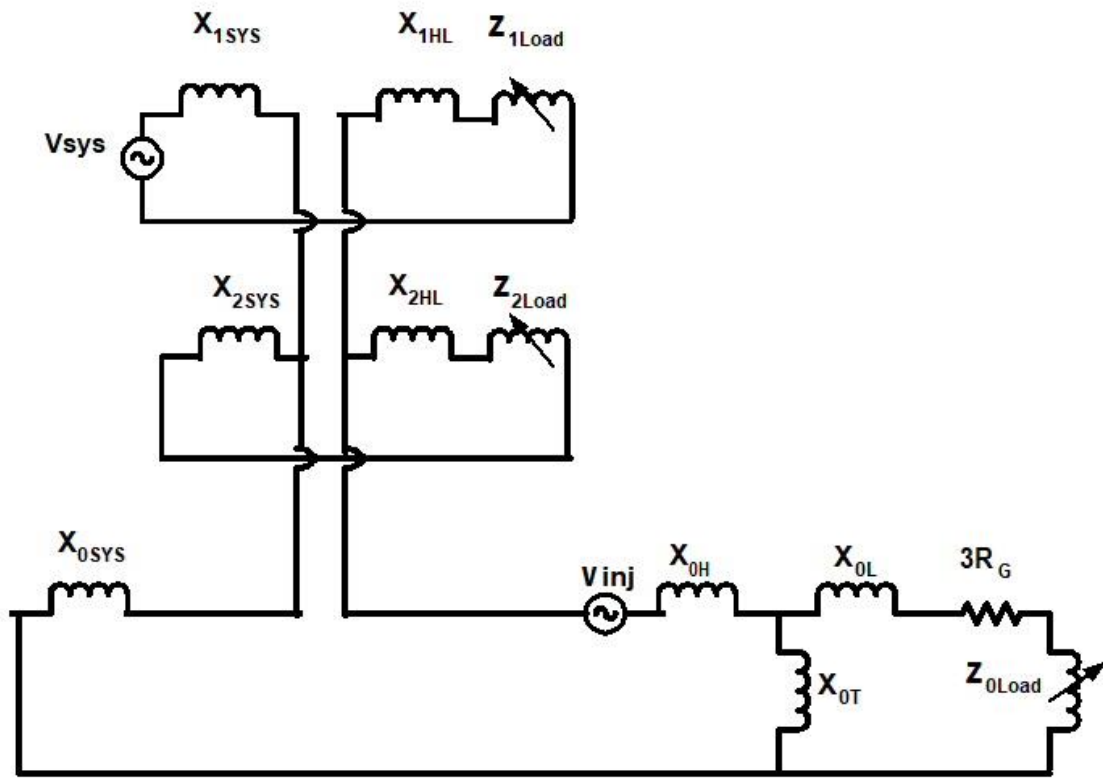


Fig. 4. Sequence network connections for a single open phase on the primary of a wye-grounded transformer

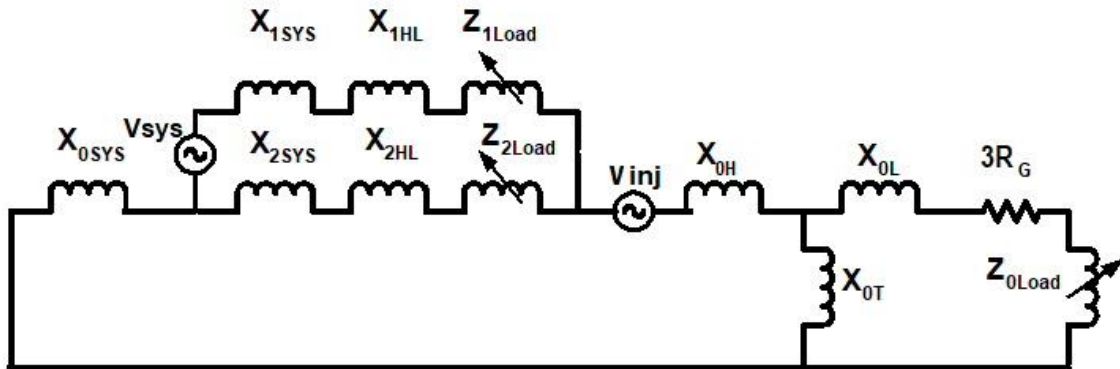


Fig. 5. Reduced sequence network for a single open phase on the primary of a wye-grounded transformer

2.9.2 Realization of the Active Neutral Detection Method

Referring to Fig. 6, the active neutral injection method essentially consists of an injection source, current transformer, and controller. The injection signal is coupled to the transformer neutral via the current transformer. The controller, along with a current detection probe, monitors the injected signal level, which represents the zero sequence impedance of the transformer. The injection signal level required depends on the zero sequence network impedance and the sensitivity of the controller to detect the injected current. Injection levels of 100-mA are typical. The injection signal frequency is typically in the 45-Hz to 90-Hz range. Standard relaying class current transformers can be used for the injection transformer.

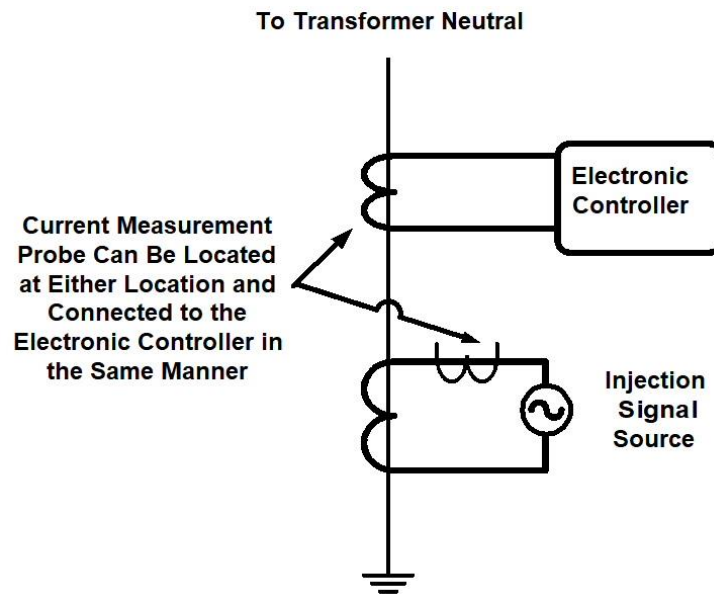


Fig. 6. Realization of the active neutral injection method

2.10 Transformer loading conditions

When considering the possible winding connections and core designs that can exist for generating unit, off-site power transformers, the most consistently reliable indicator of an open phase on the primary is the presence of negative-sequence current in the primary and secondary leads. In relying on negative-sequence current detection; however, the “natural” (steady state) presence of the component current needs to be considered. Such levels would be due to any inherent imbalance in the primary source system (such as, unequal line phase impedance due to the non-transposing of phase conductors, etc.), as well as imbalance in the down-line station service system and its connected load. Any detection would have to be set securely above the maximum steady-state levels expected. Much greater amounts of negative-sequence current, of course, can exist temporarily while unbalanced, short circuit faults are being cleared. As stressed previously in this report, initiation of an “open phase” trip would have to be delayed appropriately for

including the clearing of short circuit conditions by not just the primary protection responding, but encompassing possible backup protective responses, as well.

The greatest challenge to applying a negative-sequence current detection scheme for transformer open phase scenarios is having to depend on a minimum level of load current. Unfortunately, the auxiliary transformers that provide offsite (start-up) power are often operated supplying little to no load. This situation makes any open phase detection scheme that depends solely on the presence of negative-sequence current undependable much of the time.

A possible solution for providing better coverage with negative-sequence current detection would be an auxiliary system design that always provides adequate transformer loading for ensuring enough negative-sequence current will result for detecting an open high-side phase. The design would arrange to have each auxiliary transformer supply a sufficiently sized block of constant, balanced, non-critical load. Solutions such as this have been considered, but really have not been undertaken to any great extent as of this writing. The costs and inconvenience associated with a major rearrangement of an existing plant's station service system is probably the biggest drawback to this approach. Another drawback involves the cost of offsite power for merchant plants (A merchant power plant sells electricity in the competitive wholesale power market and is funded by investors). A generation facility that operates within another company's transmission territory can pay significantly more for offsite power than the effective cost of obtaining from their own generation bus via the normal station service transformer(s).

Introducing a "dummy", shunt-load bank that would be switched-in when the transformer is lightly loaded (or unloaded), for ensuring enough balanced transformer load current, is another solution that has been, at least, considered. Such a bank could be composed of loading resistors, inductors, capacitors, or combinations of these. Since the power they draw is not metered, reactive power banks are generally considered to be more desirable than resistive banks which could draw (and waste) a significant amount of costly real power from the system. This energy cost would be especially detrimental for a merchant power producer.

The feasibility of applying a load-based, negative sequence current detection scheme, including how much transformer loading will be required, will depend on a number of factors. The key determinant being, can enough negative sequence current be provided to the relay used for detecting the open phase condition? Reliable open phase detection will depend upon the negative-sequence current sensitivity of the relay employed, as well as the level of current provided to the relay under a reasonable level of transformer loading. The basic level of relay load current will depend on the applicable CT ratio and whether the current is to be monitored at the high or low voltage side of the transformer. When desirable or necessary to monitor at the transformer high-side, there may be great difficulty in getting enough current to the relay. The primary, high-side load current levels for an auxiliary offsite power transformer can be quite small to begin with; unless special low ratio CTs can be obtained for supplying the relay, the resulting relay currents may render a negative-sequence current detection scheme infeasible. As an example, consider a 25 MVA transformer feeding from 500 kV: the maximum rated load current in

the high-side leads is 28.9 A. A 400/1 CT ratio would supply a maximum load current to the relay of only 0.07 A, while a 100/1 CT would yield 0.29 A.

2.11 Anti-islanding technology Feasibility of Active Schemes

2.11.1 Introduction

Island detection devices, also known as anti-islanding devices were investigated for possible use in determining an open phase. Distributed Generation (DG) standards might require the use of an islanding detection scheme in order to trip off the DG so as to prevent problems to the generators and connected loads should the DG become electrically isolated from the remainder of the power system.

Fig. 7 shows the phenomenon of voltage regeneration on the open phase. Current continues to circulate in the delta due to I_B and I_C . This creates a voltage drop V_{W_a} which, in turn, generates a voltage V_{W_a} .

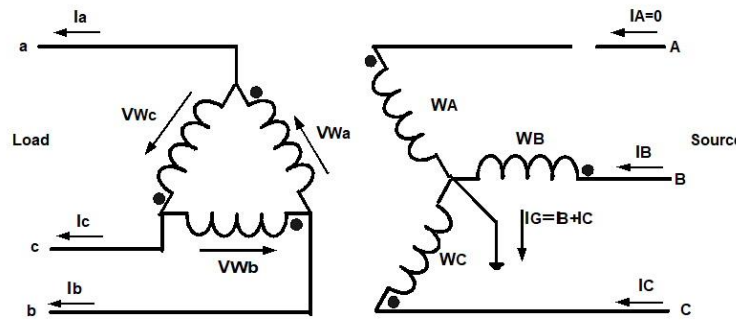


Fig. 7. Delta-Wye Transformer with an Open Phase on the Wye Winding

2.11.2 Local Injection & Impedance Measurement

The following model (Fig. 8) was implemented in a dynamic system simulation software program. A 100V, 10 kHz, three-phase source is connected to the transformer terminals using capacitors. Note that a single-phase injection scheme does not work for a delta connected secondary.

The injected current and transformer terminal voltage are used to calculate phase-ground impedance for each phase.

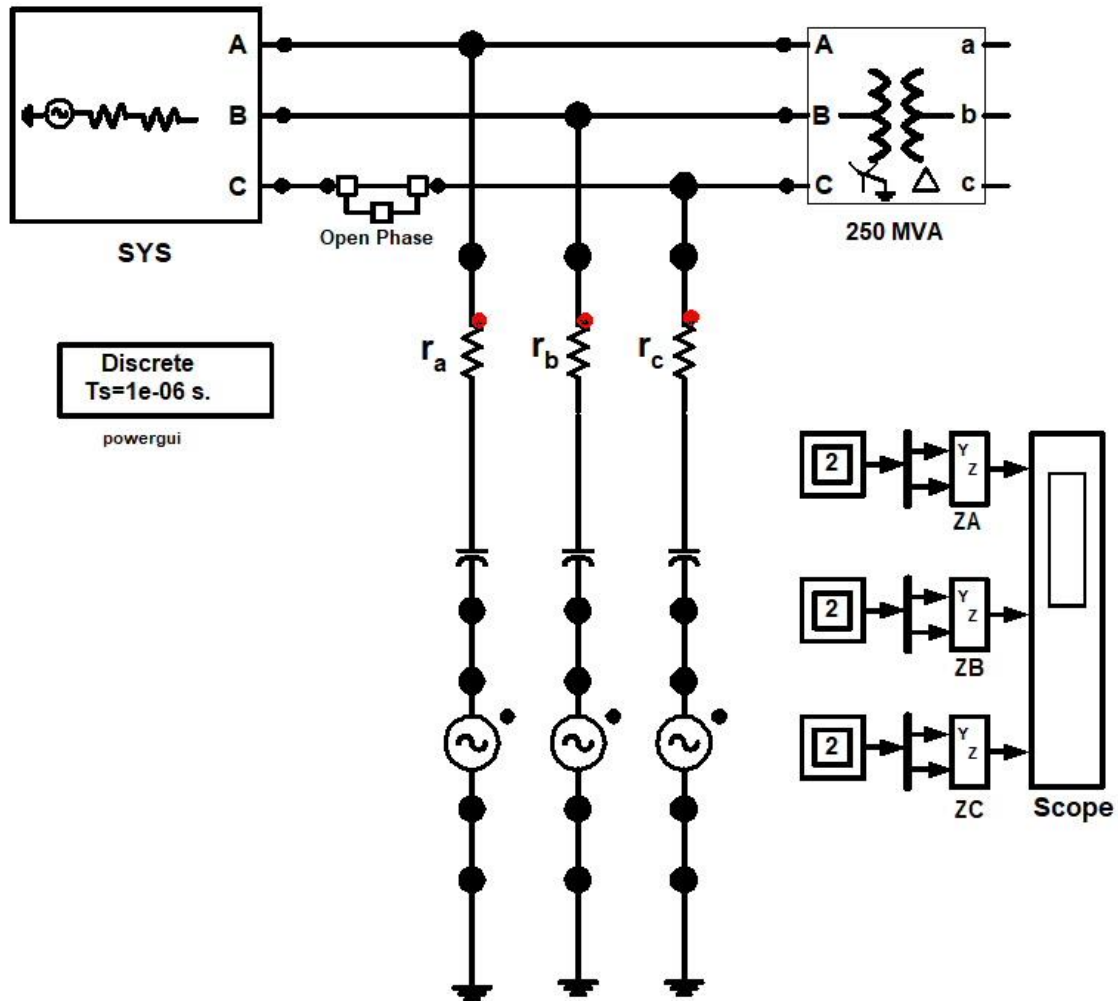


Fig. 8. Dynamic System Simulation Model

Fig. 9 shows the impact of the open phase at 0.1 seconds. Initially the three impedances are approximately equal. The phase-C impedance increases following the open phase.

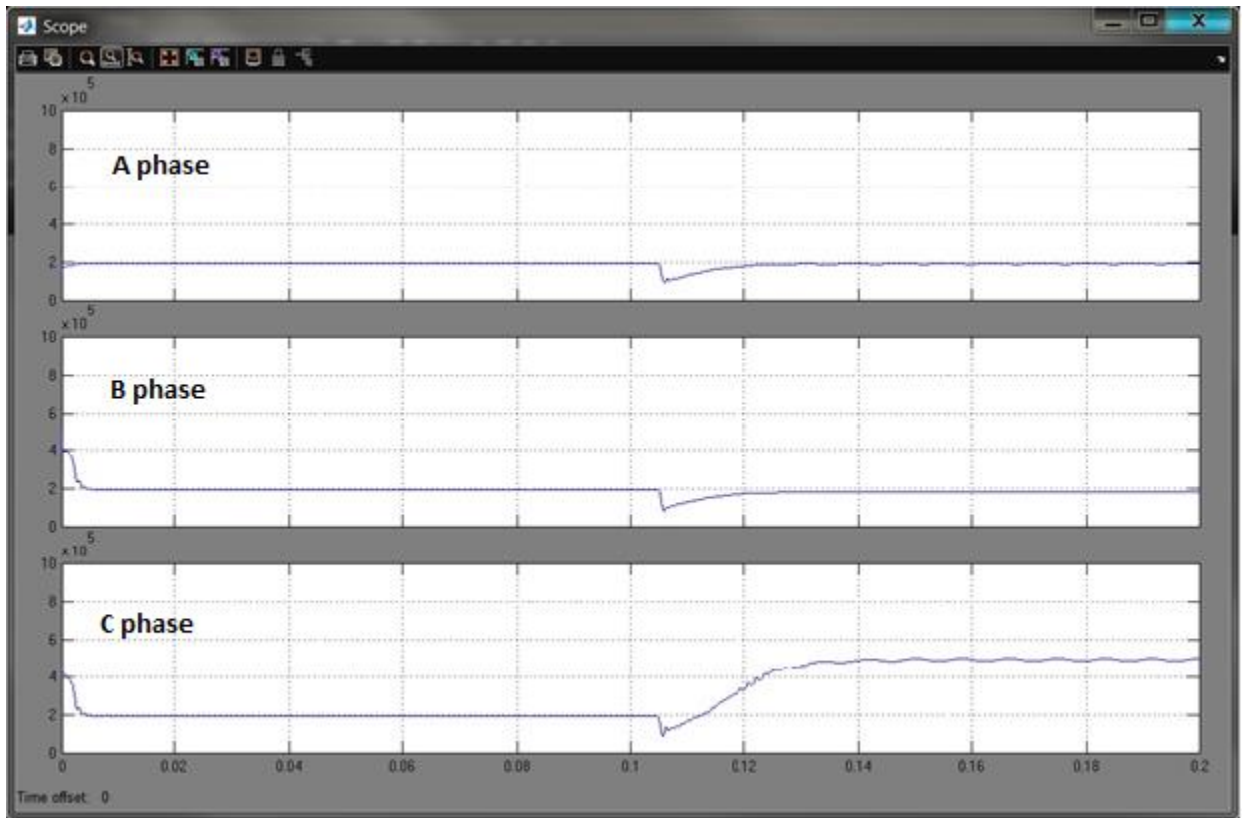


Fig. 9. Impedance Plot

A transmission line was added to the model (Fig. 10). This is a lumped parameter line model which includes positive and zero sequence shunt capacitance.

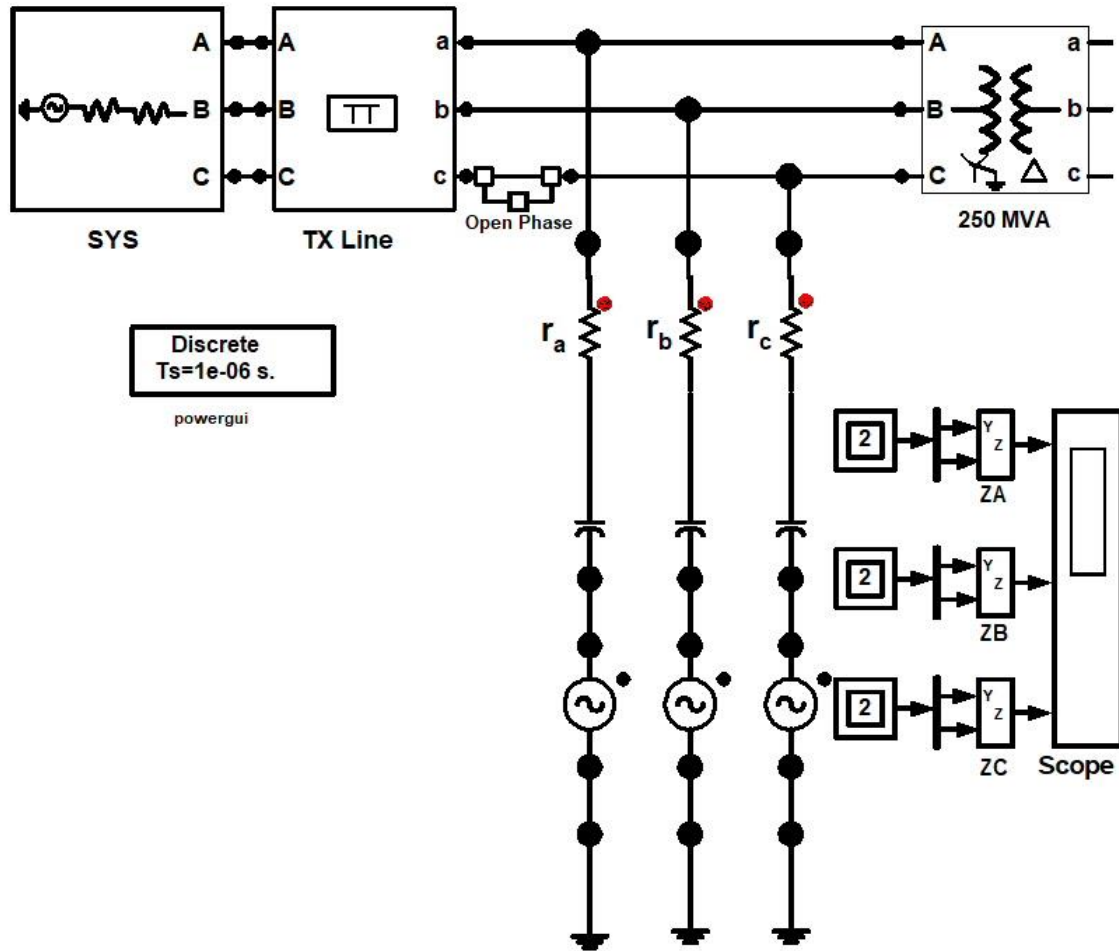


Fig. 10. Dynamic System Simulation model with Transmission line

Fig. 11 shows the impact of the open phases. Initially the three impedances are similar although not as closely matched as before. Phase A & B impedance decreases following the open phase presumably due to capacitive coupling of the line.

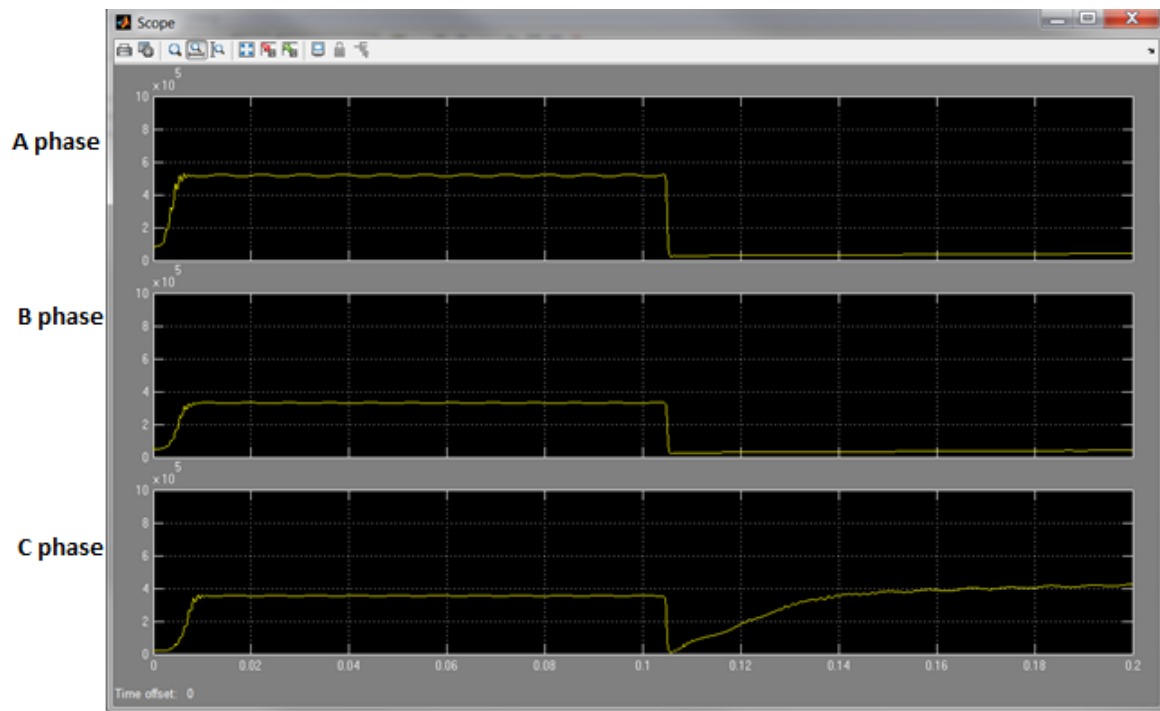


Fig. 11. Impedance Plot

The power transformer used in the dynamic system simulation model does not include capacitance. The concern would be that the capacitance will look like a low impedance to the injection source. A high frequency model of a transformer is shown in Fig. 12.²⁴

²⁴ Chimklai, Marti, Simplified Three-Phase Transformer Model for Electromagnetic Transient Studies, 1995

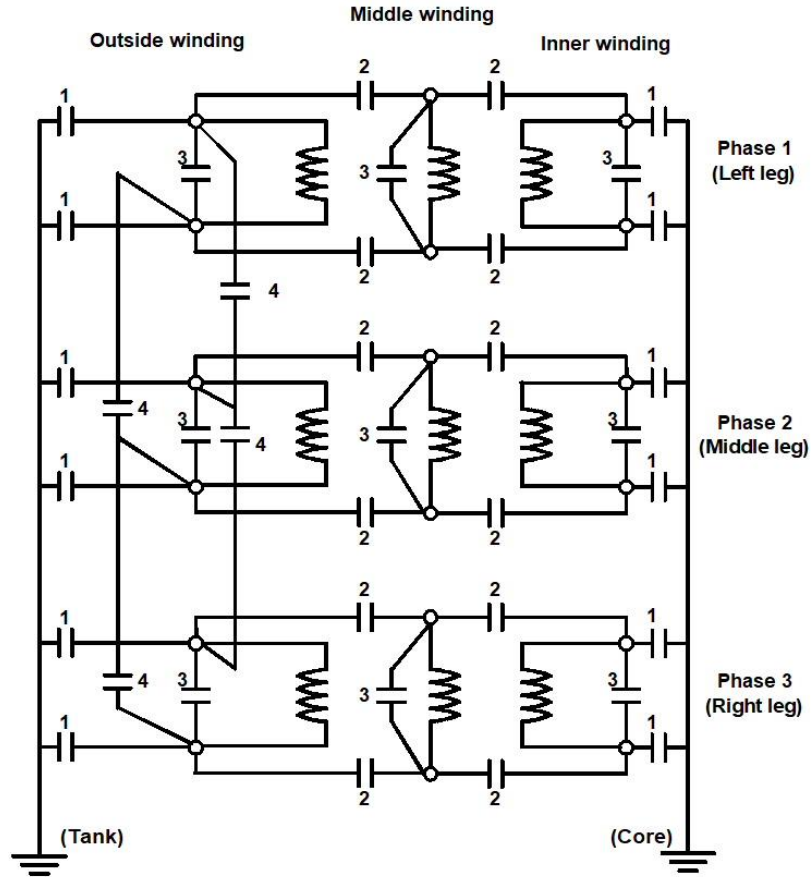


Fig. 12. Stray Capacitance in a Three Winding Transformer

As frequency goes up, the inductive reactance of the winding would increase. At the same time the capacitive reactance of the shunt capacitance would decrease. Fig. 13 shows a plot of positive sequence impedance compared with a lumped RL model (capacitance ignored).

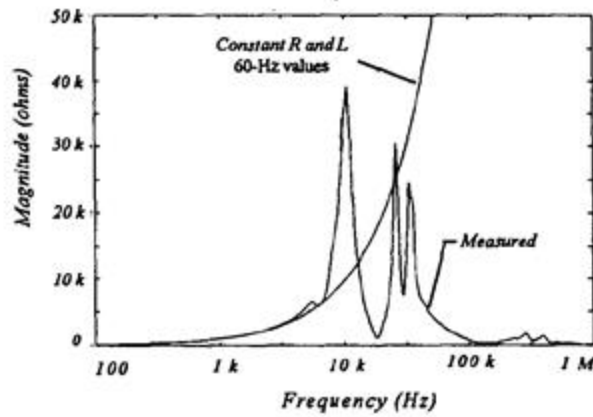


Figure 1. Measured short-circuit positive sequence impedance of a 50 MVA 115/23 kV transformer versus $(R_{60} + j\omega L_{60})$ model.

Fig. 13. Short Circuit Impedance versus Frequency

In conclusion an active scheme which measures impedance using high frequency injection might be feasible. However, consideration should be given to the impact of transformer capacitance, as well as surge capacitors, lightning arrestors, etc.

Much more work would be required to confirm that this could be a practical and effective scheme.

2.11.3 Remote Injection and Local Measurement Method

One company has a scheme that uses a remote injection and local measurement method that was investigated for possible usage in determining an open phase. Fig. 14, Fig. 15, and Fig. 16 illustrate this system.

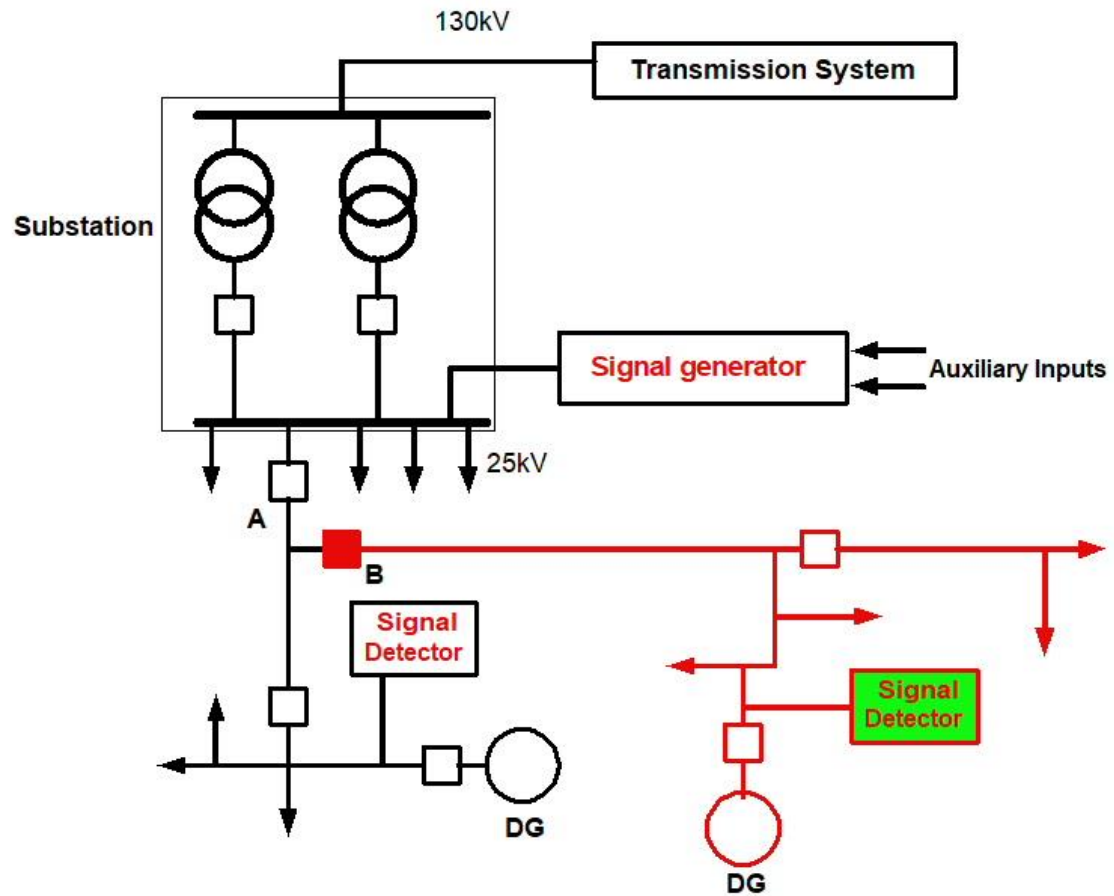


Fig. 14. Schematic Diagram

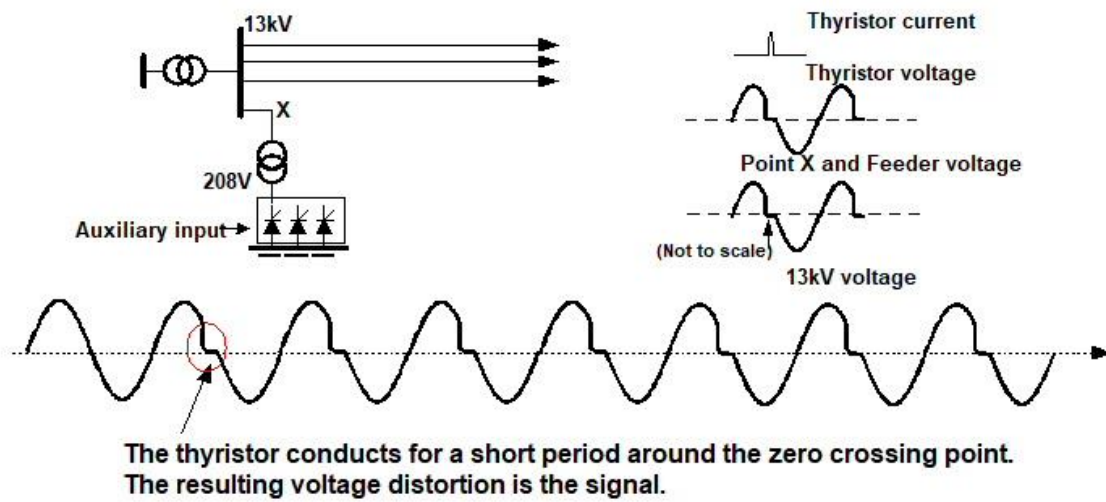


Fig. 15. Signal Generation

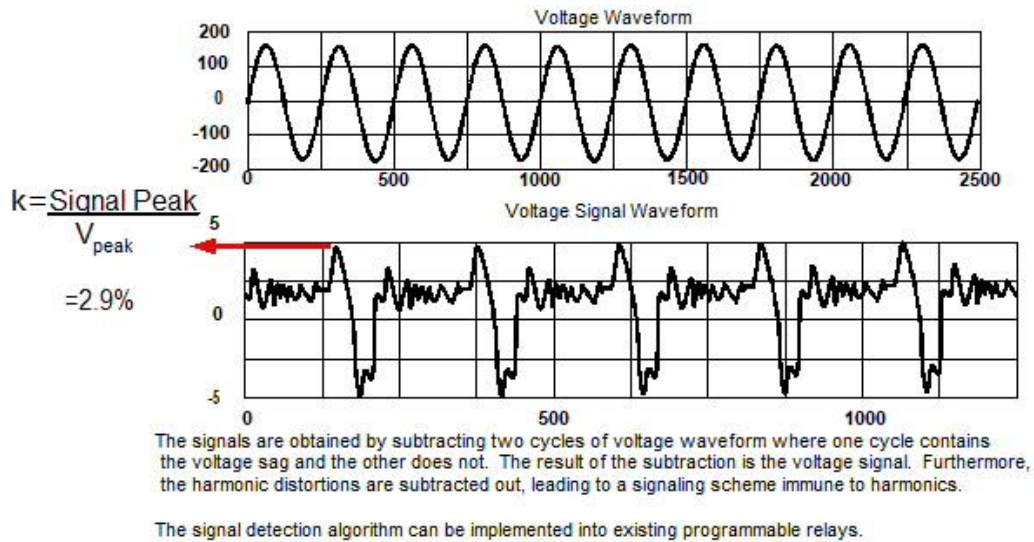


Fig. 16. Signal Recovery

Note that the manufacturer did not think this method would be suitable for open phase detection on a wye/delta transformer.

Also this system is intended to be failsafe. In a DG application, the DGs will trip if the transmitter fails.

2.12 Open Phase Detection Methods Using Analog-to-Digital Converter Behavior

Microprocessor relays use analog-to-digital (A/D) converters, which are devices that sample analog signals and convert them into digital bits. A/D converters exhibit errors, these errors are significantly amplified when the input signal is no longer available and substituted by noise.

This A/D converter behavior can be used to detect ungrounded open phase events as the excitation current signal is no longer available to be processed by the A/D converter, and the output signal becomes amplified random noise due to the A/D least significant bit toggle.

For more details on the method, refer to Appendix E.

2.13 Power Transformer Open Phase Detection by Current Transformer Open Circuiting

Appendix F presents a method that uses the open circuit voltage developed across the secondary of a CT that has its secondary momentarily open circuited intentionally (when no measurable current is present). If no primary current flows through the CT, then no voltage will be developed across the secondary when the secondary is momentarily opened. The absence of secondary voltage is the indicator that the primary has no current flow.

2.14 Power Transformer Open Phase Detection using specially designed window-type current sensors

There are several generating stations that are using an Open Phase Detection (OPD) System that is designed to identify open phase conditions on the General Design Criteria (GDC) 17 offsite power supplies to nuclear power plants by using specifically-designed, “window-type” current sensors on the high voltage bushings of the power transformer. The system covers open conditions that could occur on the direct feed from the transmission system and inside the station service transformer, including bushing connections, internal jumpers, no-load tap changer and transformer winding connections. Measurement capabilities of the system range from as low as 10% of no-load excitation current and can specifically identify which phase or phases are involved in open phase conditions.

Refer to Appendix G for a more complete discussion.

3. Security and Dependability concerns

Open phase conditions in the power supply path to a nuclear power plant station auxiliary transformer need to be detected and isolated promptly in order to assure that plant design basis conditions can be assured. Open phase conditions at non-nuclear power plants are not as critical as open phase conditions at nuclear power plants.

At the same time, open phase detection schemes need to be insensitive to transmission system occurrences that may cause sensitive open phase detection schemes to actuate inadvertently.

Open phase conditions need to be evaluated for critical motor driven loads served by offsite power for various plant configurations. The design basis considerations are motor acceleration and excessive motor heating. The concern when selecting protective relays is that overcurrent, overload, and phase unbalance protective devices may actuate and isolate critical motor driven loads unless open phase conditions are quickly detected and automatic remedial action is initiated. At nuclear power plants, this concern is heightened because three phase ac power is essential during shutdown conditions as residual heat removal from the reactor core needs to continue for an extended period of time each time the reactor is shut down.

Open phase conditions in the power supply to non-critical, balance of plant loads; such as the power supply to drive motors for condensate pumps, is less of a concern. This is because inadvertent tripping of condensate pump drive motors has minimal impact on residual heat removal systems.

The open phase scenarios that need to be considered include:

- a) Reactor at full power, normal plant operation
- b) Reactor shutdown, normal shutdown conditions
- c) Reactor startup, prior to load bus transfers
- d) Post reactor SCRAM, the interval of time between normal plant operations and cold shutdown conditions.
- e) Design Basis Event, Loss of Cooling Accident

These scenarios need to be addressed for Station Auxiliary Transformers that supply power to buses that serve emergency safeguards equipment, such as residual heat removal pump drive motors, emergency service water pump drive motors, and motor operated valve drive motors.

As detection of open phase conditions is dependent on Station Auxiliary Transformer winding configuration; assurance that protective relays will actuate needs to be evaluated for each of the aforementioned plant conditions.

3.1 Load Bus Transfers

Load Bus transfers – from generator auxiliary buses to offsite powered buses and from offsite powered buses to buses powered by onsite emergency generators – may be initiated manually via control switch, automatically via protective relay actuation, or automatically via control logic.

If an open phase condition occurs to an offsite power source, the open phase condition need to be detected quickly and have a transfer away from the open phase source occur with minimal delay, before overcurrent, overload, and phase unbalance protective devices actuate to trip circuit breakers serving critical motor driven loads that are part of emergency safeguard systems. This detection and transfer sequence is required during normal plant operations, during shutdown conditions, during reactor startup conditions, during post SCRAM conditions, and during design basis event conditions.

In addition, if an open phase condition occurs to an offsite power source, the open phase condition needs to be resolved in such a manner that the main generator does not trip off line and result in a load transfer from generator auxiliary buses that are unaffected to a station auxiliary transformers that is impacted by an open phase condition.

3.2 Emergency Generator Load Testing

During emergency generator load testing, the sensitivity of open phase detection schemes will be reduced if the emergency generator is operating parallel with the offsite power source.

Nevertheless, if an open phase condition occurs to an offsite power source while an emergency generator is being tested, the open phase condition needs to be detected quickly and have a transfer away from the open phase source occur with minimal delay, before overcurrent, overload, and phase unbalance protective devices actuate to trip circuit breakers serving critical motor driven loads that are part of emergency safeguard systems. This detection and transfer sequence is required during normal plant operations, during shutdown conditions, during reactor startup conditions, during post SCRAM conditions, and during design basis event conditions.

The reduction in the sensitivity of open phase detection schemes when emergency generators are operating in parallel with offsite power supplies needs to be evaluated and addressed.

3.3 Motor Starting and Acceleration

Motor starting conditions are problematic because of the wide variety of motor driven loads. Drive motors for larger loads, such as emergency service water pumps, may be large enough to assure that open phase detection schemes will actuate during motor starts. Drive motors for small loads, such as drive motors for motor operated valves, may not be large enough to assure that open phase detection schemes will actuate during motor starts.

Nevertheless, if an open phase condition occurs to an offsite power source while a drive motor is being started, the open phase condition needs to be detected quickly and have a transfer away from the open phase source occur with minimal delay, before overcurrent, overload, and phase unbalance protective devices actuate to trip circuit breakers serving critical motor driven loads that are part of emergency safeguard systems. This detection and transfer sequence is required during normal plant operations, during shutdown conditions, during reactor startup conditions, during post SCRAM conditions, and most importantly, during design basis event conditions.

Motor starting is problematic because, during normal nuclear power plant operations, the balance of plant motor loads are powered via main generator auxiliary transformers. With critical emergency loads in standby, the station auxiliary transformer load may be minimal. Then, when a Design Basis Event occurs, specific start sequences of critical emergency motors need to occur rapidly.

A typical scenario would be where cooling water flow must be restored to a reactor within 60 seconds of a loss of cooling accident. The present motor starting sequence may allow 6.0 seconds for two residual heat removal pumps to reach rated speed. The load sequencer will issue a signal that starts the next two motors 6.0 seconds after the last start signal was issued. If an open phase condition was undetected and a Design Basis Event occurred, the open phase needs to be detected quickly enough to transfer the bus to a different power source while meeting the 6.0 second rated speed requirement. (Alternatively, Design Basis Event timelines will need to be revised to include detection of open phase conditions as part of the scenario.)

3.4 Fault Cases

Open phase detection schemes need to be insensitive to various fault conditions that may result in needless detection, alarm, and transfer sequences. The time delay of the open phase detection schemes needs to be sufficient to assure that false bus transfers do not occur when unbalanced faults occur.

If the needed time delay of open phase detection schemes becomes excessive, the need for additional instantaneous protective relays (for the fault conditions) will need to be evaluated.

3.5 Transmission Grid Disturbances

Transmission grid disturbances can include open phase conditions at remote locations, such as an open phase of a transmission line terminating in the switchyard, and system transients that result in FIDVR. Open phase detection schemes need to not actuate for transmission grid disturbances.

During remote open phase conditions, the actuation time of residual time overcurrent ground relays needs to be compared to the actuation time of open phase detection schemes. (This is in addition to comparing the actuation time of residual time

overcurrent ground relays to the actuation time of main generator phase unbalance and negative sequence relays.)

During normal plant operations, load, voltage and current unbalance is minimal, usually much less than 3%. During FIDVR conditions, the possibility of increased load, voltage and current unbalance needs to be considered and addressed. The concern is that during FIDVR conditions, undesired load transfers caused by open phase detection schemes may exacerbate FIDVR conditions.

4. Transformer data

Data requirements for modeling transformers for open phase studies vary significantly depending on the transformer core type and winding configurations.

4.1 Core-Type wye-primary transformers

For transformers with wye-connected primary windings without a delta winding, it can be assumed that the transformer is a three-legged core design, since shell-type transformers will always have a buried delta winding. Therefore, it is necessary to accurately model the coupling between phases due to the effect of the phantom delta winding caused by the zero sequence flux path through the transformer tank. To accomplish this, the BCTRAN model is typically used. The model consists of a real and reactive matrix of coupled coils between the terminals of the transformer. This matrix was developed by EMTP developer Dr. Hermann Dommel; and software programs such as EMTP-RV and ETAP 12 contain built-in routines to compute the matrix elements. The data required are the positive and zero sequence short circuit impedances, as well as the positive and zero sequence exciting current. Of these, the most critical parameter (and the one most often omitted from test data) is the zero sequence exciting current. In the absence of this data, an assumption can be made that the zero sequence excitation impedance is equal to six times the positive sequence leakage (short circuit) impedance. Additionally, with regard to the short circuit impedances, it is important that the winding which the test is performed on is correctly identified when computing the BCTRAN matrix. For example, the per unit impedance seen from the H winding with the X winding shorted is not in general equal to the impedance seen from the X winding with the H winding shorted. Incorrect representation of the short circuit impedances can often result in unstable models.

Even with a properly computed BCTRAN matrix, the condition number for it can be large and result in unstable models. The number computed could be used as part of the model validation, to ensure accurate results. Stable BCTRAN models may have a condition number on the order of 10^6 , while unstable models may be on the order of 10^{13} or higher.

For transformers with delta secondaries, or with buried delta windings, the use of BCTRAN is not as critical, since the impedance of the delta winding dominates the behavior of the transformer during an open phase. However, if the transformer has a

three-legged core, it is the use of the BCTRAN algorithm could capture the effect of the coupling in the core.

4.2 Delta-primary transformers

In the event of an open phase on a delta-primary transformer, only one primary winding remains energized, and the voltage across the two open windings becomes 50% of the voltage on the energized winding due to the voltage division over the delta primary. Therefore, any coupling in the core of the transformer has no impact on the results, and so a traditional transformer model consisting of three single-phase units is sufficient. Only positive sequence test data is required.

4.3 Shell-type transformers

For shell-type transformers, there are additional flux paths around the outer sections of the core. Therefore, there is very little coupling between phases, and a traditional transformer model consisting of three single-phase units is sufficient. Only positive sequence data is required.

References^{25, 26} have additional details.

5. Conclusion

This technical report provides the reader with the latest methods for analyzing and detecting an open phase condition. This report is specifically reviewing the open phase condition at a Nuclear Plant Station Service or Startup Transformer, but much of what is written can be used in other situations.

The following table lists possible viability of each scheme.

<i>Scheme (clause)</i>	<i>Viable?</i>
Current differential (2.1.1)	No
Phase current unbalance (2.1.2)	Maybe
Phase comparison (2.1.3)	No
Sequence quantities (2.1.4)	No

²⁵ Interim Report– EPRI Open Phase Detection Method. EPRI, Palo Alto, CA: 2014. 3002004432.

²⁶ Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers, EPRI, Palo Alto, CA: 2012, EPRI Report 3002000764.

Hybrid scheme (2.1.5)	Maybe
Sequence Voltage and current comparison (2.1.6, Appendix B)	Maybe
Undervoltage (2.2.1)	No
Overvoltage (2.2.2)	No
Degraded voltage (2.2.3)	No
Negative Sequence differential voltage (2.3.1)	No
Impedance (2.4.1)	No
Frequency (2.5)	No
Voltage and Current comparison (2.6.1)	Maybe
Communication aided (2.7)	Maybe
Optical CT (2.8.1, Appendix C)	Yes
Rogowski coils (2.8.2, Appendix D)	Maybe
Active Neutral Signal injection (2.9)	Yes
Anti-islanding (2.11)	No
Open Phase Detection Methods Using Microprocessor Relays (2.12 , Appendix E)	Maybe
CT open circuiting (2.13, Appendix F)	Maybe
Specially designed window-type CT (2.14, Appendix G)	Yes

APPENDIX A Bibliography

A.1 NRC IN 2012-03: Design Vulnerability in Electric Power System, March 1, 2012²⁷

The NRC issued this IN 2012-03 to inform addressees of recent operating experience involving the loss of one of the three phases of an offsite power circuit. The NRC expects that recipients will review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. Suggestions contained in this IN are not NRC requirements; therefore, no specific action or written response is required. Three cases of loss of one phase are discussed in IN 2012-03.

A.2 EPRI Report 1025772: Analysis of Station Auxiliary Transformer Response to Open Phase Conditions, Technical Update June 2012²⁸

The goal of this research was to address many of the technical issues associated with detecting an open phase condition of a station auxiliary transformer over a wide range of load levels. The intended objectives were to develop generic transformer models for use in the analysis and to determine, in general, the response of the system during open phase conditions to aid in the development of system protection schemes designed to detect such conditions. Researchers used various simulation techniques that are capable of representing the behavior of three-phase transformers during open phase conditions. The techniques included both frequency domain and time-domain methods.

<http://www.epri.com/search/Pages/results.aspx?k=EPRI%20report%201025772>

A.3 EPRI Report 3002000764: Nuclear Maintenance Application Center: Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers, Final report May 2013²⁹

Open-phase condition of a station auxiliary transformer during a wide range of load levels. The objective was to develop transformer models that were not included in the initial EPRI Report Analysis of Station Auxiliary Transformer Response to Open Phase Conditions (1025772), for use in the analysis and determining, in general, the response of auxiliary electric systems during open-phase conditions.

Researchers applied various simulation techniques capable of representing the behavior of three phase transformers during open-phase conditions. Simulation techniques included both frequency-domain and time-domain methods. The open-source OpenDSS

²⁷ NRC IN 2012-03: Design Vulnerability in Electric Power System, March 1, 2012

²⁸ Analysis of Station Auxiliary Transformer Response to Open Phase Conditions, EPRI, Palo Alto, CA: 2012, EPRI Report 1025772.

²⁹ Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers, EPRI, Palo Alto, CA: 2012, EPRI Report 3002000764.

software developed by EPRI was used to perform frequency-domain simulations, and the restructured version of EMTP was used to perform time-domain simulations.

<http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002000764>

A.4 EPRI Report 1026484: Development and Analysis of an Open-Phase Detection Scheme, Technical Update, September 2012³⁰

This EPRI project addresses the technical issues associated with detecting an open-phase condition of a SAT during a wide range of load levels. Improvements in open-phase detection may lead to greater confidence in detecting and responding to abnormal conditions, which may result in an overall increase in the safety and the reliability of the system to benefit the public.

<http://www.epri.com/search/Pages/results.aspx?k=EPRI%20report%201026484>

A.5 Single phase diagram, Gary Kobet presentation at January 2013, IEEE PSRC meeting

At an IEEE PES PSRC meeting held January 15, 2013, Gary Kobet (Member, IEEE PES PSRC) presented the following one line diagrams (Fig. A-1 and Fig. A-2) illustrating the concern with an open phase on one of the connections to the primary windings of a SAT.

³⁰ Development and Analysis of an Open-Phase Detection Scheme. EPRI, Palo Alto, CA: 2012, EPRI Report 1026484.

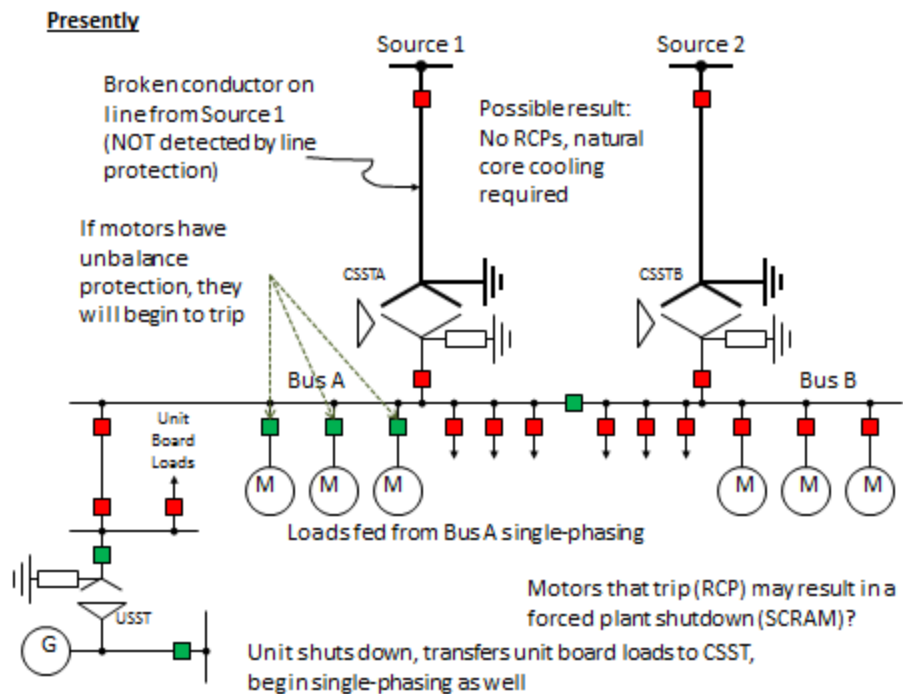


Fig. A-1. Present open phase condition protection scheme

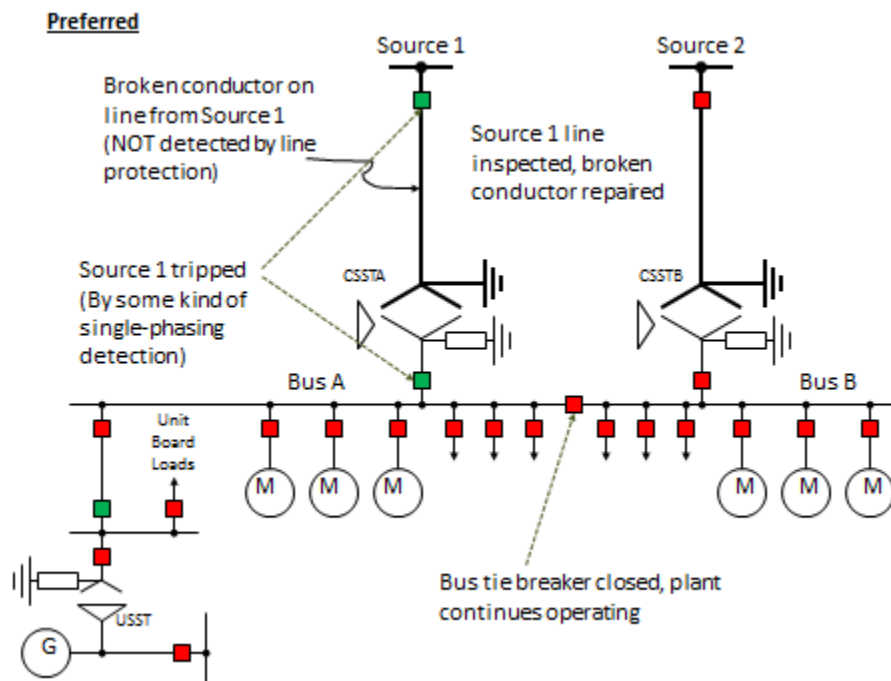


Fig. A-2. Preferred open phase condition protection scheme

A.6 Texas A&M University Relay Conference Paper: Open Phase Conditions in Transformers Analysis and Protection Algorithm, Amir Norouzi, GE Digital Energy, April 2013³¹

Powerpoint presentation that reviews effects of open phase conditions in several transformer configurations and presents methods of analyzing the resultant voltages and currents. Several examples are presented with results of detection methods plotted.

A.7 Texas A&M University Relay Conference Paper: Effect of Transformer Connection and Construction on Single Phasing Detection, Gerald Johnson & Randy Hamilton, Basler Electric Company, Sudhir Thakur, Exelon Corporation, April 2013³²

Powerpoint presentation regarding the Byron open phase event. The paper reviews the event and the root cause analysis of factors that contributed to the failure. The presentation then provides an proposed algorithm for detecting this open phase condition.

A.8 Practical Guide for Detecting Single-Phasing on a Three-Phase Power System, John Horak and Gerald Johnson, Basler Electric Company, Presented at the Western Protective Relay Conference October 2002³³

Understanding and predicting the per phase magnitude and angle of phase to phase, phase to neutral, positive, negative, and zero sequence voltage and current generated during the loss of one or two phases of a radial three phase system is fundamental to the application of protection schemes designed to detect the same. Many papers have been presented on sequence quantities available during specific faults, but protection engineers will find fewer references deal exclusively with system conditions and resultant sequence quantities generated during a single phase condition. This paper is provided as reference for that condition and includes suggested detection and protection methods for each application.

<https://www.basler.com/ResourceDownload.aspx?id=156>

A.9 EPRI Report 3002004432: Interim Report: EPRI Open-Phase Detection Method, October 2014³⁴

This EPRI report addresses the technical issues associated with detecting an open-phase condition of a SAT during a wide range of load levels; including no-loaded and lightly loaded transformers. The report describes a method of detection that has two parts:

³¹ Norouzi, A., "Open Phase Conditions in Transformers Analysis and Protection Algorithm", Texas A&M University Relay Conference, April 2013

³² Johnson, G., Hamilton, R., Thakur, S., "Effect of Transformer Connection and Construction on Single Phasing Detection", Texas A&M University Relay Conference, April 2013

³³ Horak, J., Johnson, G., "Practical Guide for Detecting Single-Phasing on a Three-Phase Power System", Western Protective Relay Conference, October 2002

³⁴ Interim Report– EPRI Open Phase Detection Method. EPRI, Palo Alto, CA: 2014. 3002004432.

passive protection and active protection that EPRI has developed in conjunction the University of Alabama at Birmingham. The passive method monitors the current flowing in a neutral connection on the high-voltage side of the transformer. The active method injects a signal onto the neutral connection of the transformer and monitoring the current flowing on the high-voltage side of the transformer.

<http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004432>

A.10 NEI Reports

Refer to the Nuclear Energy Institute (NEI) webpage for any reports that are released concerning open phase detection. The NEI webpage is <http://www.nei.org>.

A.11 Open-Phase Detection for Station Auxiliary Transformers, Dwayne Cox, Exelon Generation Company, Ahmed Abd-Elkader, and Harish Chaluvadi, Schweitzer Engineering Laboratories, Presented at the Western Protective Relay Conference October 2018

APPENDIX B Symmetrical Component Model of Phase Open Line

This paper was presented at the Western Protective Relay Conference and describes a seven open-phase detection algorithms. The following algorithms are discussed: Averaging, Digital Filters, Difference of the Ratio of the Second Harmonic to Fundamental Currents, Waveform Zero-Crossings Based, Negative-Sequence Current Based, Zero-Sequence Current Based, and Negative-Sequence Voltage Based.³⁵

B.1 Symmetrical Component Overview

Symmetrical component theory has been successfully utilized to calculate power system currents and voltages for balanced, unbalanced, faulted (short circuited), and open circuit conditions for almost 100 years. (Charles LeGeyt Fortescue introduced the methodology in 1918.)

Commonly, open phase calculations have been minimized because the concern is limited to three phase motor and generator applications as open phase conditions rarely cause transformers and power lines to be subjected to excessive current.

When developing protective relay applications to detect open phase conditions, the concern is that before setpoints can be selected for protective devices, fault and load conditions need to be carefully analyzed as inadvertent protective relay actuation for other electrical system events is unacceptable. Open phase calculations are more tedious than short circuit calculations because equivalent circuits are a function of the number of motors that are operating as well as the rotational speed, NEMA code letter (for locked-rotor KVA)-nameplate marking, etc. of each motor.

Different equivalent circuits are addressed by developing bifurcated calculations at various load levels, that is, calculations are developed at low and moderate load levels with motors rotating at rated speed and repeated with motors that are stalled or accelerating because motor equivalent circuits are a function of motor speed. When stalled, positive sequence impedance of induction motors equals negative sequence impedance with a circuit angle of approximately 85 degrees. At rated speed, positive sequence impedance of induction motors is approximately six times greater than negative sequence impedance and the circuit angle of positive sequence impedance decreases to approximately 25 degrees while the circuit angle of negative sequence impedance remains at approximately 85 degrees.

Another factor that adds complexity to open phase calculations is that large power transformers are custom products that are uniquely designed, fabricated, and connected. This includes winding connections (delta, wye, wye grounded, or wye grounded with a neutral resistor), the number of windings (2, 3 or more per phase), core design (three

³⁵ Cox, D., Abd-Elkader, A., Chaluadi, H., "Open-Phase Detection for Station Auxiliary Transformers", Western Protective Relay Conference, October 2018, <https://selinc.com/api/download/124320/>

legged (core form) or five legged (shell form) core), and the physical location of each winding on the core.

B.1.1 Symmetrical Component Networks

Symmetrical component networks used to calculate fault (short circuit conditions) for the system shown in Fig. B-1 (one line diagram for a typical nuclear power plant) are designated Positive Sequence Network (Fig. B-2), Negative Sequence Network (Fig. B-3), and Zero Sequence Network (Fig. B-4). Fig. B-1 represents normal plant operation.

Plant auxiliary loads are shown on this one line diagram because plant auxiliary loads supplied via a transformer connected to main generator leads can be transferred to offsite power during some scenarios.

Startup and emergency loads are supplied via station transformers that are served via offsite power. Emergency generators are shown on the one line diagram because emergency generators may be paralleled to offsite power during some scenarios. In the analysis for this technical report, emergency generators are not in operation.

In order to evaluate postulated conditions, component networks are connected in series – parallel combinations in accordance with theories developed by Dr. Fortescue. Faults and / or open circuits are postulated at locations in the actual power system network, appropriate connections between fault points and reference buses or between open circuits are established in the symmetrical component networks, and calculations are prepared to determine current and voltage at any point in the actual power system network.

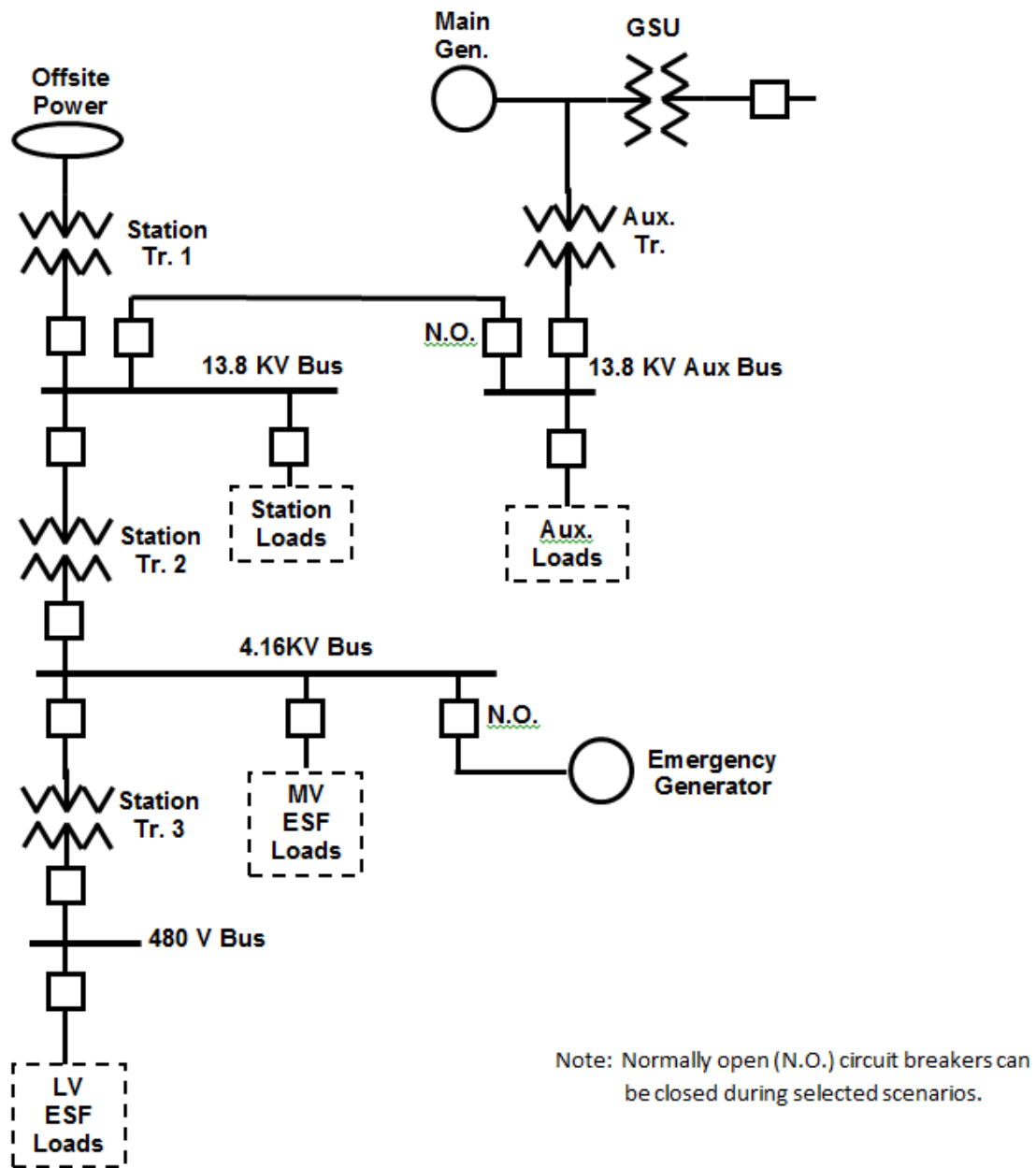


Fig. B-1. Nuclear Power Plant Electrical System One Line Diagram

The Positive Sequence Network shown in Fig. B-2 is the network used for fault conditions where the main generator is supplying plant auxiliary loads and emergency generators are not in service. The fault can be located at any node in the network.

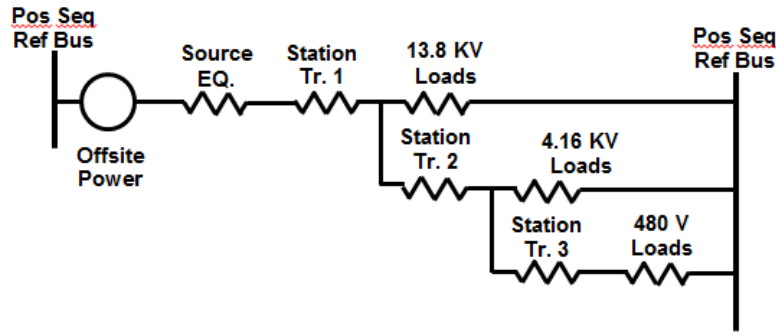


Fig. B-2. Positive Sequence Diagram for Fig. B-1

The Negative Sequence Network shown in Fig. B-3 is for the same conditions shown in Fig. B-2. Negative Sequence Networks do not include voltage sources. The fault must be located at the same node in both the positive and the negative sequence networks.

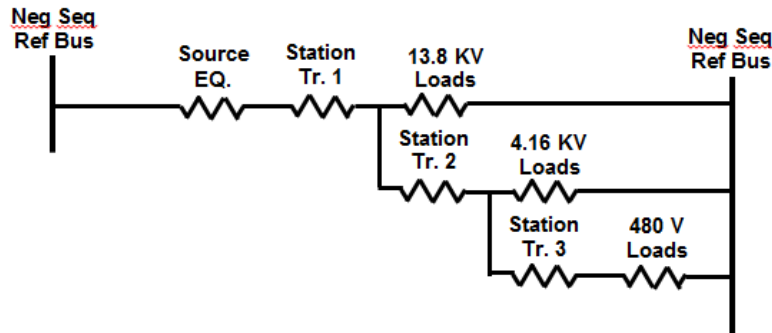


Fig. B-3. Negative Sequence Diagram for Fig. B-1

The Zero Sequence Network shown in Fig. B-4 is for the same conditions shown in Fig. B-2. The Zero Sequence Network, like the Negative Sequence Network, does not include voltage sources. The Zero Sequence Network, however, includes corrections for transformer winding connections. The fault must be located at the same node in the positive sequence, negative sequence, and zero sequence networks.

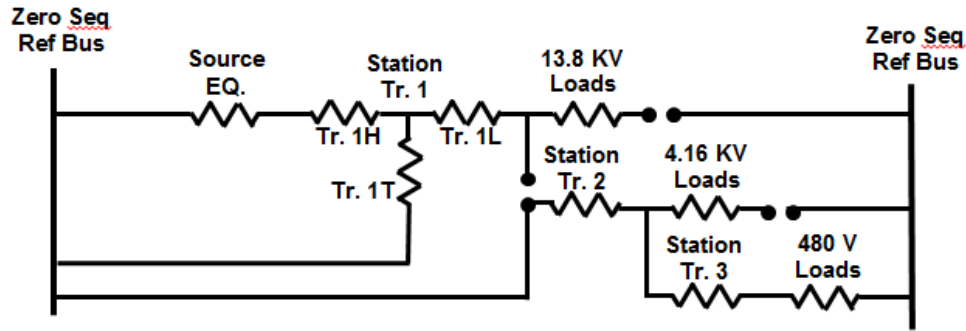


Fig. B-4. Zero Sequence Diagram for Fig. B-1

Transformer Equivalent Circuits

The representation for Station Transformer 1 in Fig. B-4 is the equivalent circuit for a three winding, wye-grounded, wye-grounded, delta transformer or for a two winding, wye-grounded, wye-grounded transformer with a three-legged core.

The representation for Station Transformer 2 in Fig. B-4 is the equivalent circuit for a two winding, delta-wye grounded transformer.

The representation for Station Transformer 3 in Fig. B-4 is the equivalent circuit for a two winding, wye-grounded, wye grounded transformer.

Three different transformer winding connections are shown to illustrate the impact of transformer winding connections on Zero Sequence Networks.

Load Equivalent Circuits

The representation for loads is a function of circuit connections. In Fig. B-4, 13.8 kV loads are represented as delta connected loads. 4.16 KV loads are represented as delta connected loads, and 480 volt loads are represented as wye-grounded connected loads.

B.1.2 Symmetrical Component Networks for Open Phase Conditions

Symmetrical component networks used to calculate open circuit conditions are strongly influenced by motor load and transformer connections as phase current and phase voltage is a function of positive sequence impedance in series with the parallel combination of negative sequence impedance and zero sequence impedance.

For the system illustrated in Fig. B-5 (one line diagram with “A” phase open on the primary side of Station Tr. 1), the symmetrical component networks are Open Phase Positive Sequence Network (Fig. B-6), Open Phase Negative Sequence Network (Fig. B-7), and Open Phase Zero Sequence Network (Fig. B-8).

Fig. B-5 represents normal plant operation with an open phase condition. Plant auxiliary loads are supplied via a transformer connected to the generator leads. Startup and

emergency loads are supplied via station transformers that are served via offsite power. Emergency generators are not operating.

During normal operating conditions, station loads, MV ESF loads and LV ESF loads served by offsite power supplies may be minimal. During Design Basis Events, station loads, MV ESF loads and LV ESF loads served by offsite power supplies may be maximum. The transition from minimum load to maximum load may occur in approximately one minute.

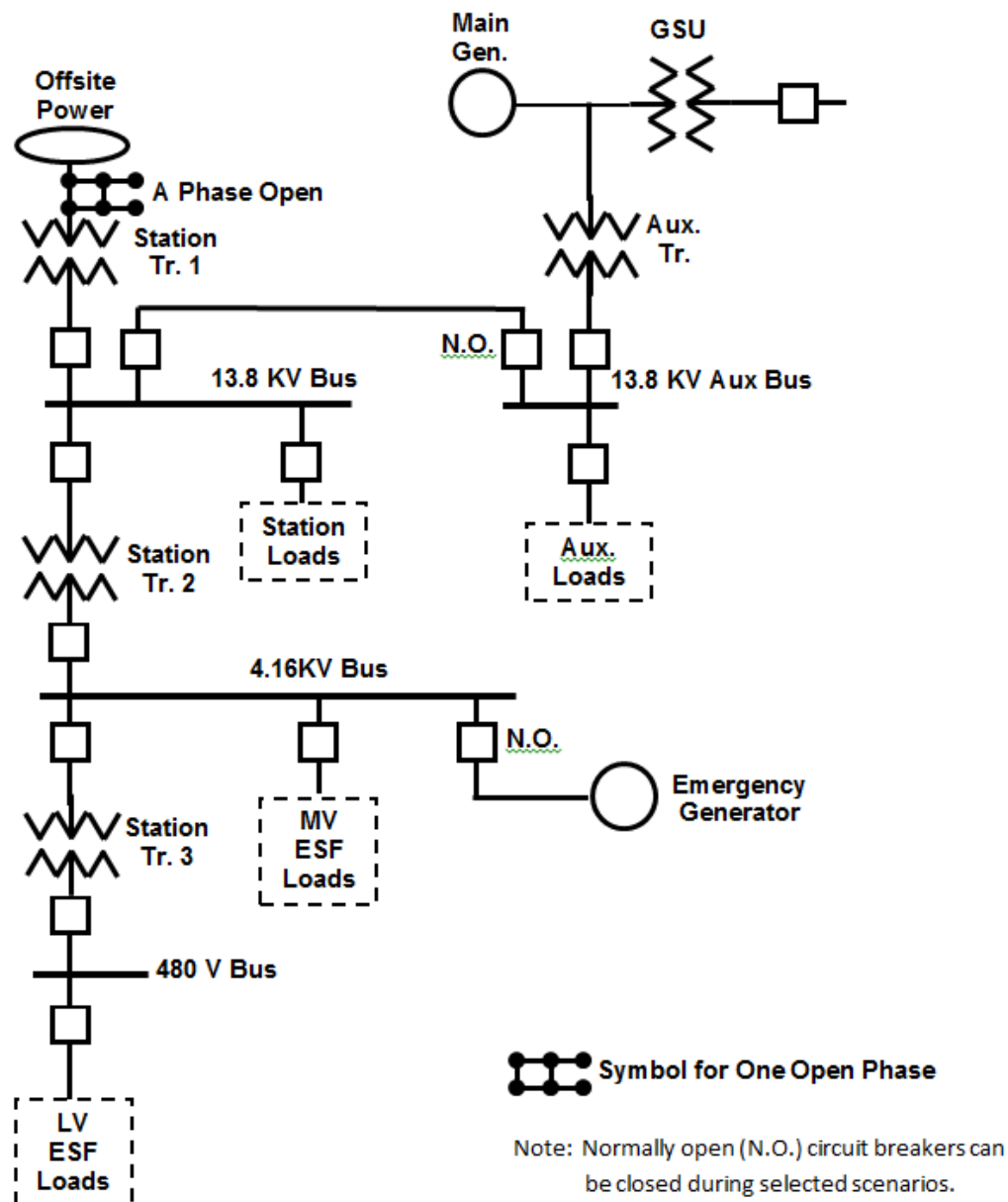


Fig. B-5. Nuclear Power Plant Electrical System One Line Diagram--Open Phase Condition

The Positive Sequence Network for Open Phase conditions shown in Fig. B-5 is for the scenario where the main generator is supplying plant auxiliary loads and emergency generators are not in service are shown below in Fig. B-6. Typical impedance values for all components are shown in Table B1, Table B2, Table B3, and Table B4. These tables show typical impedance values that are used in calculations.

Note: S designates Transmission System side of the open phase.
P designates Plant side of the open phase.

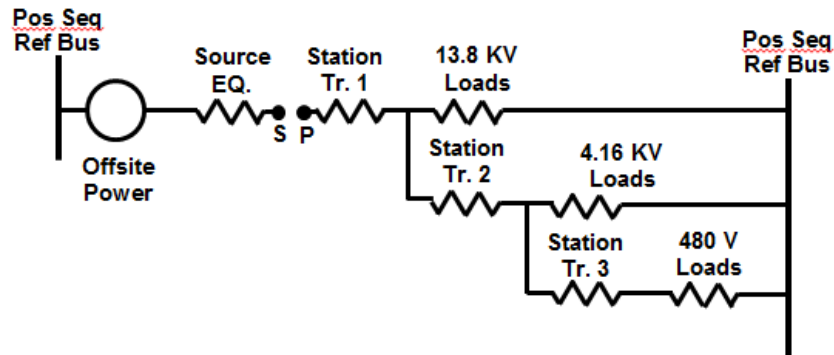


Fig. B-6. Open Phase Positive Sequence Diagram for Fig. B-5

The Negative Sequence Network for Open Phase conditions shown in Fig. B-7 is for the same conditions shown in Fig. B-6. Equivalent motor impedances, however, are a function of motor rotational speed and may be less in the negative sequence than in the positive sequence.

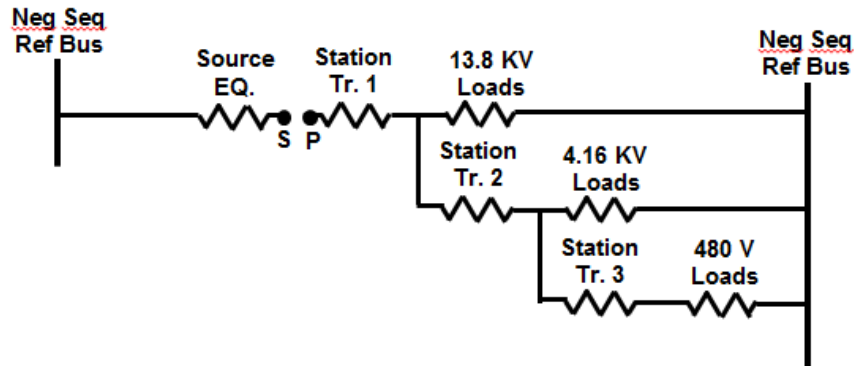


Fig. B-7. Open Phase Negative Sequence Diagram for Fig. B-5

The Zero Sequence Network for Open Phase conditions shown in Fig. B-8 is for the same conditions shown in Fig. B-6. The Zero Sequence Network for Open Phase conditions is influenced by transformer winding connections in the same manner as the Zero Sequence Network for fault conditions.

For the transformers illustrated in this example:

- a. Station Tr.1 construction, winding connections, equivalent circuit and impedance can significantly affect results
- b. motor zero sequence impedance does not affect the results as all loads are isolated in the zero sequence equivalent circuit

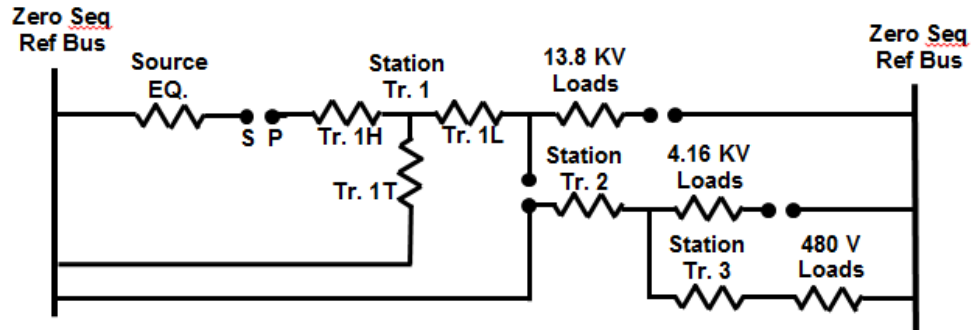


Fig. B-8. Open Phase Zero Sequence Diagram for Fig. B-5

B.1.3 Symmetrical Component Network Connections for Open Phase Conditions

Fig. B-9 shows positive, negative, and zero sequence network connections used to calculate open circuit current and voltage for the condition shown in Fig. B-5. Note that a jumper is shown from node S (P) in the positive sequence to node S (P) in the negative sequence and to node S (P) in the zero sequence as directed by Dr. Fortescue in 1918.

Fig. B-9 can be simplified as shown in Fig. B-10. By observation, it can be noted that the positive sequence network is in series with the parallel combination of the negative and zero sequence networks.

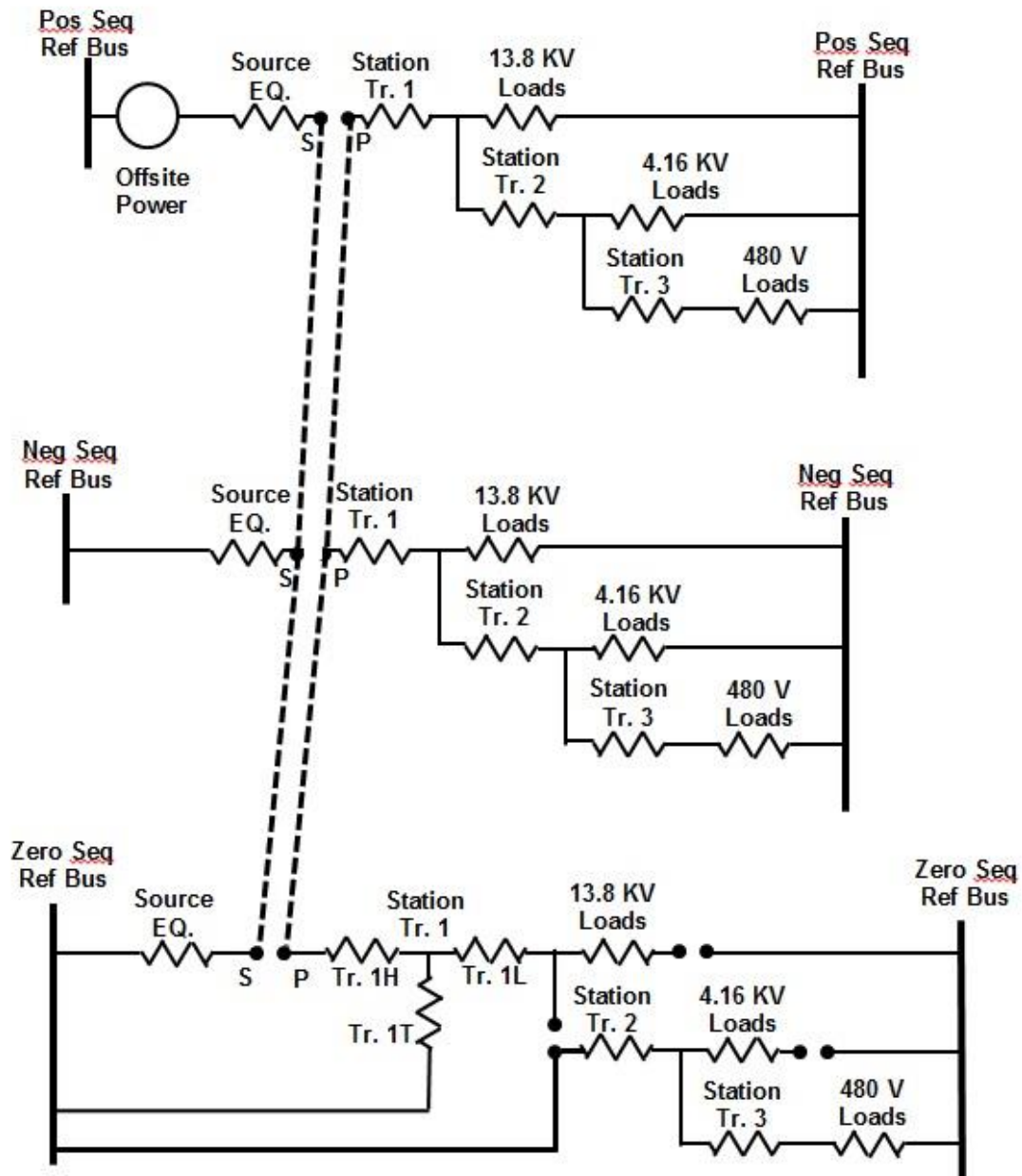


Fig. B-9. Symmetrical Component Network Connections for Open Phase Conditions shown in Fig. B-5

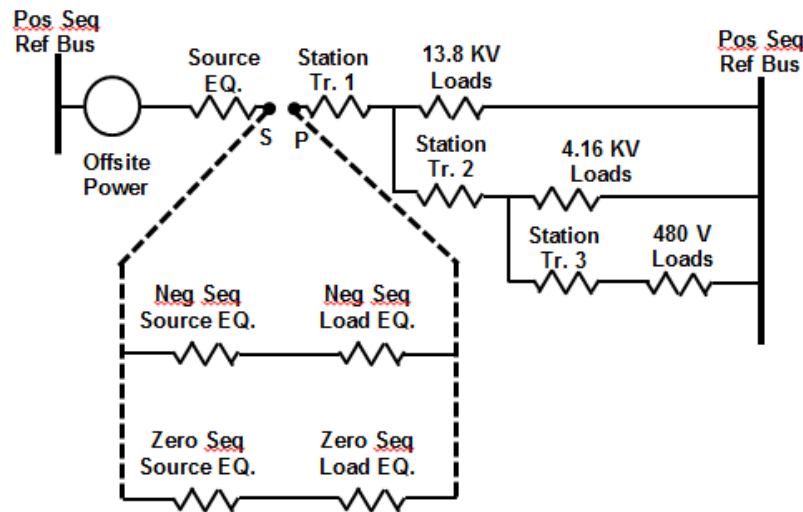


Fig. B-10. Simplified Component Network Connections for Open Phase Conditions shown in Fig. B-5

Impedance data listed in Table B1, Table B2, Table B3, and Table B4 and the equivalent circuit shown in Fig. B-10 can be utilized to assess continued motor operation when motors are operating before an open phase condition occurs as well as to assess motor acceleration if a motor is started while an open phase condition exists.

When the equivalent zero sequence is low, the zero sequence impedance will shunt the negative sequence impedance. This means that continued motor operation and even motor acceleration would not be significantly impacted by an open phase condition.

When the equivalent zero sequence is high, the zero sequence impedance will have very little effect on the negative sequence impedance and continued motor operation will not be significantly impacted by an open phase condition if motor mechanical torque is less than the torque produced by an electric motor. Motor heating can, however, be excessive and continuous motor operation may not be advisable.

When the equivalent zero sequence is high, zero sequence impedance will have very little effect on negative sequence impedance and motor acceleration will be impacted by an open phase condition.

Table B1. Typical Light Load Impedance Values, Normal Operation

Typical Light Load Impedance Values, Normal Operation		
Positive Sequence Values	Z (pu)	Angle
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	200.00	25
4.16 kV Loads	666.67	25
480 V Loads	2000.00	25
Negative Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	33.33	85
4.16 kV Loads	111.11	85
480 V Loads	333.33	85
Zero Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89

Table B2. Typical Light Load Impedance Values, Accelerating Motors

Typical Light Load Impedance Values, Accelerating Motors		
Positive Sequence Values	Z (pu)	Angle
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	33.33	85
4.16 kV Loads	111.11	85
480 V Loads	333.33	85
Negative Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	33.33	75
4.16 kV Loads	111.11	75
480 V Loads	333.33	75
Zero Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89

Table B3. Typical Load Impedance Values, Significant Load

Typical Load Impedance Values, Significant Load		
Positive Sequence Values	Z (pu)	Angle
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	50.00	25
4.16 kV Loads	200.00	25
480 V Loads	666.67	25
Negative Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	8.33	85
4.16 kV Loads	33.33	85
480 V Loads	111.11	85
Zero Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89

Table B4. Typical Load Impedance Values, Significant Load, Accelerating Motors

Typical Load Impedance Values, Significant Load, Accelerating Motors		
Positive Sequence Values	Z (pu)	Angle
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	8.33	85
4.16 kV Loads	33.33	85
480 V Loads	111.11	85
Negative Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89
Station Tr. 2	0.70	89
Station Tr. 3	0.80	88
13.8 kV Loads	8.33	75
4.16 kV Loads	33.33	75
480 V Loads	111.11	75
Zero Sequence Values		
Source	0.017	89
Station Tr. 1	0.30	89

B.1.4 Simplified Symmetrical Component Analysis

- a. Open Circuit Zero Sequence Network, motors continue rotating

If the zero sequence equivalent network is an open circuit and one phase opens and the mechanical load is less than the motor capability, motors will continue operating, but heat up rapidly. The reason is that motor positive sequence impedance will predominate as the motor positive sequence impedance can be six times greater than the motor negative sequence impedance.

b. Open Circuit Zero Sequence Network, motor acceleration

If the zero sequence equivalent network is an open circuit and one phase opens, motors will not accelerate. The reason is that the motor positive sequence impedance will be equal to the motor negative sequence impedance and accelerating power will be significantly lower than needed for motor acceleration.

c. Low Impedance Zero Sequence Network, motors continue rotating

If the zero sequence equivalent network is a low impedance circuit and one phase opens and the mechanical load is less than the motor capability, motors will continue operating and motor heating will be much less than the open circuit zero sequence condition. The reason is that the low zero sequence network impedance will bypass the motor negative sequence impedance and motor power can be essentially unchanged.

d. Open Circuit Zero Sequence Network, motor acceleration

If the zero sequence equivalent network is a low impedance circuit and one phase opens, motors will accelerate if the impedance of the source is significantly less than the apparent impedance of the accelerating motors as the low zero sequence network impedance will bypass the motor negative sequence impedance and accelerating power can be significant.

B.1.5 Discussion of Symmetrical Component Analysis of Open Phase Conditions

Two conditions need to be evaluated. First, motor heating when an open phase occurs while a motor is in operation. Second, motor heating when a motor start is attempted while one phase is open.

Using symmetrical components to calculate motor heating, temperature, speed and acceleration as a function of sequence quantities will reveal the amount of motor stall torque that occurs and the amount of motor rotor heating contributed by negative sequence quantities.

Motor overheating while a motor is in operation can take several minutes as windage will help cool the motor as it rotates.

The allowable duration for motor heating during attempted acceleration with an open phase will be longer than motor safe stall time because motor inrush current will be much less than rated motor accelerating current.

Using symmetrical components, sequence quantities and microprocessor based relays, open phase conditions can be detected at any point in the network where motor current and voltage can be monitored. Some typical setpoints are listed in paragraphs 2.1.6.1 and 2.1.6.2.

APPENDIX C Optical CT

Fig. C-1. OPTICAL CT shows a simplified block diagram of the optical CT. The sensor is a reciprocal interferometer^{36, 37, 38}. As such, it does not respond to reciprocal effects such as strain and temperature, but does sense non-reciprocal Faraday phase shifts due to magnetic fields. The optical circuit is a derivative of a fiber optic gyroscope and its major signal processing schemes have been adapted to this current sensor.

In the design for open-phase detection, the sensing ring along with the modulator is mounted on the transformer, while the light source, detector, and electronics are housed in a 19 inch rack mounted chassis that resides in a control room or outdoor cabinet. Both a fiber optic and a modulator trunk cable are required to interconnect the electronics chassis to the sensors mounted on top of the transformer.

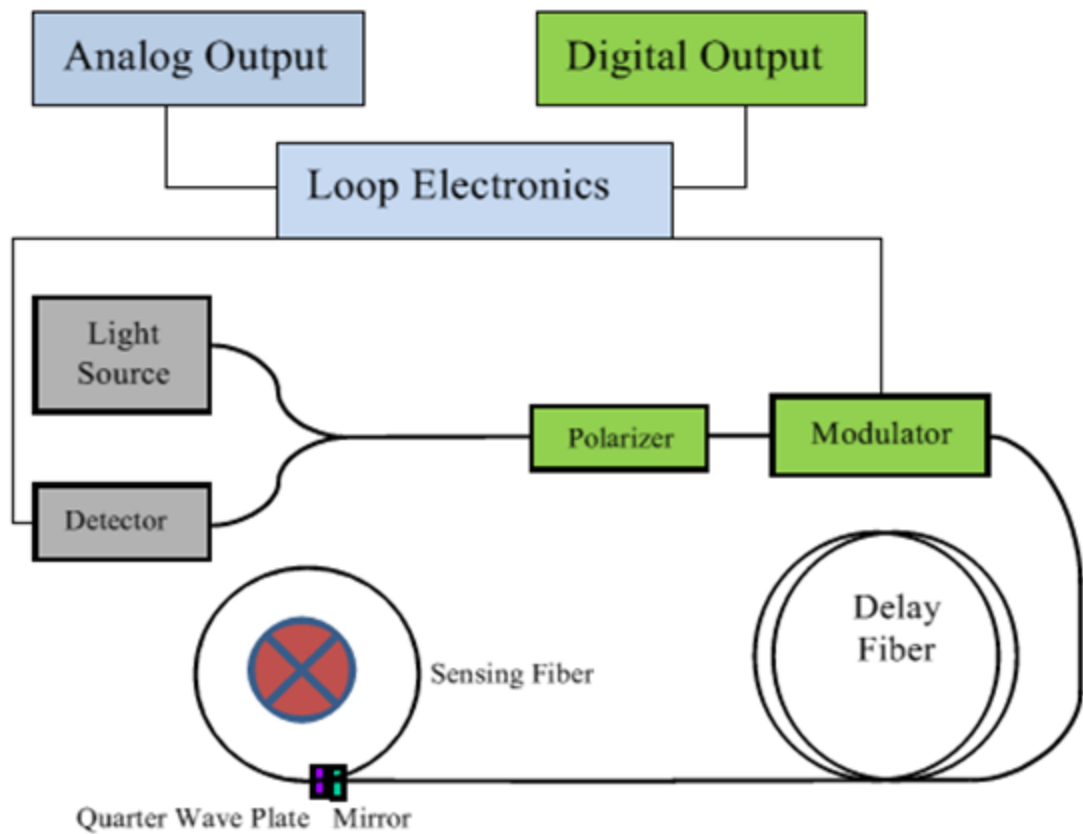


Fig. C-1. OPTICAL CT

³⁶ Blake, J., Tantaswadi, P., de Carvalho, R. T., "In-Line Sagnac Interferometer Current Sensor" IEEE Trans. Power Delivery, Vol. 11, 116-121 (1996).

³⁷ Short, S. X., Tselikov, A. A., de Arruda, J. U., Blake, J. N., "Imperfect Quarter-Waveplate compensation in Sagnac Interferometer-Type Current Sensors," J. Lightwave Technol., Vol. 16, 1212-1219 (1998).

³⁸ Blake, J., "Current Sensors based on the Sagnac Interferometer," Proc. SPIE, 2837, 166-171 (1996).

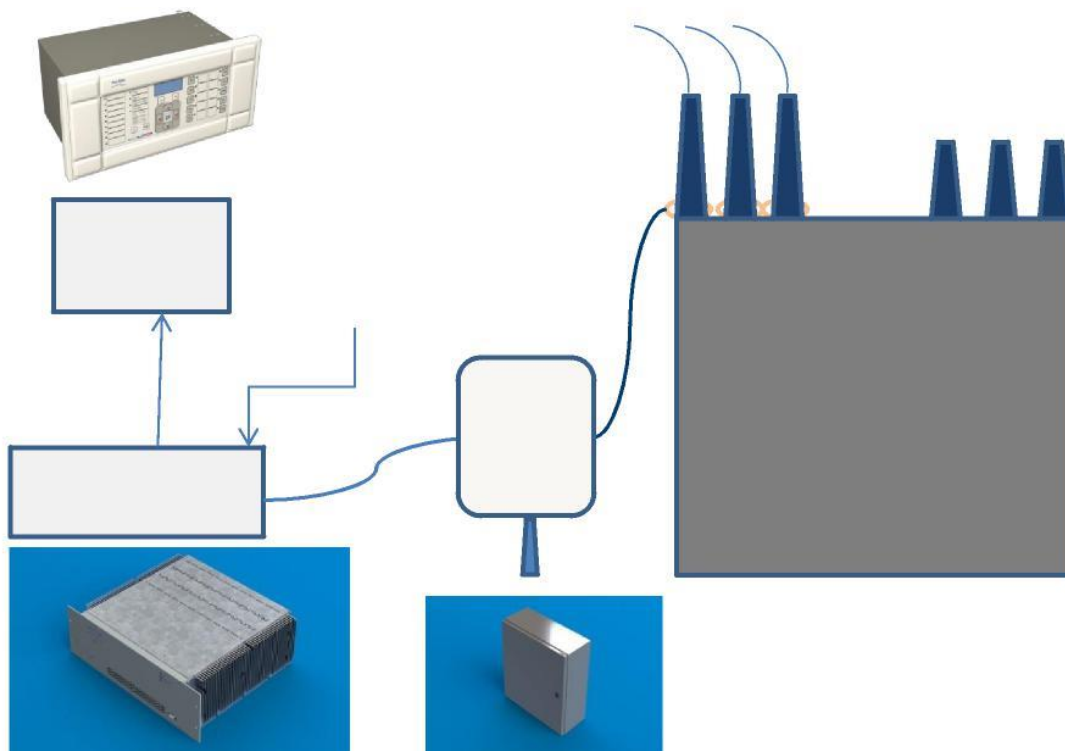


Fig. C-2. Open Phase Detection Architecture

C.1 System components

Fig. C-2. Open Phase Detection Architecture shows the system architecture for the detection of an open phase on a loaded or unloaded power transformer. Optical CTs are mounted on each phase of the high side of the transformer to be monitored. An outdoor cable box is provided near the transformer to make the optical and modulator connections to a trunk cable which runs between the transformer and the electronics. A single electronics box located in a control room (or outdoor cabinet) powers the three CTs, and provides a digital output representation of the currents in each phase following the IEC 61850-9-2LE optical Ethernet protocol. In addition to each phase current, the digital protocol also provides the mathematical sum of the three phase currents, thus yielding the calculated neutral current as part of the data frame. A 9-2LE Process Bus compliant relay reads and processes the digital data from the CTs.

C.2 Dual stream data processing

The open-phase detection system is designed to work for both loaded and unloaded transformers. However, the current levels and the response times required are quite different for these two cases. In the case that the transformer is unloaded, the current levels are low ($\ll 1A$), while the response time needed for OPC detection and verification can be many seconds. In the case that the transformer is loaded (even lightly loaded) the current levels exceed 1A, but the response time for detection and verification need to be

much faster; perhaps 100 msec, but perhaps longer depending on relay coordination requirements with other protection systems.

To implement the OPC system to operate in both loaded and unloaded scenarios, the scheme uses a dual stream digital signal processing approach. Inside the signal processing chip, the raw digital data for each current sensor is split into two separate digital streams and are assigned different addresses. The first stream is heavily filtered using a frequency tracking comb filter with narrow pass bands located at the fundamental power frequency and several higher harmonics in order to provide a low noise version of the mA level signals flowing into the high side of the unloaded power transformer. The elimination of all non-harmonic noise allows for the measurement of currents down to approximately 1 mA. The second stream is lightly filtered using a weak band pass filter around 60 Hz and the data from this stream is used for determining the open phase condition when the transformer is loaded.

These two data streams (heavily filtered comb and lightly filtered band pass), being assigned different addresses, are sent to the relay encoded as readings from different CTs. The relay determines whether or not there is an OPC in the unloaded case by looking at the first (heavily filtered) signal, and in the loaded case by looking at the second (lightly filtered) signal. In this way, the manufacturer's approach avoids the need for physically separate CTs to provide protection in both the loaded and unloaded cases.

C.3 Redundant VT frequency reference

A 120 V (20 – 200 V) input from a local voltage transformer (or other source) is additionally provided to the optical CT electronics chassis. The purpose of this signal is to provide a frequency reference for the digital comb filter provided within the signal processing of the optical CT. The comb filter has a (tunable) pass band of approximately 1/4 Hz around each of the first several harmonics of the power frequency. Since the power frequency itself may vary over time by 1/4 Hz or more, it is necessary that the comb filter be frequency tracking in real time. The center frequency for the comb is locked to that of the VT input. The electronics allows for redundant VT inputs so that the open-phase detection system will continue to work if one VT input is lost or becomes corrupted. The transition between the use of the two inputs is seamless; no false alarm will ensue during the switch over time if one input is lost. Additionally, there is no requirement on the phase relationship between the redundant VT inputs. The only requirement on these inputs is that they be synchronous with the line frequency.

C.4 Relay logic description

To validate the relay logic methodology, the test transformer and incoming lines were modeled and digital power system simulation testing was performed on production system hardware. This testing was 100% successful in correctly detecting the range of simulated faults, with no false positives. For the loaded transformer case, the relay looks at the lightly filtered data while for the unloaded transformer case, the relay looks at the heavily filtered data. For the loaded case, an OPC is determined by the combination of an unusually low level on one of the phase currents, confirmed by an unusually high level of

negative sequence current. For the unloaded case, an OPC is determined by the combination of an unusually low level of one of the phase currents, confirmed by an unusually high level of zero sequence current. For long lines, an open phase at a distance greater than 1 km can result in line charging which could mask the effect of an open phase condition based simply on a low phase current. In this case, a negative sequence test would be beneficial if added to the unloaded case. For additional security for the relay logic (though not included in the digital power system simulation testing), the manufacturer recommends including another input to the relay which is an indicator of the state of the low-side circuit breaker, whether open or closed. Based on the level of currents flowing, the loading of the transformer can be inferred. However, it is possible to fool the relay logic by setting the low/high current thresholds very close to the operating current.

Also note that the delay times programmed into the relay logic need to be coordinated with the existing protection to minimize over tripping. Some open phase condition faults will also trip out the existing protection. An example is a grounded power line feeding the high side of the transformer that remains connected at its source (Fig. 1). In this case, there will be no (or very low) voltage applied to one phase of the transformer, and thus the current in that phase will drop. However, there will be a huge fault current flowing from the power source to the ground fault. As with any type of fault it is desirable for it to be detected and cleared at the switch yard so as to trip as quickly as possible, to trip the minimum amount of equipment and to not rely on remote detection that is often time delayed.

C.5 Redundancy

The OPD (Open Phase Detection) system can be easily configured for redundancy. Up to 4 optical sensors can be installed in the same ring, but the cabling, the CT electronics, and the relays are all duplicated. The relays may be wired for various voting logic schemes (e.g., 2/3 reverting to 2/2 voting logic in the case of equipment failure, or 2/2 reverting to 1/1 voting in case of equipment failure.)

The next three figures (Fig. C-3. Test of Normally Connected Power Transformer, Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current, Fig. C-4. Test of Faulty Connected Power Transformer (Phase B Open), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current, Fig. C-5. Test of Faulty Connected Power Transformer (Phase B Grounded), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current) illustrate the current levels detected for a transformer that was under test.

•Phase A connected, Phase B connected, Phase C connected; 100% excitation voltage, 138kV

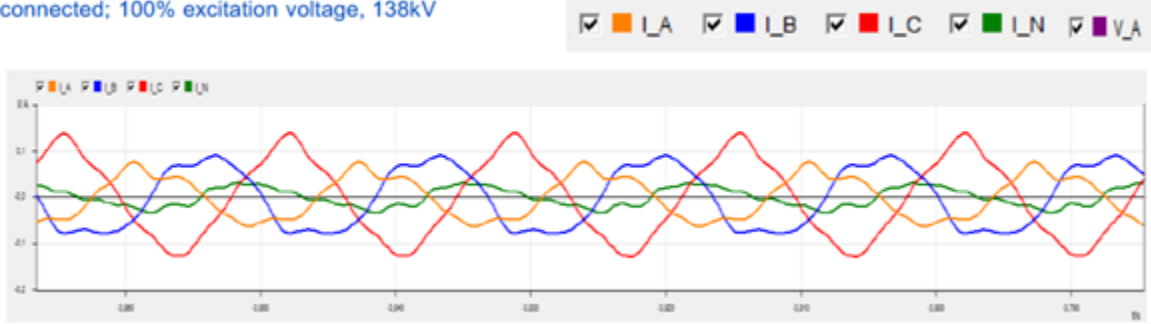


Fig. C-3. Test of Normally Connected Power Transformer, Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current

Phase A connected, Phase B open, Phase C connected
100% excitation voltage, 138kv

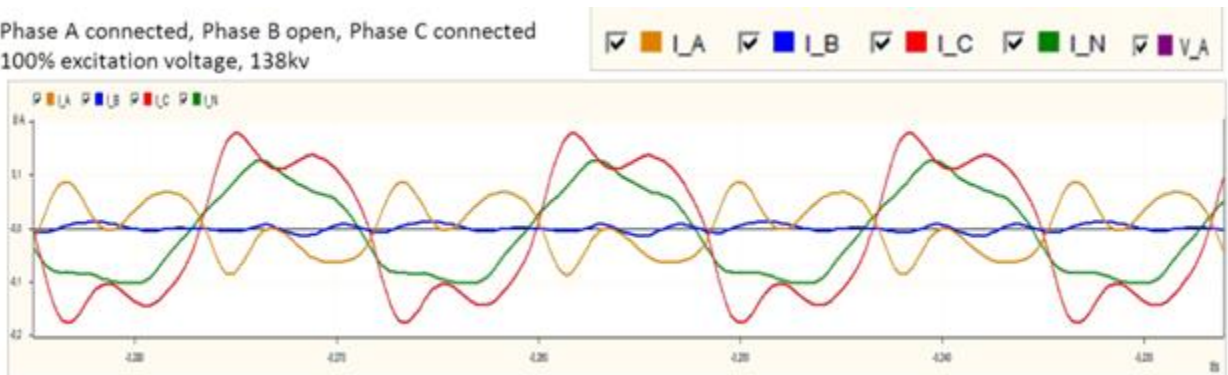


Fig. C-4. Test of Faulty Connected Power Transformer (Phase B Open), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current

Notice that there is a drop in the B phase current.

Phase A connected, Phase B grounded, Phase C connected
100% excitation voltage, 138kv

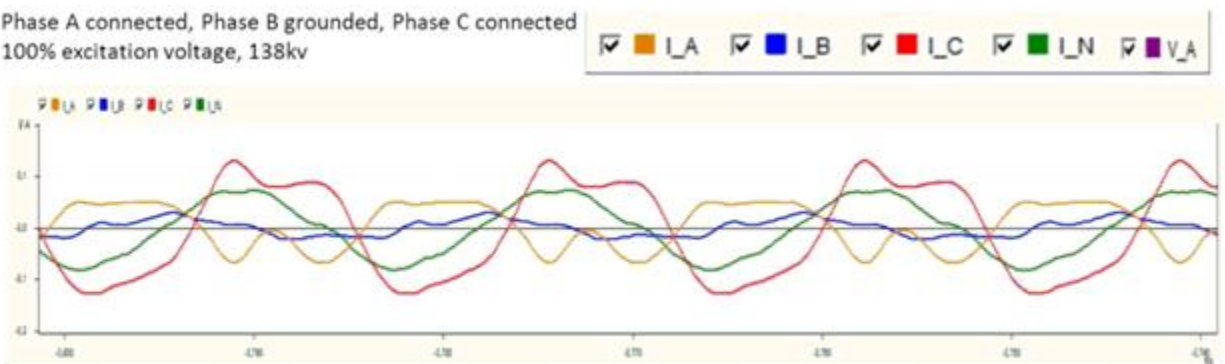


Fig. C-5. Test of Faulty Connected Power Transformer (Phase B Grounded), Showing Several Cycles of the Phase Currents, along with the Mathematically Summed Neutral Current

APPENDIX D Rogowski Coils

Rogowski coils may be designed with different shapes, such as round and oval. The coils may be made of rigid or flexible materials. They can be made as non-split style, or alternatively as split-core construction that can be opened to assemble around a conductor that cannot be opened (see examples in Fig. D-1. Examples of Rogowski Coil Designs). The cross-sectional shape upon which the coil is formed is generally either circular or rectangular. Rigid Rogowski coils may be designed using printed circuit boards (PCBs) as window (non-split-core) style or split-core style. PCB Rogowski coils can be designed using one or two printed circuit boards to imprint windings. Designs using one PCB have both windings imprinted on the same PCB. Designs using two PCBs have one coil imprinted on each PCB, wound in opposite directions. PCB Rogowski coils may have higher accuracy than flexible Rogowski coils.

Rogowski coils can be applied near conductors that carry high currents. Such applications are possible because the coils are immune to external electromagnetic fields resulting from nearby conductors. Also because of the precise design of the coil, the conductor inside the coil opening does not need to be centered to preserve metering accuracy.

Rogowski coils have the following main characteristics:

- Can be designed for metering accuracy class,
- Wide current measurement range (from 1 A to over 100kA),
- The same coil can be used for both protection and metering,
- Frequency response up to 1 MHz (special designed coils above 1 MHz),
- Window-type design provides high short-circuit current withstand ratings,
- Provide galvanic isolation from the primary conductor,
- Wide current measurement range results in reduced number of sensor types and reduced storage requirements,
- Installation is simple (split-core style coils can be mounted around conductors or bushings without requirements to open primary conductors),
- Compact and robust design,
- Lightweight construction (weight: Rogowski coil < 5 pounds vs. 600/5 A C200 CT > 60 pounds)
- Safer for personnel (no open-secondary high-voltage hazard)
- Immune to EMI (shielded)

Rogowski coils can be applied at any voltage level. Rogowski coils designed with low-voltage insulation level can be used in high-voltage systems such as gas-insulated switchgear (GIS) and air-insulated switchgear. For applications in GIS, Rogowski coils are implemented in the switchgear enclosure that is a ground potential (see Fig. D-2a). For applications in air-insulated substations, Rogowski coils may be installed around the power transformer bushings or around power cable bushings in their base that is ground potential (see Fig. D-2b). Rogowski coils may also be installed at high-voltage levels directly such as around primary high-voltage conductors (see Fig. D-2c). For such applications, Rogowski coils can be designed with low-voltage insulation level. The principle of the measurement system operation is simple. The line currents are measured by Rogowski coils. Their analog signals can be converted to digital signals at the coil location using A/D converters (Remote Unit).

Data from the high-voltage level to ground potential can be transmitted using a fiber-optical cable. Power required for the electronics located at the high-voltage level can be provided by power LEDs (lasers) located at the ground level powering the Remote Unit installed at the high-voltage level through another fiber-optic cable.

The advantages of optically-powered solutions using Rogowski coils when compared to the conventional designs (high-voltage, free-standing, iron-core CTs) are: no oil or SF6 gas (environmentally friendly); light weight; and no seismic or explosion concerns.

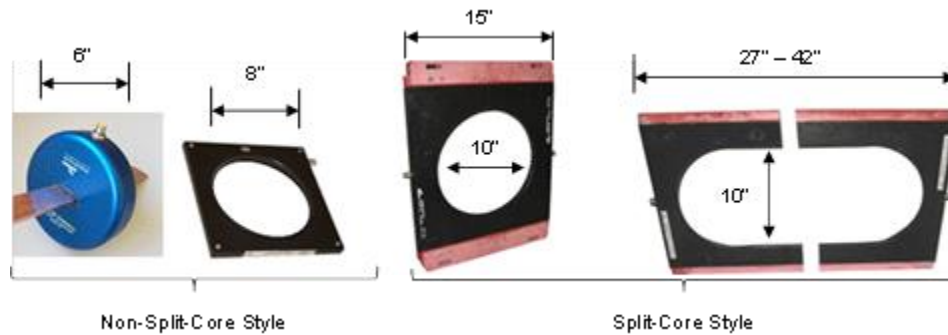


Fig. D-1. Examples of Rogowski Coil Designs

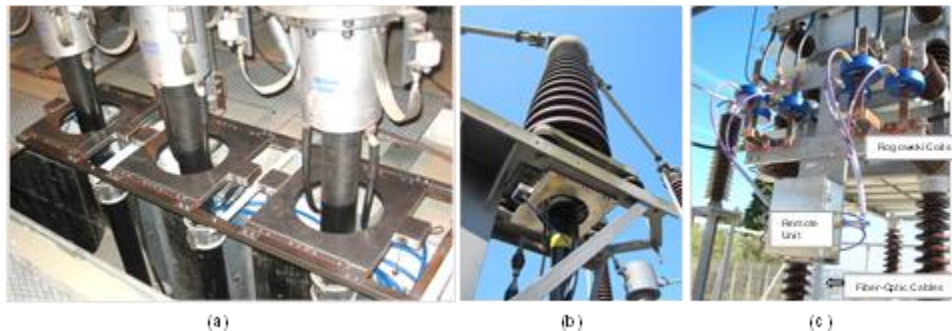


Fig. D-2. Examples of Rogowski Coil Installations

APPENDIX E Open Phase Detection Methods Using Microprocessor Relays³⁹

E.1 Difference Between The Ratio Of The Second-Harmonic To Fundamental Currents

Microprocessor relays use analog-to-digital (A/D) converters, which are devices that sample analog signals and convert them into digital bits. A/D converters exhibit errors, these errors are significantly amplified when the input signal is no longer available and substituted by noise.

This A/D converter behavior can be used to detect ungrounded open phase events as the excitation current signal is no longer available to be processed by the A/D converter, and the output signal becomes amplified random noise due to the A/D least significant bit toggle.

When a transformer is operated at no load, the currents flowing through the primary circuit are mainly the transformer excitation currents. These currents contain a significant harmonic content as a percent of fundamental and are different in magnitude due to the mutual coupling between the phases and the transformer core geometry. The ratio of second-harmonic to fundamental currents remains fairly small and constant when the transformer is unloaded.

If an ungrounded open phase event occurs, no current flows from the source to the transformer on the open phase. This method looks at the difference between the present ratio of the second-harmonic to the fundamental contents of the excitation currents and the same ratio 2 milliseconds prior on all three phases. This difference remains fairly small under normal operating conditions.

Once an open phase event occurs, this difference becomes random as a result of the A/D converter behavior as shown in Fig. E-1. Once this randomness is detected, a counter starts to tally how many times the difference exceeds a predetermined threshold over a specified time. If the counter threshold is reached during this time, an open phase condition is detected.

³⁹ Cox, D., Abd-Elkader, A., Chaluadi, H., "Open-Phase Detection for Station Auxiliary Transformers", Western Protective Relay Conference, October 2018, <https://selinc.com/api/download/124320/>

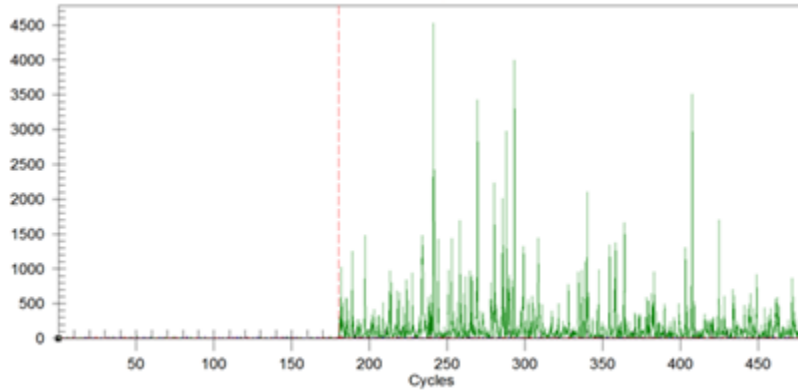


Fig. E-1. Difference Between The Ratio Of The Second-Harmonic To Fundamental Currents

This method can be used to detect ungrounded open phase events on wye or delta connected primaries. In cases where the transformer is fed through long cables or has high-side coupling capacitor voltage transformers (CCVTs) installed close to the bushings used for line protection, the current does not drop to zero after the open phase event. This is because the opened phase remains energized through the other two phases supplying capacitive current to the cable or CCVT as shown in Fig. E-2. This issue is less prominent on transformers fed through overhead transmission lines with no high-side bushings CCVTs.

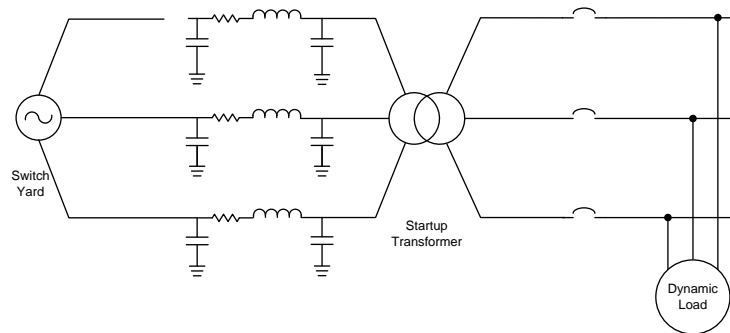


Fig. E-2. Open Phase Event Involving Long Cables

E.2 Digital Filters

The main problem with open phase detection is when the transformer is unloaded and only drawing excitation currents. These currents are inherent to each transformer and are not expected to change significantly over time. Another approach to solving this problem is to look at the current magnitude on each phase. If the excitation current on each phase is monitored and stored, then the magnitude of each phase current could be compared with its stored value. If the current drops below a specified threshold, then an open phase condition can be detected. See Fig. E-3.

This approach could be achieved through the use of Infinite Impulse Response Digital Filters. The output response of an IIR filter to an impulse input reaches a new value asymptotically after a certain time delay.

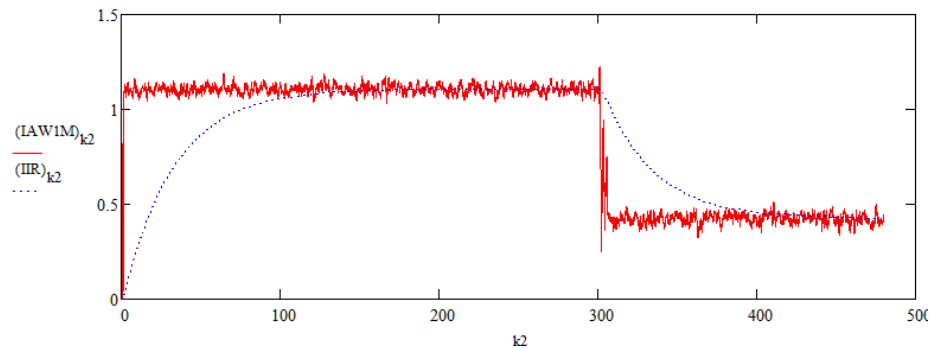


Fig. E-3. IIR Filter Response

The red quantity is the measured phase excitation current that is the input to the IIR filter; the blue quantity is the IIR filter output response. The algorithm compares the measured phase current to the IIR filter output. If the phase current drops below a set percentage of the IIR filter response, then an open phase condition is detected. The main advantage of this approach is that the IIR filter output (threshold) adjusts dynamically to the system conditions prior to the open phase event accounting for variations in the phase currents due to system imbalance.

The drop percentage is based the highest expected capacitive current post an open phase at the farthest electrical point in the zone of detection. If the current does not drop by 25 percent or more, then this algorithm cannot be implemented without a minimum load. The proposed minimum load current is 1.5 times the maximum charging current, which remains substantially lower than the load required when using conventional relaying in detection schemes. For example, a transformer with 10 mA secondary excitation current (from CT into relay) seeing 15 mA of secondary capacitive current after an open phase event would need a minimum load of $1.5 \cdot 15 = 22.5$ mA in order to detect a drop in current. This load is lower than the 100 mA needed when using conventional current detection methods in 1 A relays and the 250 mA in 5 A relays.

This method can be used to detect grounded and ungrounded open phase events on delta connected primaries, and ungrounded open phase events on wye connected primaries under no or light loading levels.

E.3 Zero-Crossings Measurements

The zero-crossings logic shown in Fig. E-4 can be used to detect ungrounded open phase events on delta or wye connected primaries when the transformer is operated under load. This logic measures the zero crossings and current magnitudes of each phase. If the logic does not detect a zero-crossing or the current drops below 0.1A secondary (from CT into

relay) on one or two phases within $5/8$ of a power system cycle, an open phase condition is detected. Fig. E-4 is illustrative for one phase. The times listed are in cycles.

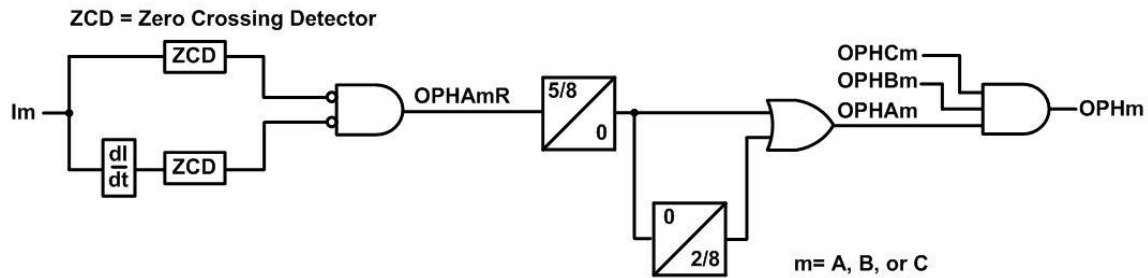


Fig. E-4. Zero-Crossings Open Phase detection logic

E.4 Zero-Sequence To Positive-Sequence Currents Ratio

Grounded open phase events (Fig. 1) result in significant zero-sequence currents at the primary of the transformer on grounded wye primaries. The ratio of the zero-sequence to positive-sequence currents can be used to detect grounded open phase events under all loading conditions.

The use of the ratio of the zero-sequence to positive-sequence currents enhances the detection reliability across a wider range of open phase to ground impedances. This ratio can be supervised by the maximum expected zero-sequence current imbalance under normal operating conditions and coordinated with the existing plant protection to enhance system security.

E.5 Negative-Sequence To Positive-Sequence Currents Ratio

Grounded open phase events (Fig. 1) on the primary of the delta connected primaries result in negative-sequence currents at the primary of the transformer. The magnitude of the negative-sequence current is dependent on the loads fed by the transformer at the time of the open phase event. The ratio of the negative-sequence to positive-sequence currents can be used to detect grounded open phase events (Fig. 1) on the primary of the transformer when operated under load.

The use of the ratio of the negative-sequence to positive-sequence currents enhances the detection reliability across a wider range of open phase to ground impedances and transformer loading levels. This ratio can be coordinated with existing plant protection to enhance system security.

APPENDIX F Power Transformer Open Phase Detection by Current Transformer Open Circuiting

This appendix describes an innovative method for detecting the open phase condition. This new method uses conventional current transformers and protective relays and requires no specialized instrumentation or equipment.

F.1 Introduction

For some designs of three-phase power transformers such as the three-legged core type with wye-wye configuration, an open primary phase cannot readily be detected with traditional unbalance protection schemes when the bank is unloaded or lightly loaded.^{40,41} Assume the three-legged core type transformer shown in Fig. F-1 is excited by balanced primary voltages on any two phases with the third phase open. Due to flux summation the third leg will still have normal flux flow which will induce normal primary and secondary voltage in that phase. This presents a serious concern at nuclear generating stations that require offsite emergency power to be available immediately for safety reasons from transformers that may be unloaded or lightly loaded until needed.

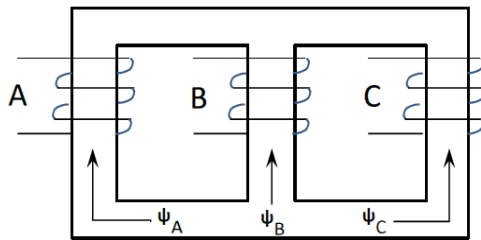


Fig. F-1. Three legged core transformer.

F.2 Scheme Description

The basis for the new scheme is the fact that when a current transformer has current flowing in its primary and the secondary is open circuited a voltage is developed across the open secondary. For normal load levels this voltage can be very high. Current transformers conforming to “shall be capable of operating under emergency conditions for 1 min with rated primary current times the rating factor with the secondary circuit open if the open-circuit voltage does not exceed 3500 V crest.”⁴² However, the currents

⁴⁰ J. Horak; G. Johnson, “A Practical Guide for Detecting Single-Phasing on a Three-Phase Power System,” presented at the 29th Annual Western Protective Relay Conf., Spokane, WA, 2002.

⁴¹ G. Johnson; R. Hamilton; S. Thakur, “Effect of transformer connection and construction on single phasing detection,” in Protective Relay Engineers, 2013 66th Annual Conference for, vol., no., pp. 177-188

⁴² IEEE Standard Requirements for Instrument Transformers, IEEE Standard C57.13-2008, Jul. 2008.

experienced during the brief test period described as follows are well below rated current and the resulting open circuit voltages are more than an order of magnitude smaller. In fact, the voltages developed using this new scheme are less than those commonly expected in high-impedance bus differential schemes in which current transformers are intentionally driven into saturation.

The scheme uses simple overcurrent detectors to block the open-circuiting test if the current present is measurable above the minimum pickup of the protective relay. If current is above the minimum pickup of the overcurrent detector then there is no need to run the open-circuit test on that phase.

A standard digital high-impedance bus differential protective relay was used for the scheme. This relay has voltage inputs rated for 150 V continuous, linear to 3000 V symmetrical. The range on the voltage element is 20-800 V (instantaneous voltage) and the element can operate in as fast as 1ms. The voltage inputs have MOVs to clamp the voltage to safe levels in the relay's normal role of high-impedance differential.⁴³ The current inputs can be specified as standard 5 A or 1 A input. For the 5 A relay the overcurrent detectors have a minimum pickup of 0.5 A secondary. For the 1 A version the overcurrent detectors have a minimum pickup of 0.1 A secondary.

F.2.1 Configuration

Fig. F-2 shows the basic scheme design. Not shown is a 2000 Ω stabilizing resistor in parallel with the voltage input (59 V) required when the relay is used in a high-impedance differential scheme. The method proposed in this paper can be implemented in a variety of ways but the scheme used here is one that can easily be implemented in an off-the-shelf protective relay and can be automated if desired.

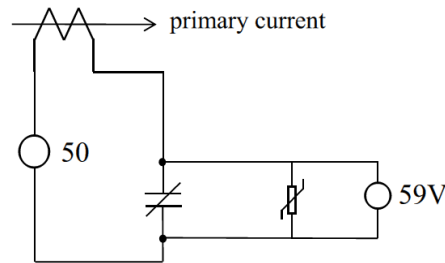


Fig. F-2. Basic scheme design.

F.2.2 Scheme Operation

At some periodicity determined by the user the open-phase logic will be initiated (e.g. once per day). If the fundamental current measured by the overcurrent detector (50) at the time of the test exceeds the minimum setting the open-circuit test is blocked from operation. If current is present at a measureable level then that is confirmation that the

⁴³ D. Costello, "Open-circuited CT misoperation and investigation," in Protective Relay Engineers, 2014 67th Annual Conference for, pp. 383- 392.

primary phase is intact and no further testing is required. However, if the overcurrent detector cannot measure current then the open circuit test is allowed to proceed. The normally closed contact is opened for one or two cycles to open circuit the current transformer. If the voltage element (59V) asserts then a positive indication of primary current flow is received. If there is concern that the normally closed contact may fail in the open position during testing then a normally open contact may be placed in parallel with it and be closed sometime after initiation of the test based on user desired logic.

The scheme would alarm if an open circuit test failed to assert the voltage element. Simple logic in the relay could trigger an event record that would be reviewed. Alternatively, the scheme could be completely manually supervised so as to only operate when commanded by an operator.

F.2.3 Lab Testing

The scheme was tested using a multi-ratio C800 CT with core with dimensions 10.00"ID x 14.63"OD x 2.50"SW and a full tap ratio of 600:5. A test current representative of transformer magnetizing current was created as shown in Fig. F-3 and applied to the primary of the current transformer. This current has components of 20% third harmonic and 6% fifth harmonic and is simply amplitude scaled for each test.

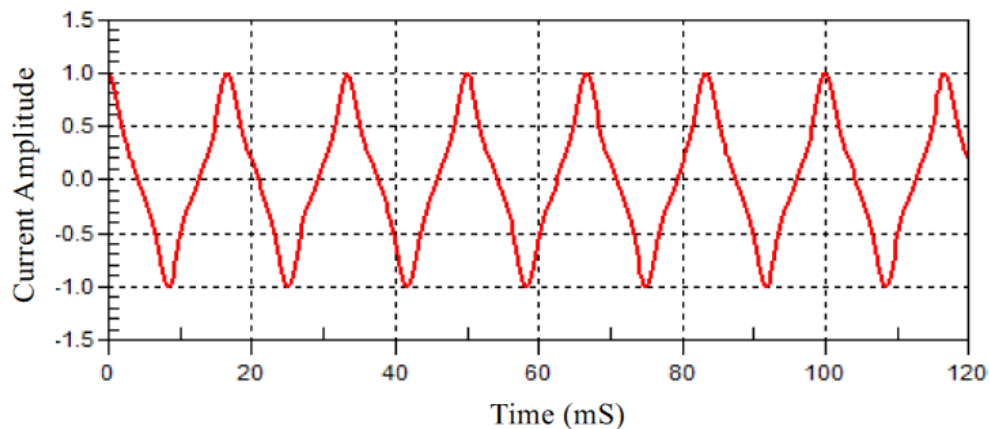


Fig. F-3. Magnetizing test current applied to current transformer primary.

Five tests were performed with peak currents of 2 A, 3 A, 5 A, 10 A, and 20 A respectively. The voltage was recorded using a laboratory oscilloscope. The results are shown in Fig. F-4, Fig. F-5, Fig. F-6, Fig. F-7, Fig. F-8, Fig. F-9, and Fig. F-10 and are summarized in Table F1. It is clear from the data that the secondary current presented to the relay for the tests is well below the minimum level at which the overcurrent detector in the test relay can detect (500 mA).

However, the voltages that result during the test are clearly in a range that could be detected and positively identify indicating primary current is present.

Table F1. Summary of Test Results

Primary Current Peak (A)	Primary Current divided by 120:1 (mA)	Peak open-circuit Voltage (V)
1	8.3	3.2
2	16.7	10.0
3	25.0	11.0
5	41.7	25.0
10	83.3	64.0
20	166.7	125.0

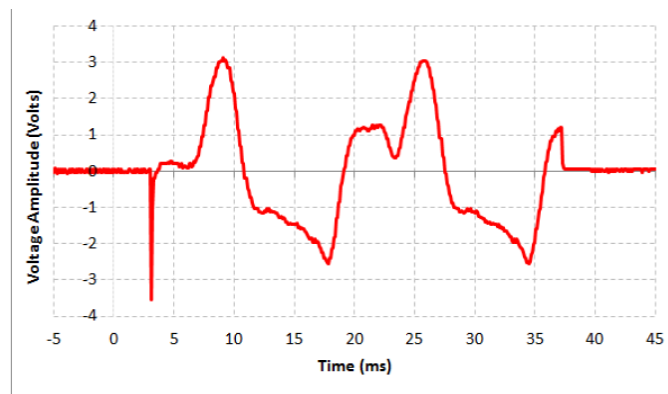


Fig. F-4. Voltage measured across current transformer secondary when open circuited (primary test current 1 A peak).

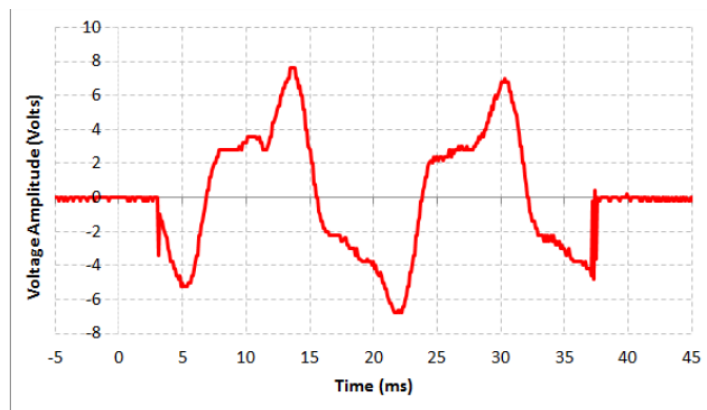


Fig. F-5. Voltage measured across current transformer secondary when open circuited (primary test current 2 A peak).

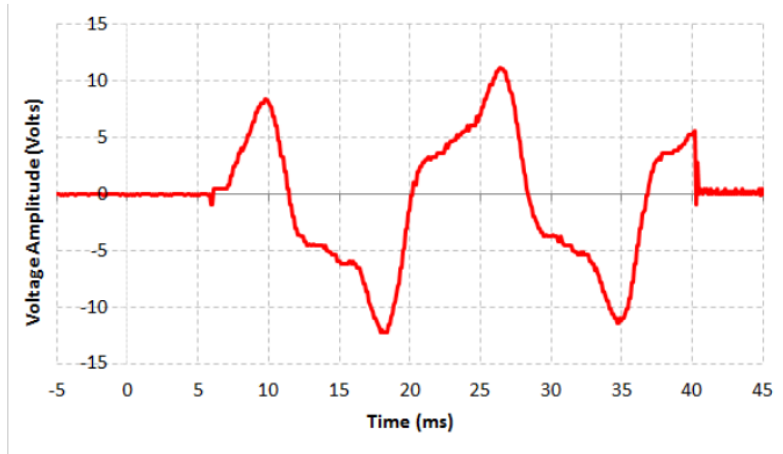


Fig. F-6. Voltage measured across current transformer secondary when open circuited (primary test current 3 A peak).

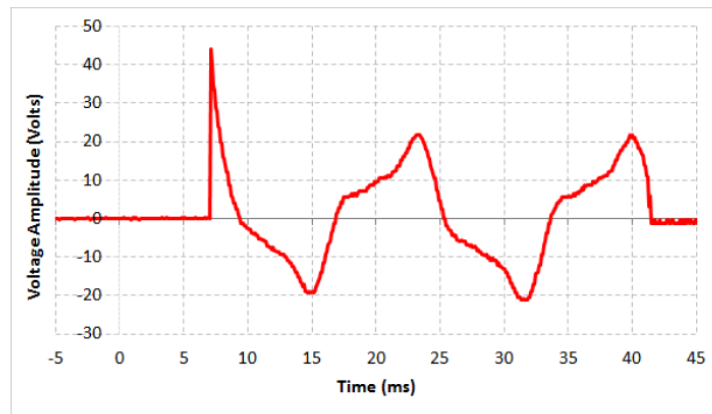


Fig. F-7. Voltage measured across current transformer secondary when open circuited (primary test current 5 A peak).

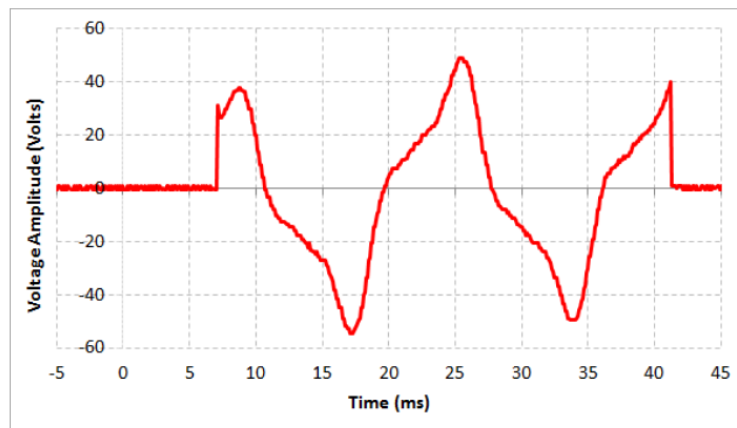


Fig. F-8. Voltage measured across current transformer secondary when open circuited (primary test current 10 A peak).

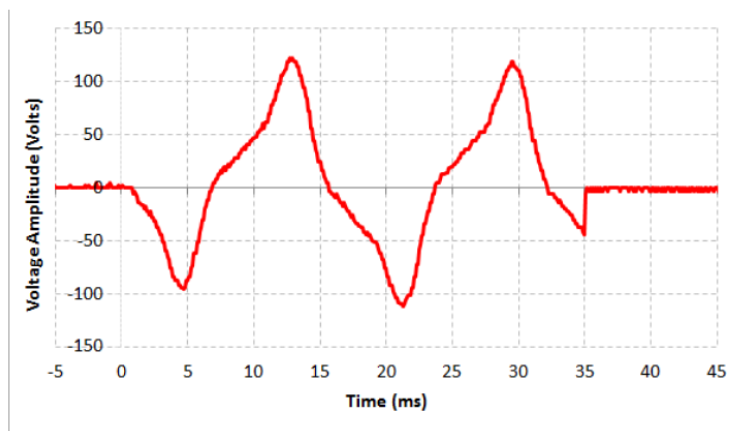


Fig. F-9. Voltage measured across current transformer secondary when open circuited (primary test current 20 A peak).

The waveform in Fig. F-9 was Fourier analyzed and found to be comprised of a 60 Hz component of 42.75 V peak, 120 Hz component of 1.82 V, 180 Hz component of 12.7 V, and 300 Hz component of 3.87 V (other harmonics negligible). These values are shown graphically in Fig. F-10.

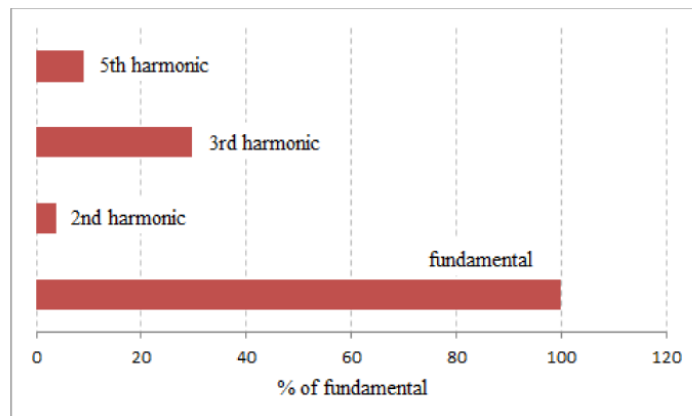


Fig. F-10. Harmonic content of the waveform of Fig. F-9.

The results presented in Table F1 can be compared to estimated peak magnetizing currents for 230kV power transformers of 0.2-2% of base transformer rating resulting in Table F2.

**Table F2. Estimated Base Rating of 230kV Transformer
based on Magnetizing Current Estimate**

Primary Current peak (A)	MVA at 0.2% excitation	MVA at 1% excitation	MVA at 2% excitation
0.5	70.4	14.1	7.1
1	140.7	28.1	14.1
2	281.8	56.4	28.2
3	422.5	84.5	42.3
5	704.3	140.9	70.4
10	---	281.7	140.9
20	---	563.4	281.7

Table F2 is arrived at by simply dividing the primary current peak by 0.2%, 1%, and 2% respectively to produce an estimate of the transformer base rated current. This base rated current estimate is used to compute what the transformer base MVA rating would be at 230kV. This table can be reproduced for other voltage levels by using the following formula which estimates the RMS current as $\sqrt{2}$ smaller than the peak.

$$VA = \frac{\text{Primary current peak} \times 100}{\text{Percent assumed excitation}} \times V_{\phi\phi} \times \frac{\sqrt{3}}{\sqrt{2}}$$

F.2.4 Field Testing

The scheme was tested at the Tennessee Valley Authority's Widows Creek Fossil Plant on a four-winding 25MVA common station service transformer as shown in Fig. F-11. The primary winding configuration was wye grounded with two wye-grounded secondaries and one delta connected secondary winding. The CTs tested were bushing type and fed a set of electromechanical time-overcurrent relays (dashed box in Fig. F-11).

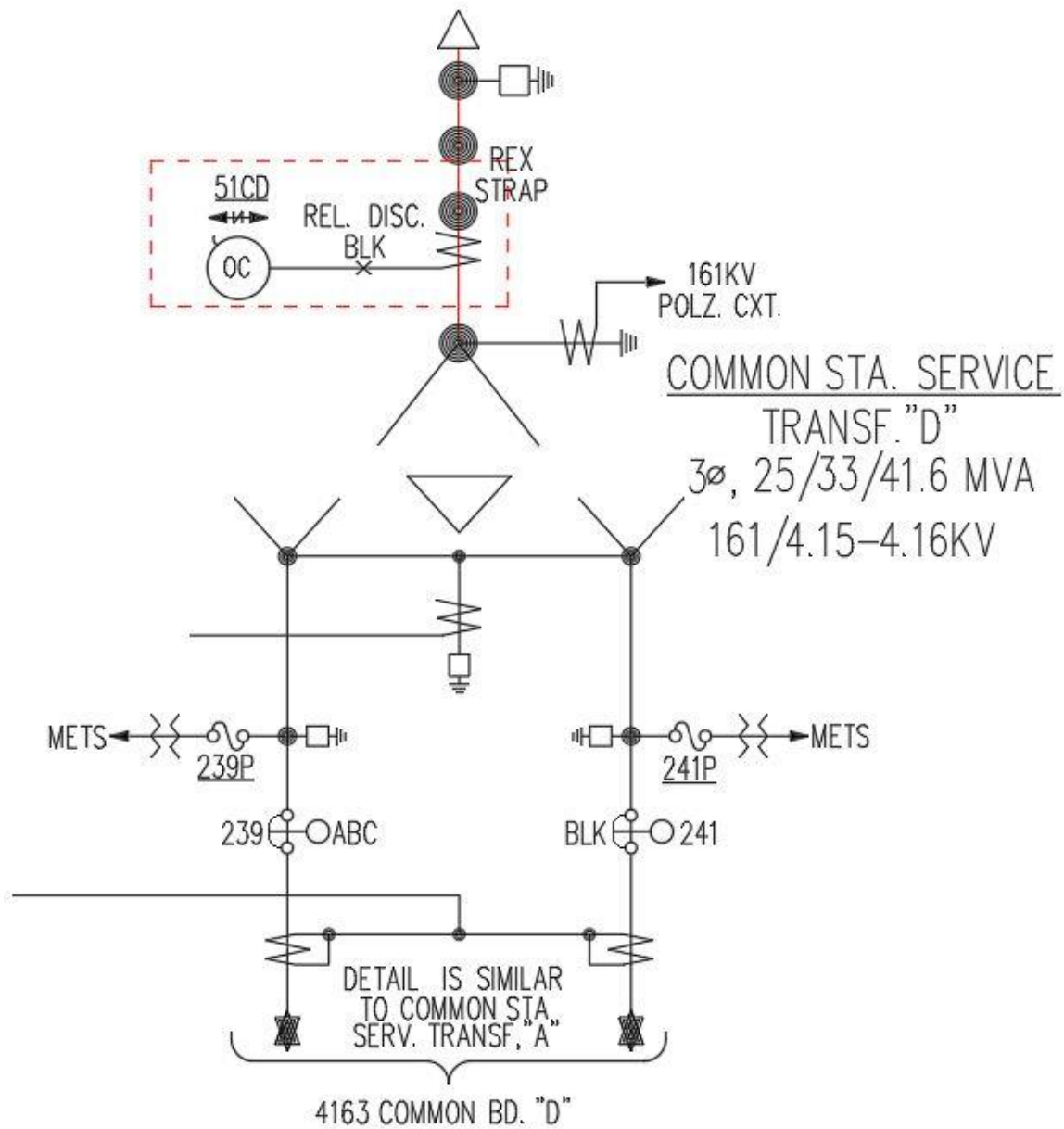


Fig. F-11. Protection one-line drawing of power transformer on which the scheme was tested.

The voltage developed across the open contact for the Aphase test is shown in **Fig. F-12** and has a peak just over 100 V.

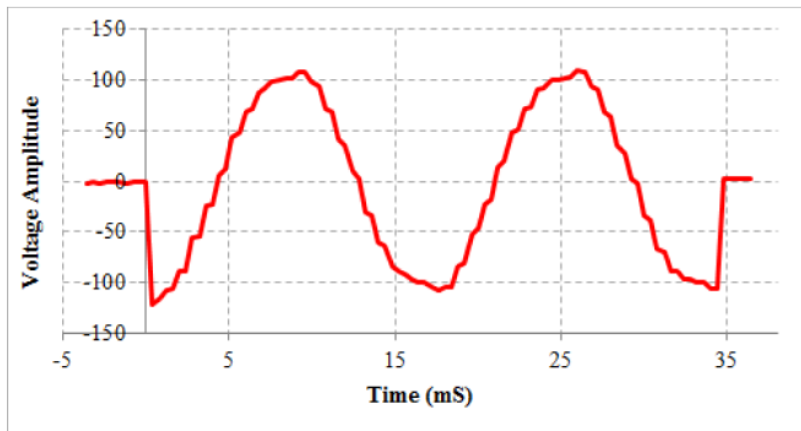
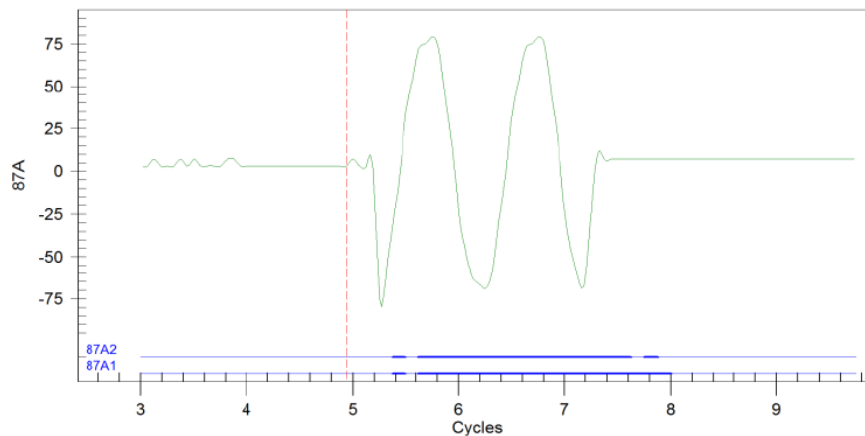


Fig. F-12. Voltage measured across A-phase current transformer secondary when open circuited.

The event as recorded by the test relay is shown in Fig. F-13. The voltage channel is referred to as “87A” since this is a high-impedance differential relay. Two levels of voltage were set in the relay. The first level, 87A1, was set on 20 V and the second level, 87A2, was set on 30 V. Both elements are seen to assert within ¼ cycle of contact opening. Note that the amplitude of the waveform shown in Fig. F-13 is $\sqrt{2}$ smaller than in Fig. 12 due to an artifact in the event display software.



**Fig. F-13. Raw voltages measured by test relay when A-phase CT open circuited.
Scale by $\sqrt{2}$ to see actual waveform amplitude.**

Similar results were obtained when testing on B-phase and C-phase. Note that the transformer bank load was estimated to be between 7A and 12A from the supervisory control system with the bus operating around 169kV.

F.2.5 Scheme Improvement

The primary limitation to the scheme as implemented in the test relay is the sensitivity of the voltage element. This element is designed to operate quickly on much higher voltages (typically >200V) in its intended role as a high impedance bus differential. As such, the relay as presently configured will limit the lower level of primary current that can be securely detected. Quantization error is obvious in reviewing the relay event reports and clearly will affect the lower limit achievable as the relay is presently designed.

Another limitation to the scheme would be the presence of significant loads between the current transformer location and the power transformer. If significant, these loads would draw current through the current transformer primary and result in a positive result during the open circuit test, regardless of the state of the phase connection to the power transformer. This concern is mitigated when the current transformers are bushing transformers on the high-voltage terminals of the power transformer.

While the scheme as-is will be capable of detecting open circuit conditions on relatively small MVA banks, it can be improved by a redesign of the relay to improve accuracy in the low range.

F.3 Conclusions

This paper has presented a new method for detection of an open phase connection to the primary of a power transformer. Laboratory and field testing both confirm the validity of the scheme. The scheme may be implemented in relays that have adequate voltage measurement sensitivity. The scheme can be automated or manually initiated.

Field testing of particular installations as shown in Fig. F-11 is simple and can be done prior to outlay of capital expenditures to prove the scheme would operate as intended.

In power transformers that have extremely low excitation current it may be necessary to ensure some minimum level of station service load is connected.

The scheme presented is independent of the core type or transformer winding configuration used for the power transformer.

APPENDIX G Power Transformer Open Phase Detection using specially designed window-type current sensors

There are several generating stations that are using an Open Phase Detection (OPD) System that is designed to identify open phase conditions on the General Design Criteria (GDC) 17 offsite power supplies to nuclear power plants by using specifically-designed, window-type current sensors on the high voltage bushings of the power transformer. These current sensors are not considered metering CTs and use an optimized copper to iron ratio for the cores. The sensors employ two cores that when combined provide linear operation from excitation current to fault current. The system covers open conditions that could occur on the direct feed from the transmission system and inside the station service transformer, including bushing connections, internal jumpers, no-load tap changer and transformer winding connections. Measurement capabilities of the system range from as low as 10% of no-load excitation current (Fig. G-2). The system can specifically identify which phase or phases are involved in open phase conditions as seen in Fig. G-3. The system can be applied to any transformer winding or core configuration.

A single sensor set provides measurement from no-load excitation to load current levels. The sensors are sized based on power transformer characteristics and configuration.

The system layout drawing (Fig. G-1) shows an overview of the standard OPD system and its components installed on a typical transformer. Each system is utilizing a set of phase and neutral sensors that are then fed into transmission class microprocessor protective relays that monitor current magnitudes, phase angles, sequence components and waveforms. An application specific relay algorithm is then used to determine if there is an open phase condition.

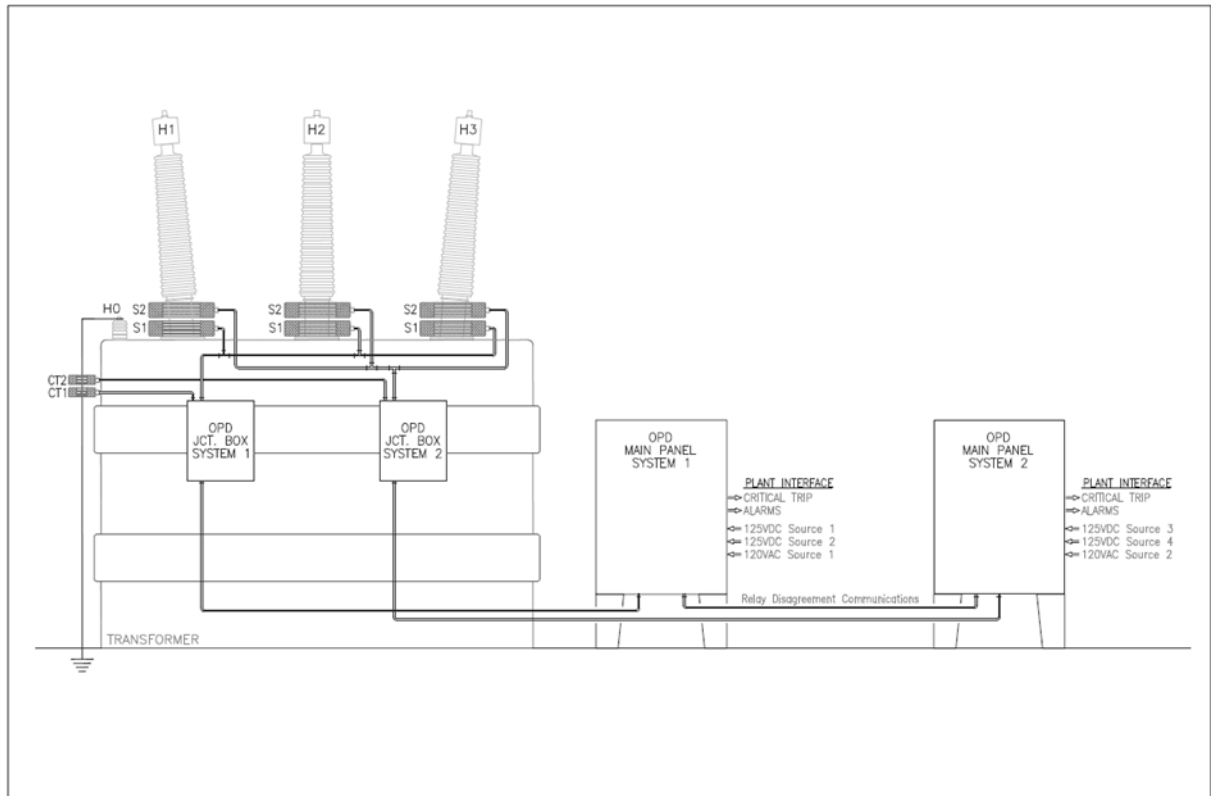


Fig. G-1. System Layout Drawing

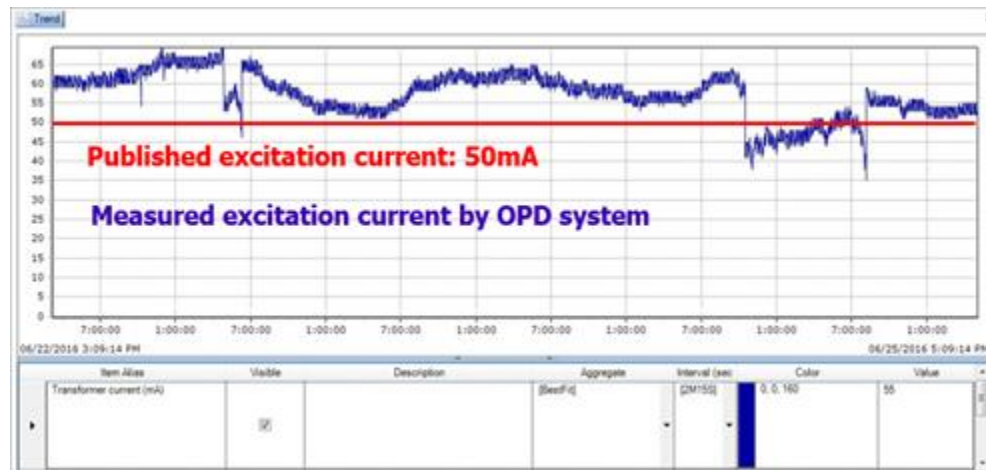


Fig. G-2. Field data on 345kV transformer exciting current (3φ avg.)

Field data vs. published data



Fig. G-3. Lab data from “A”-phase open test case.