Effect of Transformer Connection and Construction on Single Phasing Detection

Gerald Johnson (Basler Electric Company), Randy Hamilton (Basler Electric Company),
Sudhir Thakur (Exelon Corporation)

I. Introduction

On January 30, 2012, Unit 2 at Exelon Corporation’s Byron Generating Station experienced an event that resulted in a unit trip and a loss of offsite power to the unit. The root cause of the event was determined to be the failure of an under hung insulator on the phase C feed to the Unit 2 Station Auxiliary Transformers (SAT). An insulator on a bus support broke and grounded the high voltage bushing of the SAT, causing a short section of 345 kV bus to become disconnected. The section on the SAT side also fell to ground. See Figure 1. This bus section was associated with the phase C offsite source to the SATs. This event caused an open circuit on phase C; however, neither the protective relay system in the switchyard nor the plant relaying detected the loss of phase C. This paper will provide an outline of the event, failure analysis and follow-up actions as a result of the event, including a microprocessor based relay solution, as well as transformer theory relevant to single phasing issue.

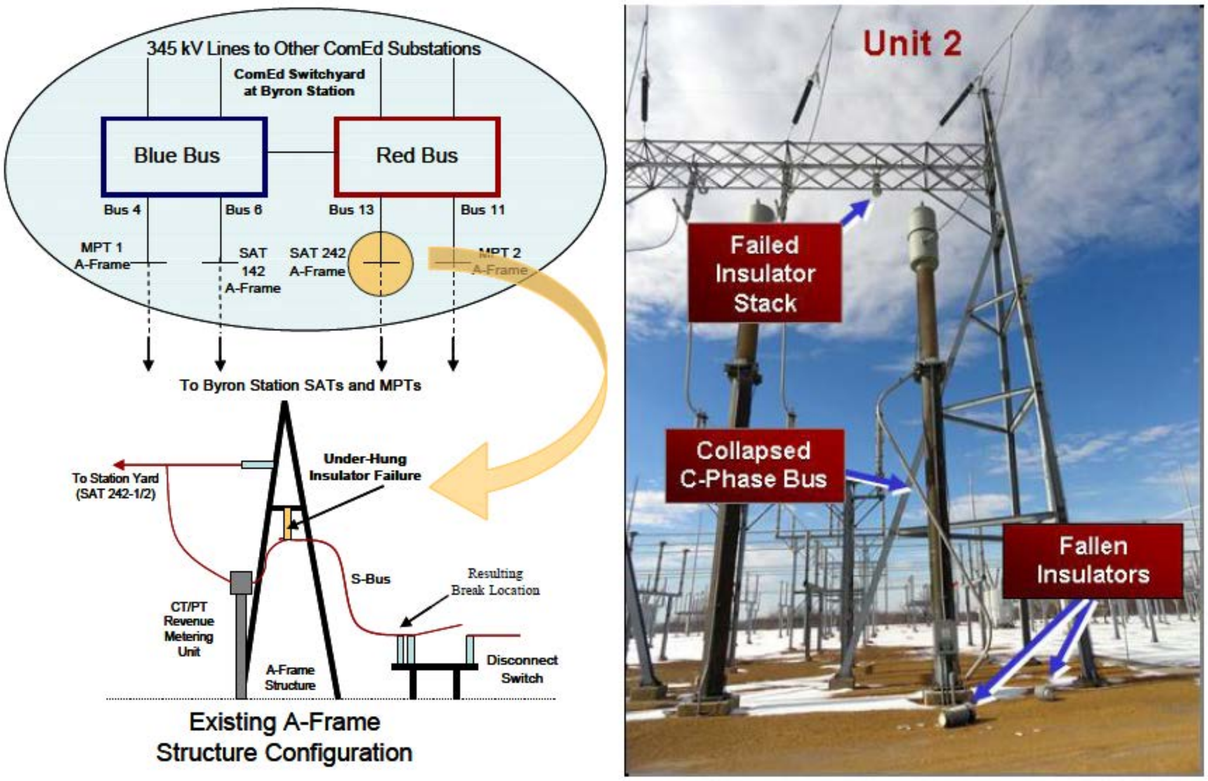


Fig. 1 - Byron Generating Station Unit 2 Switchyard – Phase C Failure [1]

II. Background

Each unit at the Byron Generating Station has two SATs; 142-1/142-2 for Unit 1 and 242-1/242-2 for Unit 2. Each SAT is a three-winding, wye/wye-wye connected step down, 345 kV/6.9 kV–4.16 kV with the primary winding solidly grounded and both secondary windings resistance grounded. The 4.16 kV winding supplies one division of the safety bus and one of the non-safety bus loads. The 6.9 kV windings supply one non-safety bus load. See Figure 2. Each Emergency Core Cooling System (ECCS) Division is supplied from separate transformers.

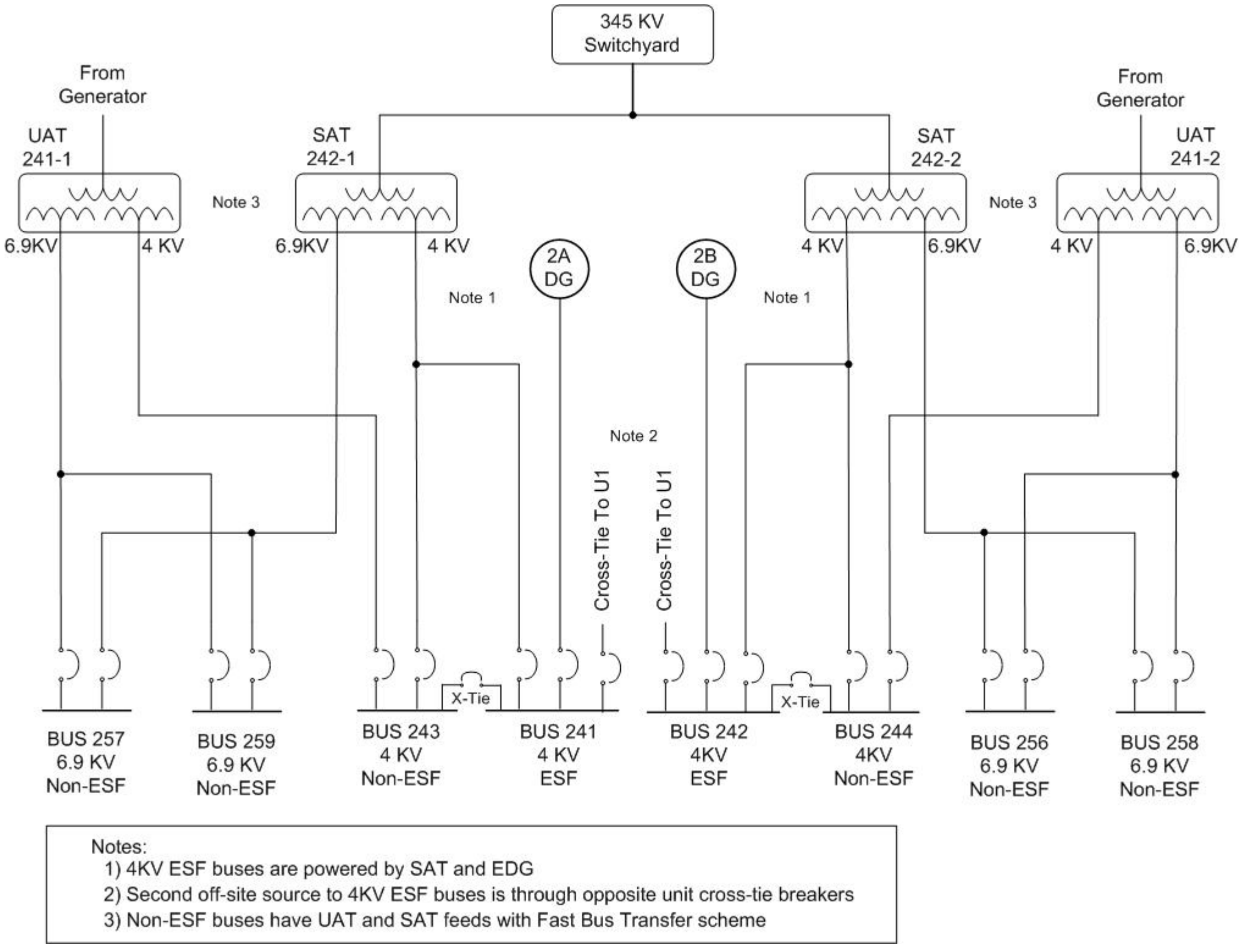


Fig. 2 – Byron Generating Station Unit 2 Auxiliary Power System One Line Diagram [1]

The transformer high side for a given unit is connected to a common 345kV switchyard bus section. In Figure 3, the connection to the SATs is from the 345 kV bus in to a solid pipe "S-Bus", through flexible connections to the revenue metering "combo units" and finally to a common bus that feeds both SATs.

On a loss of the SATs, the non-safety buses are fast transferred to the Unit Auxiliary Transformers (UATs). See Figure 2. The safety bus loads are transferred to the emergency diesel generators (EDG). The second offsite power source to the 4kV

Emergency Safety Buses (ESF) is from the opposite unit SAT via cross tie breakers. Manual operator action is required to close the cross tie breakers.

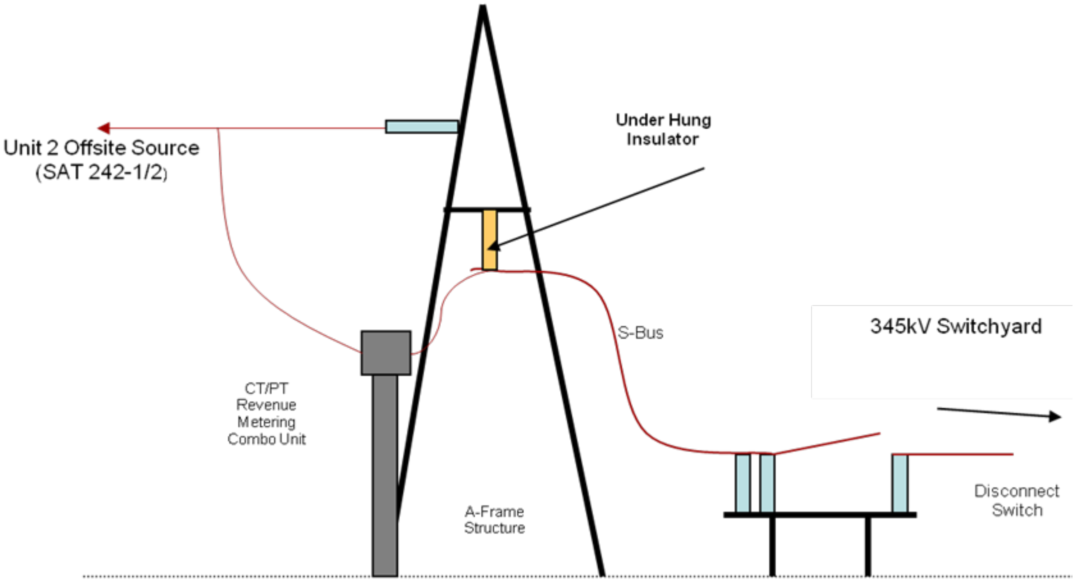


Fig. 3 - Byron Generating Station Auxiliary Power Transformer Connection *[1]*

A voltage unbalance created by an open circuit on either the A or C phase from the offsite grid to the SAT is not designed to actuate the degraded grid voltage relays on the 4.16kV safety bus that provides isolation from the offsite grid and the automatic start and loading of the emergency onsite diesel generators. In actuality, an open on any phase supplying the primary of a core form wye-g/wye-g/wye-g transformer will not actuate the protective relays on the 4.16kV unless the transformer is heavily loaded. If the open phase condition occurred on the 4.16kV side of the transformer, then the open phase condition may be detected

The two under-voltage relays provided on each 4.16kV safety bus are combined in “two out of two” logic to generate a loss of power signal. The relays sense voltage between two phases on the 4.16kV low side winding (i.e., A&B and B&C). If any phase opens on the circuit supplying the 345kV winding of this wye-g/wye-g/wye-g, three legged “core form” transformer, the two-out-of-two logic on the 4.16kV safety buses remain energized with a bus undervoltage situation and result in equipment protective devices actuating from over-current conditions. [1]

III. The Event

On January 30, 2012, the 345kV switchyard phase C insulator failed. This resulted in the loss of phase C power to both of the Unit 2 SATs. The failure mode did not result in a ground fault on the 345 kV. Instead, it led to a “single phasing condition” of the Unit 2 SATs. The resulting voltage imbalance cascaded to the station buses through the SAT at which point the reactor tripped on the Reactor Coolant Pump (RCP) bus undervoltage (two-out-of-four logic). Motor driven and diesel driven Auxiliary Feedwater (AF) pumps received a start signal as a result of the RCP bus undervoltage. The diesel driven AF pump started successfully, but the motor driven AF Pump did not accelerate as a result of the low voltage from the SAT. Also, as a result of low bus voltage, the essential service water, component cooling and condensate booster pumps tripped on overcurrent. The degraded voltage relay scheme actuated and alarmed following the 10 second time delay; however, the alarm cleared in approximately 2 seconds. Additional loads continued to trip on overcurrent and small loads tripped due to Thermal Over Load (TOL) relays.

Approximately 30 seconds after the reactor trip, the reverse power main generator trip occurred as expected and the fast bus transfer occured from UAT to SAT. The remaining two RCPs tripped following the transfer, and operators, recognizing the voltage imbalance eight minutes into the event, manually opened the SAT feeds to all buses. The Emergency Diesel Generators (EDGs) automatically started and re-energized the safety buses.

An unusual event was declared. The 4kV non-safety buses are subsequently re-energized from the safety 4kV buses to provide EDG power to select non-1E loads. The switchyard insulator was repaired, off site power was restored, and the unusual event was terminated. [1]

IV. Root Cause

The root cause was found to be a manufacturing defect of the porcelain insulator. The porcelain was not fully fired in the kiln when manufactured. Forensic examination of the failed insulator showed it was caused by service propagation of a large manufacturing material defect that covered approximately 40% of the fracture cross-section. The defect was characterized as poorly vitrified porcelain that contained a high density of porosity and micro-cracks. There was no evidence that the internal porcelain defect was open to the external surface of the insulator until the final fracture. Also, there was no evidence that external cracking or a projectile impact preceded the failure. See Figure 4.

The insulator was an Ohio Brass under hung four stack insulator manufactured in 1977. The Byron Generating Station had experienced failures of these insulators used on rotating switches in the past. The failure mode was related to the torque on the porcelain during switch operation. All switches in this application had been replaced.

Fig. 4 – Bus Insulator Fracture [1]

V. Protective Relaying Objective

The objective of the protective relaying scheme, using microprocessor based relays and other relays, is to detect the loss of a phase with or without ground on the preferred offsite source for the safety related buses and initiate actions to separate that source from the onsite distribution system. The operation of the plant auxiliary system under the open phase condition may lead to motor damage on the safety related buses. This protective relay scheme, with modifications to suit different transformer configurations and loading conditions, will be used at other Exelon nuclear plants. A protective relaying scheme should be secure during normal unbalance of the grid voltages and unbalanced auxiliary system faults and must detect the open phase condition for the various possible loading conditions on the 4.16 kV and 6.9 kV buses. This scheme should not adversely impact the availability of the preferred offsite source where reliability is essential. [2], [3]

The protective relaying scheme must coordinate with the upstream and downstream protective devices so all other faults, including phase-to-phase and ground faults, will be cleared by the existing protective devices without spurious actuation (under all other anticipated, credible fault conditions) of the recommended open phase detection scheme. When the open phase is detected, the offsite source will be tripped to allow the onsite safety related auxiliary power system to be fed from the emergency diesel generator. As in most relaying applications, the relay must operate only for the conditions it is intended to operate (dependability) and must not operate for those faults for which it is not intended to operate (security). [2], [3] An open phase event consists of a failure on the HV connection between switchyard and the station auxiliary transformers in which a single phase conductor on the HV side of the SAT becomes disconnected from the high voltage transmission interconnection. The energized high voltage transmission line does not short to ground so there is no ground fault current to be detected by the overcurrent protection in the switchyard. The open phase conductor on SAT high voltage side can either short to ground or remain suspended above the ground. The goal is to develop a protective relaying scheme to detect the loss of a phase on the preferred offsite source for the safety related buses and initiate actions to separate the source from the onsite distribution system.

VI. EMTP Studies

Exelon has conducted extensive Electromagnetic Transients Program (EMTP) studies to simulate various scenarios for dependability and security purpose. The EMTP was chosen because of its capability to model unbalanced conditions. The biggest challenge in configuring the EMTP studies is in modeling the transformer, especially zero sequence magnetizing impedance. Also, the program must be able to model the unbalanced zero sequence impedance under various scenarios. The transformer manufacturer's input is crucial in modeling the zero sequence since test data on these old transformers typically is not available. Exelon modeled more than 200 scenarios. See Appendix A.

The analyzed scenarios included the following:

1. Unbalance in the grid: The unbalance can cause both negative and zero sequence voltages in the source voltage.
2. Variations in the grid voltage: Both maximum and minimum grid voltages were considered.
3. Faults on the transmission line. The relay must coordinate with back up line relaying.
4. Faults in the plant auxiliary system.
5. Transformer energization.
6. Unequal loading of the two SATs.
7. Light and heavy loading on the auxiliary buses.
8. Motor starting and bus transfer scenarios.

VII. Transformer Theory and Core Construction

Developing a reliable, secure and effective protective relaying scheme requires a thorough understanding of how the transformer connection and core construction affect the outcome of a single phasing condition.

A. Transformer theory

The loss of one or two phases on the primary feeding a transformer has different effects on the resultant primary and secondary voltages depending on the transformer winding configurations (i.e., delta or wye) and whether the three phases are comprised of three single phase transformers (called a 3x1-phase bank here-in), a three legged core form bank, a four legged core form bank, or a five legged shell form bank. [4]

In the following discussion, "primary" and "secondary" will refer to the high and low voltage sides, respectively, of the transformer. The primary is the power source side in most applications, but conditions arise where the secondary may be the power source side. The focus of this discussion will be on the three legged core form construction found in wye ground/wye ground transformers, and wye ground/wye ground/delta transformers; these are the configurations commonly used in Exelon's nuclear power plant applications as well as many other nuclear power plants around the country. Exelon does have some plants with delta wye configuration where detecting a single phase condition would be easier. For a complete discussion of single phasing conditions on a variety of transformer connections and core designs, and derivation of symmetrical components used in the analysis, consult the references found at the end of this paper. [4], [5]

B. Core Construction

1. Three legged core form transformer

Examine the three legged transformer in Figure 5. Under normal conditions, essentially all excitation flux remains in the steel and negligible excitation flux passes through air. For this condition, the flux in any one leg must equal the flux in the other two legs.

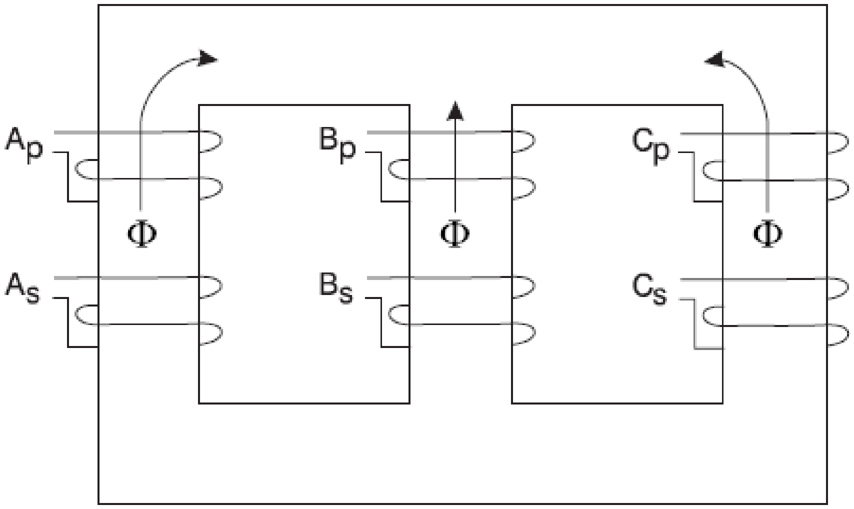


Fig. 5 – Three Legged Core Form *[4]*

Generally, three legged core transformers are not preferred for wye-g/wye-g transformers. One reason is that lost phases will be recreated via a flux balance process with a resultant power flow in directions and paths that were not intended and possible overload of phases. Another reason is directly related to the flux balance analysis. If zero sequence voltage or triplen harmonic voltage (triplen is odd multiples of 3: 3rd, 9th, 15th, 21st, etc.) is applied to the three windings of a wye-g/wye-g three legged core form transformer, the flux in each core is oriented in the same direction in every leg and, without a separate independent leg in the core for a flux return path, the flux is forced to pass through the transformer oil, air and tank. The excitation impedance for zero sequence voltages applied to a wye-g/wye-g three legged core transformer is therefore very low (i.e., a very high level of excitation current is required to occur if any amount of zero sequence or triplen harmonic voltage is on the transformer). The flux flow through the tank can cause transformer damage and ease of saturation by zero sequence voltages can contribute to ferroresonance conditions.

In most three legged core form transformers, if there is a wye-g winding there is also a delta winding. For example, the transformer is wound delta/wye-g or wye-g/wye-g/delta. The delta winding is sometimes needed for its stabilizing properties. It counters the lack of a zero sequence flux path in the core. If the power source is on the delta side, there is no zero sequence flux since zero sequence flux cannot be created from voltages applied to the delta. If a zero sequence voltage is applied to a wye winding, a zero sequence voltage is induced in the delta and a circulating current is generated in the delta. The zero sequence voltages on the wye are in effect shorted out by the delta and minimal zero sequence voltage can occur on the wye. Any appreciable zero sequence voltage that does occur is then shorted by the very low zero sequence excitation impedance of the core form transformer. The combination of shorting the zero sequence voltage by both the delta and the excitation path results in a low zero sequence impedance as seen by the wye-g winding. On a delta/wye-g transformer zero sequence impedance is typically equal to: $Z0 = 0.8\text{-}0.95 \times Z1$. [4]

2. *Four legged core form transformer*

The four legged design is an expansion of the three legged design, as shown in Figure 6. The fourth leg provides the zero sequence flux path that is missing in the three legged core form transformer. This type of transformer core is used in wye-g/wye-g (no delta tertiary) transformers, especially for higher power and higher voltage designs. This design may be readily excited by zero sequence voltages. However, the fourth leg has the same cross section as the main winding legs so it cannot support all three legs being supplied by full nominal zero sequence voltage. For instance, if all three phases were excited by the same full single phase source voltage, the fourth leg would see three times as much flux as each winding leg, resulting in the fourth leg saturating. By inspection, one can see that if the thickness of the fourth leg is the same as the phase leg (the normal design), the fourth leg can only support 33% zero sequence voltage in the normal design.

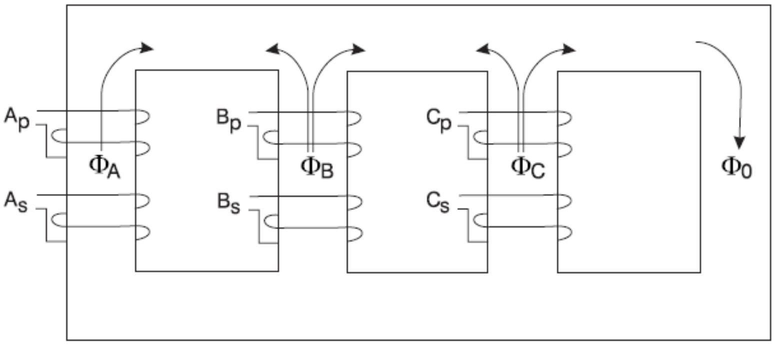


***Fig. 6 – Four Legged Core Form** [4]*

3. Wye-g/wye-g transformer bank analysis

In this instance, the SAT is a Y-ground, Y-ground, Y-ground with a three legged core. An open phase on the 345kV primary A, B, or C phases results in an unpredictable change of the low side voltage. Different voltage is caused by the different flux patterns that flow in a three legged transformer core.

The different flux patterns are the result of having closed or open zero sequence current paths depending on the ground connection of the primary (high voltage) winding.

For a normally balanced system, the zero sequence voltage and current are zero. Since the zero sequence current, I0, is zero, connecting or disconnecting the ground on the primary winding has no effect and the transformer performs as expected.

In an ideal three legged transformer, there is no zero sequence flux path and no zero sequence flux. See Figure 7. Therefore, the total flux in the three legs must sum to zero. Since flux is proportional to voltage, the voltage phasors can be used to analyze the flux expected in the transformer core. Assuming the normal secondary system is 120 V_{LN} three-phase, the phasors are the following:

$V_{an} = 120 \angle 0°$, $V_{bn} = 120 \angle 240°$, $V_{cn} = 120 \angle 120°$

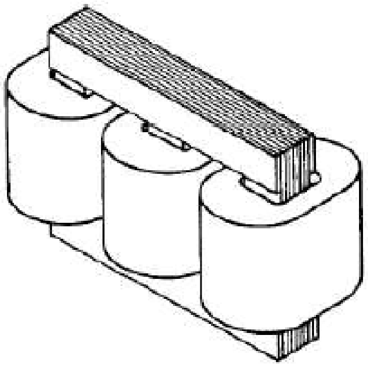


Fig. 7 – Three Legged Core form [6], [7]

When primary phase B is disconnected with a grounded neutral, the following conditions occur:

Phase A leg flux is proportional to $120 \angle 0^\circ$

Phase B leg flux is initially unknown

Phase C leg flux is proportional at $120 \angle 120^\circ$

Because the sum of the fluxes must equal zero in a three legged core:

Flux A + Flux B + Flux C = 0 or:

Flux B = - (Flux A + Flux C) = - ($120 \angle 0^\circ + 120 \angle 120^\circ$) = - ($120 \angle 60^\circ$) = $120 \angle 240^\circ$

The sum of the flux present in the phase B leg induces a voltage in the phase B coil that replicates the lost phase B voltage. On the transformer secondary windings, there is no phase-to-phase or phase-to-neutral undervoltage, and no negative-sequence or zero sequence voltages (V2 or V0), so there is no easy detection of this condition with voltage sensing elements. This indicates, when using a grounded wye transformer, a single phasing condition cannot be detected with V2 or V0 quantities because these do not exist. The only reliable single phasing detection method for the grounded wye condition is logic based on sequence current on the grounded wye connection on the primary side of the transformer. This method requires relaying accuracy CTs located on the phase leads of the high side bushings of the transformer, as well as a sensitive relay to detect single phasing on light load conditions. [4], [6]

C. Prediction, Test and Verification

1. Prediction

The prediction is that there will be no negative sequence current. The transformer's secondary load is 100% positive sequence. When a primary phase is lost, the three legged core replicates the missing phase and the secondary load essentially remains 100% positive sequence. In order to supply this load with a missing phase, the primary current in the healthy phases must change magnitude and angle to support the core flux and load normally supplied by the missing phase.

For a lost phase C, the simulation indicates:

1) IA will shift from $1 \angle 0^\circ$ to $1.73 \angle -30^\circ$
(increase by $\sqrt{3}$ and -30° shift)
2) IB will shift from $1 \angle -120^\circ$ to $1.73 \angle -90^\circ$.
(increase by $\sqrt{3}$ and +30° shift)
3) IC =0

The result is IA and IB are 60° apart and equal in magnitude. This creates a special set of conditions where negative sequence is zero and positive sequence is 1pu. The zero sequence component is the portion supplying core flux for the missing leg.

$$I1 = \frac{(IA + IB \times 1 \angle 120° + IC \times 1 \angle 240°)}{3} = \frac{(1.73 \angle -30° + 0 + 1.73 \angle -90° \times 1 \angle 120°)}{3}$$

$$= \frac{(1.73 \angle -30° + 1.73 \angle +30°)}{3} = \frac{3 \angle 0°}{3} = 1 \angle 0°$$

$$I2 = \frac{(IA + IB \times 1 \angle 240° + IC \times 1 \angle 120°)}{3} = \frac{(1.73 \angle -30° + 0 + 1.73 \angle -90° \times 1 \angle 240°)}{3}$$

$$= \frac{(1.73 \angle -30° + 1.73 \angle 150°)}{3} = \frac{0 \angle 0°}{3} = 0 \angle 0°$$

$$I0 = \frac{(IA + IB + IC)}{3} = \frac{(1.73 \angle -30° + 0 + 1.73 \angle -90°)}{3} = \frac{3 \angle 60°}{3} = 1 \angle -60°$$

To check further, we can apply the law of conservation of energy which tells us the power in must equal the power out.

Complex Power = VAxIA* + VBxIB* + VCxIC* (*=conj).

Assuming all V=1 and I=1 gives:

$$P_{out} = (1 \angle 0° \text{ x}1 \angle 0°) + (1 \angle -120° \text{ x}1 \angle 120°) + (1 \angle 120° \text{ x } 1 \angle -120°) = 1 \angle 0° + 1 \angle 0° + 1 \angle 0°$$

$$= 3\text{w, } 0\text{vars}$$

$$P_{in} = (1 \angle 0° \text{ x } 1.73 \angle -30°) + (0\text{x}0) + (1 \angle 120° \text{ x } 1.73 \angle -90°) = 1.73 \angle -30° + -0 + 1.73 \angle +30°$$

$$= 3\text{w, } 0\text{vars}$$

2. Test and Verification

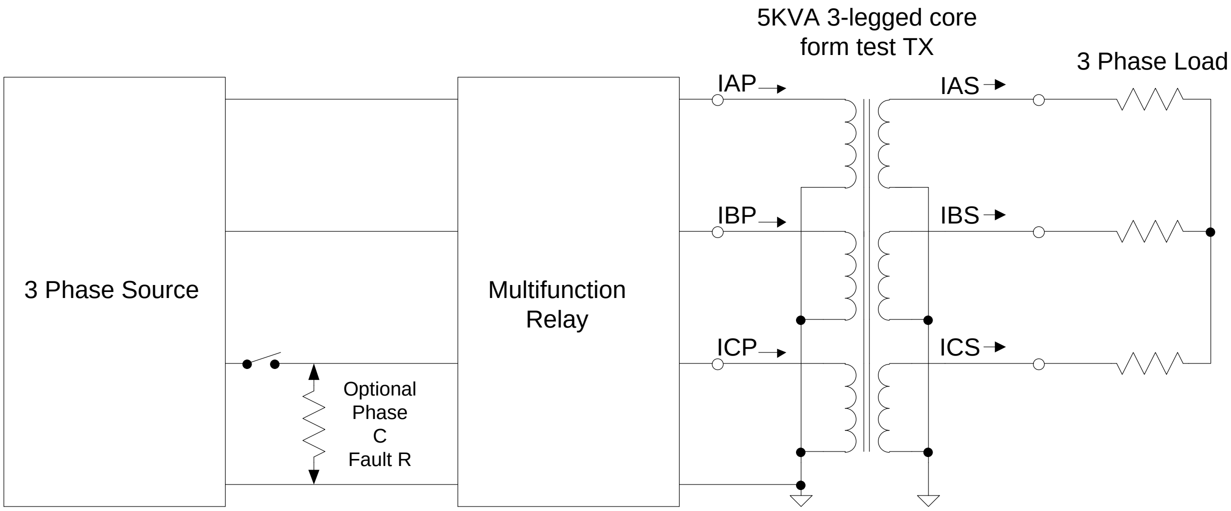


Figure 8 – Test Connection for Open Phase with Ground Simulation

Figure 8 shows a basic schematic of the test setup used the open phase C testing. Three basic tests were run using a 5 kVA, three legged core form test transformer. A Comtrade file for each of the tests was recorded by a multifunction relay. Each Comtrade file was triggered by opening phase C's lead so that normal operation (pre-fault) and abnormal operation (fault) data were captured on the same trace. The Comtrade file names identify which files go with each test and the files are included in Appendix B of this document.

Test 1: Wye-g/wye-g transformer connection:

a) Normal connection, all three-phases good.
b) Open phase C while leaving phase C connection floating (the optional 20 ohm resistor was not connected).

Test 2: Wye-g/wye-g transformer connection:

a) Normal connection then open phase C while simultaneously connecting phase C to neutral though a 20 ohm resistor (the optional resistor is connected).

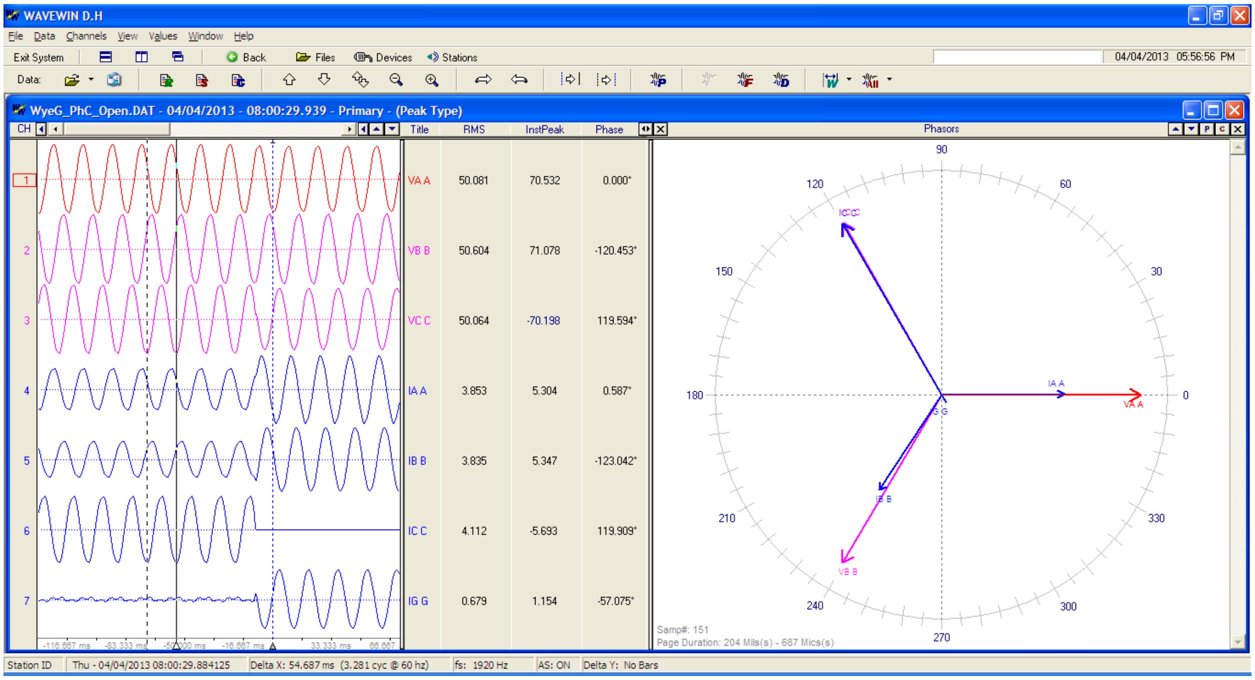
Expectations for Test 1:

a) Healthy A, B, and C phase voltage and current with 120 degrees between phases.
b) Healthy A and B phase currents end up 60 degrees apart to replicate the missing phase voltage.

Expectations for Test 2:

a) The A and B phase currents to move closer together (< 60°) in order to partially replicate the missing phase and to supply current into the fault resistance through the replicated phase C voltage circuit.

When performing tests 1 and 2, make certain that the resistor is located upstream of the MR monitoring the primary current. During pre-fault, the MR will see the normal primary load current into the transformer, but when the switch is opened, the MR will see the fault current back into the fault resistance.



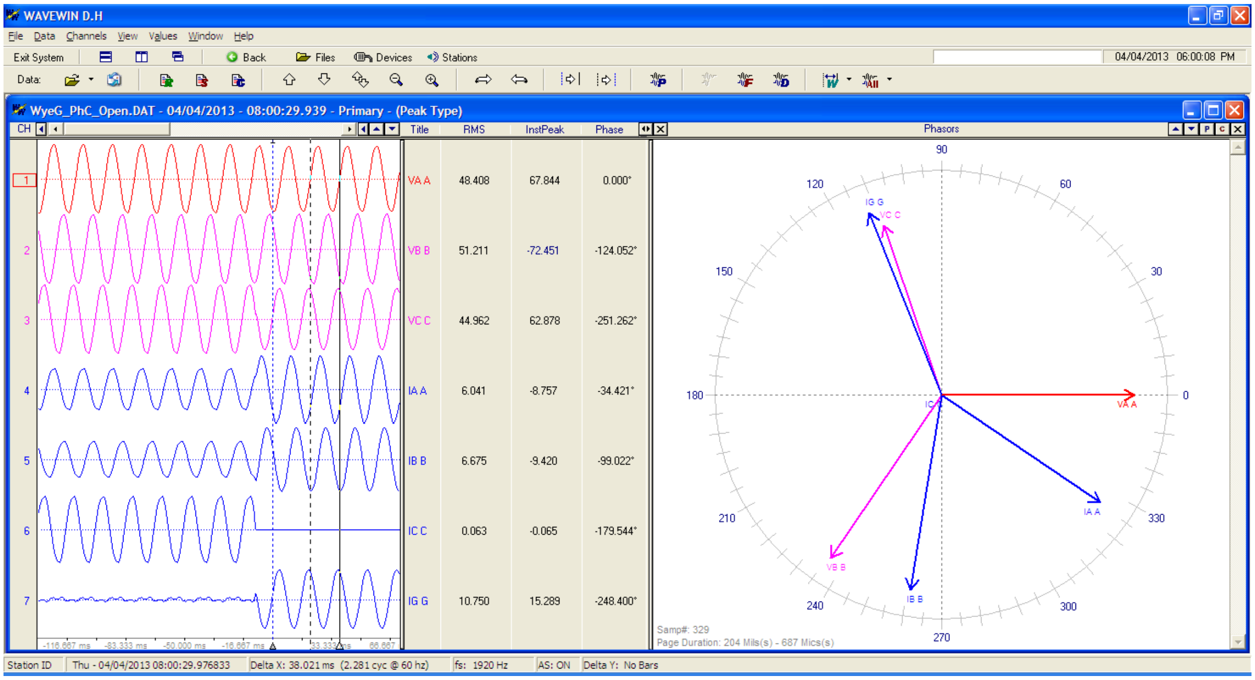
WyeG_PhC_Open.DAT - 04/04/2013 - 08:00:29.939 - Primary - (Peak Type)

CH	Title	RMS	InstPeak	Phase
1	VA A	50.081	70.532	0.000°
2	VB B	50.604	71.078	-120.453°
3	VC C	50.064	-70.198	119.594°
4	IA A	3.853	5.304	0.587°
5	IB B	3.835	5.347	-123.042°
6	IC C	4.112	-5.693	119.909°
7	IG G	0.679	1.154	-57.075°

Samp#: 151
Page Duration: 204 Mils(s) - 687 Mics(s)

Station ID | Thu - 04/04/2013 08:00:29.884125 | Delta X: 54.687 ms (3.281 cyc @ 60 hz) | fs: 1920 Hz | AS: ON | Delta Y: No Bars

Figure 9 – Test TX, Normal Three-Phase Connection



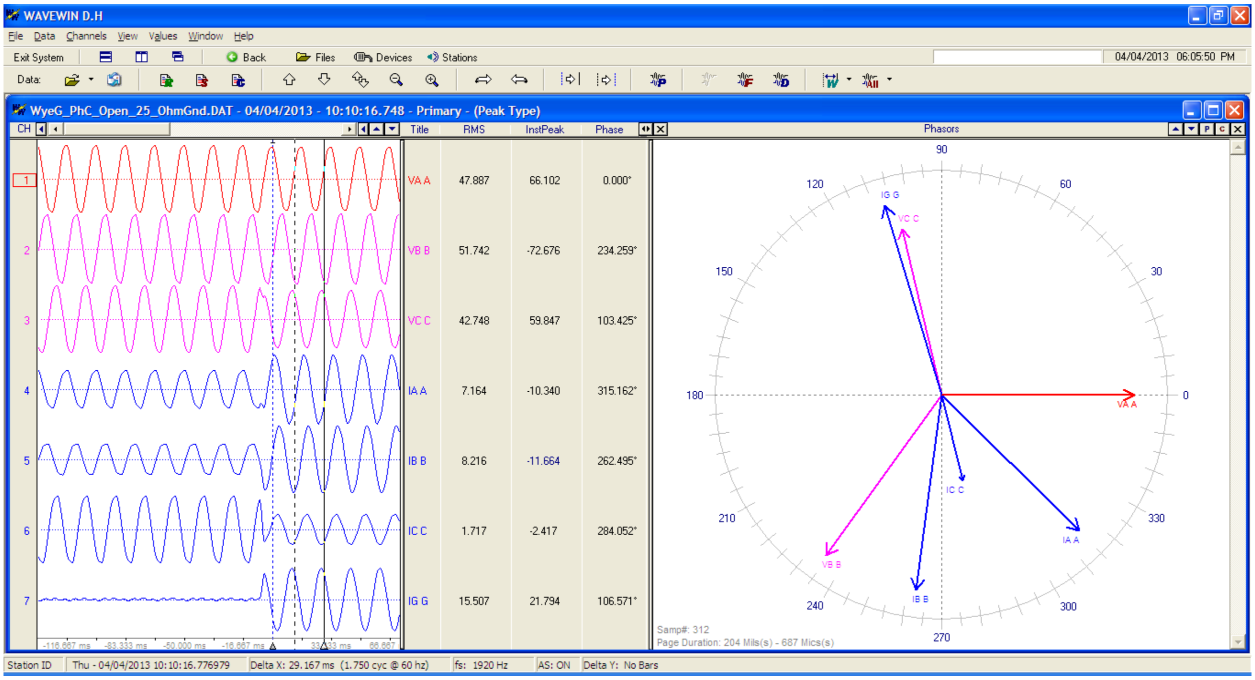
WyeG_PhC_Open.DAT - 04/04/2013 - 08:00:29.939 - Primary - (Peak Type)

CH	Title	RMS	InstPeak	Phase
1	VA A	48.408	67.844	0.000°
2	VB B	51.211	-72.451	-124.052°
3	VC C	44.962	62.878	-251.262°
4	IA A	6.041	-8.757	-34.421°
5	IB B	6.675	-9.420	-99.022°
6	IC C	0.063	-0.065	-179.544°
7	IG G	10.750	15.289	-248.400°

Samp#: 329
Page Duration: 204 Mils(s) - 687 Mics(s)

Station ID | Thu - 04/04/2013 08:00:29.976833 | Delta X: 38.021 ms (2.281 cyc @ 60 hz) | fs: 1920 Hz | AS: ON | Delta Y: No Bars

Figure 10 – Test TX, “C” Open



WyeG_PhC_Open_25_OhmGnd.DAT - 04/04/2013 - 10:10:16.748 - Primary - (Peak Type)

CH	Title	RMS	InstPeak	Phase
1	VA A	47.887	66.102	0.000°
2	VB B	51.742	-72.676	234.259°
3	VC C	42.748	59.847	103.425°
4	IA A	7.164	-10.340	315.162°
5	IB B	8.216	-11.664	262.495°
6	IC C	1.717	-2.417	284.052°
7	IG G	15.507	21.794	106.571°

Samp#: 312
Page Duration: 204 Mils(s) - 687 Mics(s)

Station ID | Thu - 04/04/2013 10:10:16.776979 | Delta X: 29.167 ms (1.750 cyc @ 60 hz) | fs: 1920 Hz | AS: ON | Delta Y: No Bars

Figure 11 – Test TX, "C" Phase Open with 20 Ohm Ground on "C" Phase

VIII. The Protection Scheme

The existing schemes (overcurrent, neutral overcurrent, lead and transformer differential) were not sensitive enough to detect this condition. Also, the degraded voltage scheme applied at Byron Generating Station was not sensitive enough to detect this condition. As for the wye-wye connected transformers with a three legged core, the inter-phase flux coupling keeps the secondary voltage on the open phase close to the normal value if the transformer is unloaded. For the units without a buried delta, the zero sequence flux path is through the tank which acts as a high impedance delta. For units with a buried delta, the zero sequence flux is circulated in the delta. Depending on the zero sequence impedance, this configuration requires moderate to high loading to detect this condition using voltage. For delta-wye transformers, voltage detection might work regardless of loading. With no load, an open on one phase will result in a drop to approximately 0.5 pu voltage on two phases. The other phase will remain at 1 pu voltage. However, there are other scenarios which need to be considered for security before using this scheme. [2], [3], [6]

If there are multiple transformers in series between the switchyard and the safety bus, each transformer needs to be considered. Exelon conducted a full study to develop a differential voltage scheme. This required detailed transformer design information and test data. The transformer vendor's input regarding zero sequence magnetizing impedance is essential for completing the studies and developing a scheme. However, in this instance, the data and information did not exist for most of the older transformers. The wye/wye-wye scheme is required high minimum load. For Byron Generating Station, the minimum load to be detectable is approximately 2.5 MVA. The normal minimum load is approximately 2.5 MVA with periods of several hours with load as low as 500 kVA. For units with wye/wye-wye with buried delta, the minimum load requirement was approximately 14 MVA. The normal operating load was approximately 16 MVA and the minimum load (outage periods) is approximately 3.5 MVA with periods as low as 500 kVA. It is a secure scheme but uses many components, such as auxillary PTs and test switches; there are issues with Coupling Capacitor Voltage Transformer (CCVT) drift. Because the security of this scheme is sensitive to CCVT output voltage drift, Exelon chose not to install this scheme.

Exelon has developed, installed and is in process of installing additional microprocessor based relay solutions using current detection and logic based on the symmetrical component of currents. This scheme monitors the primary side (high voltage side) current and is not dependent on the voltage. An algorithm has been developed to ensure dependability as well as security from false tripping. Proof of concept testing was successfully completed using Common format for Transient Data Exchange (COMTRADE) files developed from EMTP simulations. During testing, and also during commissioning, some issues discovered in the logic had to be resolved.

The example scheme in Figure 12 uses CTs from the high side of the transformer and a microprocessor-based relay. It is similar to that used by Exelon, but not necessarily the same:

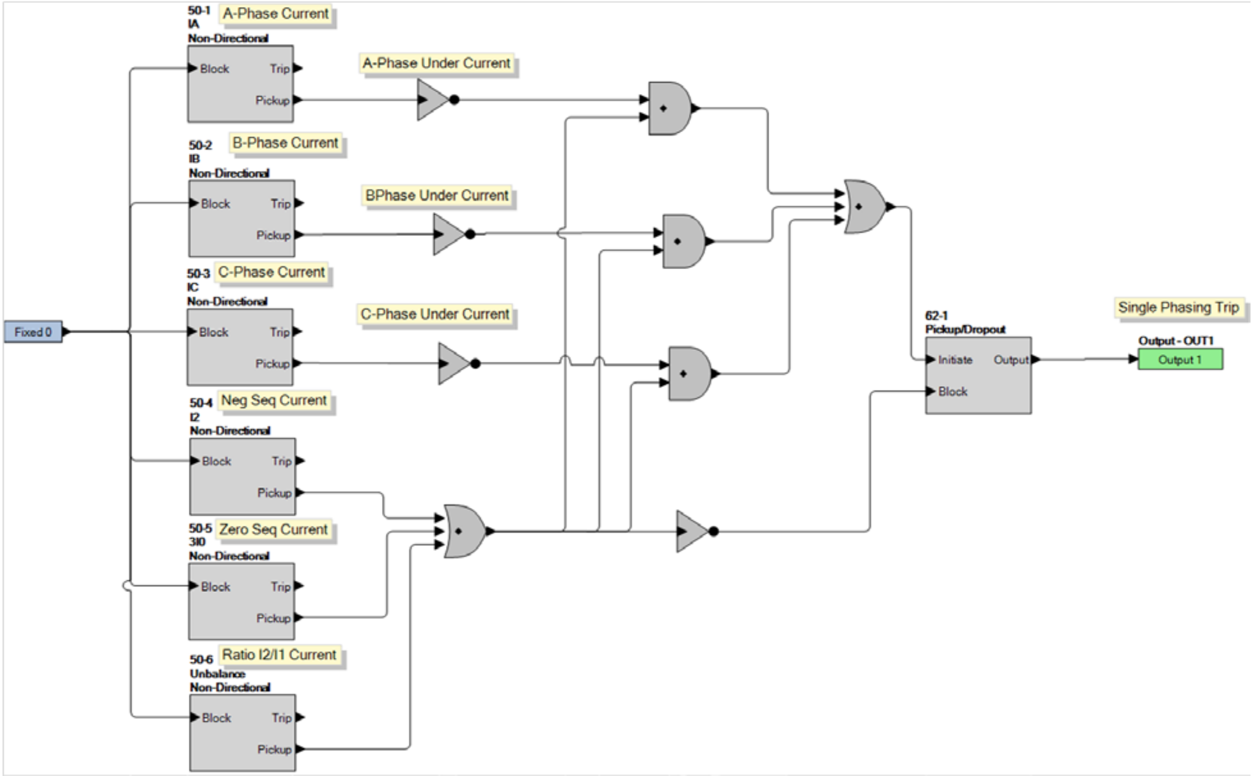


Fig. 12 – Example Logic Scheme

IX. References

[1] Sudhir Thakur, Senior Staff Engineer, Exelon Generation, EPRI Nuclear Utility Relay Users Group Meeting, November 13-15, 2012.

[2] J. Lewis Blackburn, Thomas J. Domin, 2006, Protective Relaying- Principles and Applications, 3rd ed. CRC Press.

[3] Walter A. Elmore, Protective Relaying: Theory and Applications, 2nd Edition, Marcel Dekker.

[4] John Horak and Gerald F. Johnson, 2002, A Practical Guide for Detecting Single-Phasing on a Three-Phase Power System, Basler Electric, Western Protective Relay Conference.

[5] J. Lewis Blackburn and Dekker, 1993, Symmetrical Components for Power Systems Engineering.

[6] Jialong Wang and Raluca Lascu, “Zero Sequence Circuit of Three-legged Core Type Transformers”. (Basler Electric)

[7] IEEE C57.105™-1978 (R2008), IEEE guide for application of transformer connections in three-phase distribution systems.

Vita

Gerald Johnson is Applications Engineering Supervisor for Basler Electric Company and is based in Richmond, Virginia. Prior to joining Basler in 1999, Gerald spent 29 years in the System Protection organization of Dominion VA Power, including 12 years as Director of the System Protection Engineering. Gerald is a graduate of Virginia Commonwealth University and is a registered professional engineer in the State of Virginia. He is a senior member of IEEE, a member of the Power System Relaying Committee, a member of IEEE SCC21 Standards Coordinating Committee, and a member of the Texas A&M and Georgia Tech Planning Committees.

Randy Hamilton is the Director of Engineering for Basler Electric Company. He has worked for Basler for 33 years with experience in test and design in the areas of magnetic transformers, power supplies, voltage regulators and, for over 20 years, protective relays. Randy is a graduate of Southern Illinois University at Edwardsville, a member of IEEE PES and several working groups in the Power System Relaying Committee (PSRC).

Sudhir Thakur is a Senior Staff Engineer in Corporate Engineering of Exelon Generation and is based in Kennett Square, Pennsylvania. Prior to joining Exelon in 1997, Sudhir spent 18 with Raytheon Engineers including 7 years as Supervising Electrical Engineer and was involved in designing Generation Facilities. Sudhir has a BSEE degree in Electrical Power and also holds an MBA and MSEE. He also has a Senior Reactor Operator Certification for Management, and is a registered professional engineer in the State of Pennsylvania. He is a member of IEEE, a member of the Power System Relaying Committee, a member of SC-4 of NPEC of IEEE.

Appendix A

http://www.basler.com/downloads/SinglePhasing-Appendix A.xls

Basler Electric®
www.basler.com

Highland, Illinois USA
Tel: +1 618.654.2341
Fax: +1 618.654.2351
email: info@basler.com

Suzhou, P.R. China
Tel: +86 512.8227.2888
Fax: +86 512.8227.2887
email: chinainfo@basler.com