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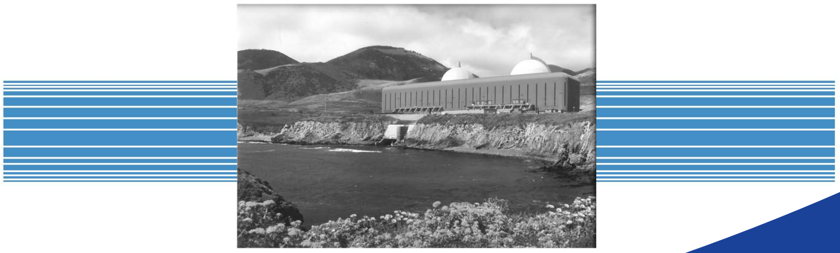
Nuclear Maintenance Application Center: Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers



Nuclear Maintenance Application Center: Development and Analysis of an Open Phase Detection Scheme for Various Configurations of Auxiliary Transformers

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PRODUCT DESCRIPTION

Two recent failures have highlighted the need to detect open-phase conditions that can occur in the power delivery system. The analysis described in this report was performed to determine the response of system auxiliary transformers during open-phase conditions to aid in the development of system protection schemes to detect such conditions.

Background

In January 2012, an auxiliary component tripped due to a bus under-voltage. The cause of the event was the failure of the C-phase insulator stack for the system auxiliary transformer revenue-metering transformer. Part of the insulator stack fell to the ground, resulting in a simultaneous unbalanced condition: C phase opened—C phase-to-ground faults. This condition resulted in a voltage imbalance that cascaded down to the station buses through the system auxiliary transformer, resulting in a reactor trip. The resulting open-phase condition did not cause any of the protective relays to operate, which allowed the condition to exist for an extended period. Ground fault current flowed from the system auxiliary transformers, but the magnitude of the current was approximately 60 A, which is well below the pick-up level of the phase overcurrent relays that protect the transformer.

In February 2012, another event occurred at the same plant. A 345-kV, under-hung porcelain insulator on the system auxiliary transformer’s A-frame structure failed due to a manufacturing defect. The 345-kV line fell to the ground, causing a phase-to-ground fault that tripped the system auxiliary transformer lockout scheme, which caused the 6.9-kV buses to fast-transfer to the unit auxiliary transformer and the emergency safety feature buses to be deenergized and then reenergized by the diesel generators.

Objectives

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 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 the system during open-phase conditions.

Approach

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 Distribution System Simulator (OpenDSS) software developed by the Electric Power Research Institute (EPRI) was used to perform frequency-domain simulations, and the restructured version of the electromagnetic transients program (EMTP-RV) was used to perform time-domain simulations.

Results

Research findings confirmed that the system response to an open-conductor condition can be accurately predicted through modeling. Results show that the system response to an open-conductor event depends on the transformer connection and core configuration.

Open-phase conditions can easily be detected by existing voltage and current relaying for some transformer configurations, whereas others will require more sophisticated detection and protection.

Applications, Value, and Use

The transformer models provided in this report will assist in determining the system protection method needed to detect an open-conductor condition and the analysis to assess the response of various station auxiliary transformers to open-phase conditions.

Keywords

Electromagnetic transients program (EMTP)
Open phase
OpenDSS
Station auxiliary transformer
Transformer model

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

On January 30, 2012, an auxiliary component of Exelon's Byron Unit 2 tripped due to a bus under-voltage. The cause of the event was the failure of the C-phase insulator stack for the Unit 2 system auxiliary transformer (SAT) revenue-metering transformer (see Figure 1-1).

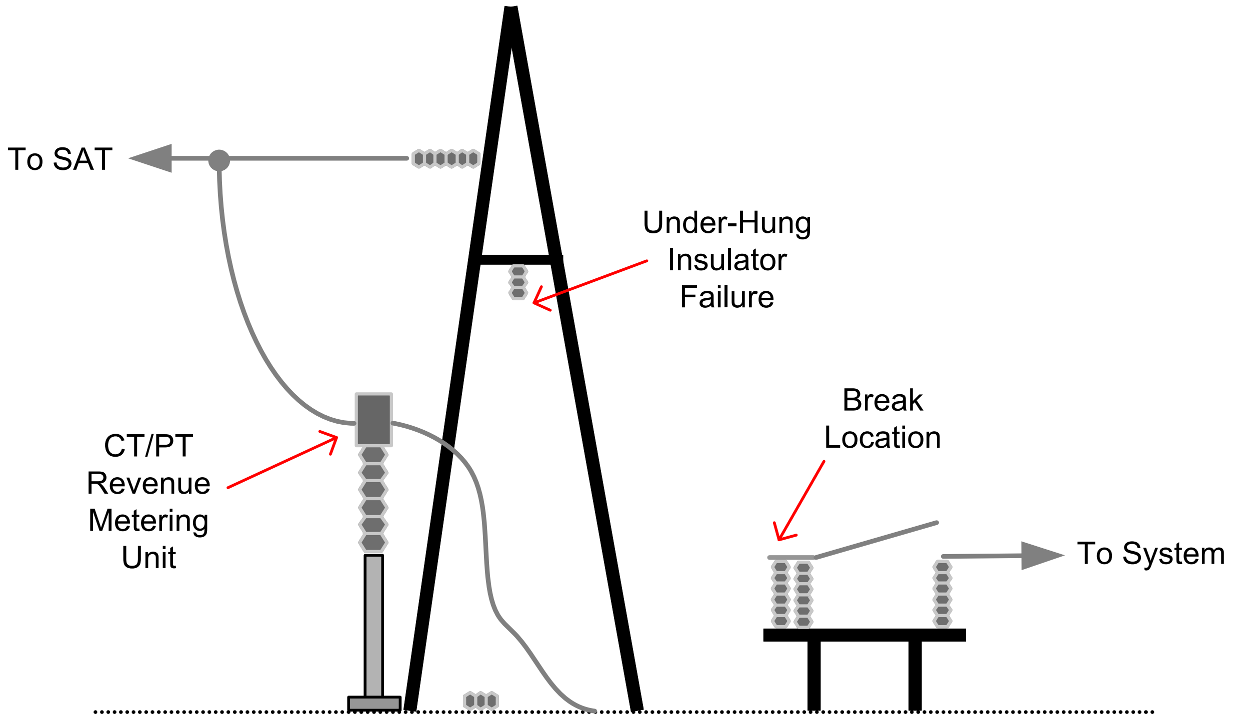

Figure 1-1
Failure of Byron Unit 2 system auxiliary transformer feed
Source: "Byron Station Single Phase Failure" [1]

Upon failure, part of the insulator stack fell to the ground, resulting in a simultaneous unbalanced condition: C phase opened—C phase-to-ground fault. This condition resulted in a voltage imbalance that cascaded down to the station buses through the SAT, resulting in a reactor trip.

The resulting open-phase condition did not cause any of the SAT protective relays to operate, which allowed the condition to exist for an extended period. Ground fault current (a combination of medium-voltage motor contribution and the magnetic coupling of the three-legged core transformer design) did flow from the SATs; however, the magnitude of the current was only approximately 60 A, which is well below the pick-up level of the phase overcurrent relays protecting the transformer.

On February 28, 2012, another event occurred at the Byron plant. A 345-kV under-hung porcelain insulator on the Unit 1 SAT's A-frame structure failed due to a manufacturing defect. The 345-kV line fell to the ground, causing a phase-to-ground fault that tripped the SAT lockout scheme, causing the 6.9 kV buses to fast-transfer to the unit auxiliary transformer and the emergency safety feature buses to be deenergized and then reenergized by the diesel generators.

These failures have highlighted the need for detecting open-phase conditions that can occur in the power delivery system. The analysis described in this report was performed to determine the response of SATs during open-phase conditions to aid in the development of system protection schemes designed to detect such conditions.

2

ANALYSIS

Various simulation techniques capable of representing the behavior of three-phase transformers during open-phase conditions were applied to this study. Simulation techniques included both frequency-domain and time-domain methods. The open-source Distribution System Simulator (OpenDSS) program developed by EPRI was used to perform frequency-domain simulations, and the restructured version of the electromagnetic transients program (EMTP-RV) was used to perform time-domain simulations.

This section describes the models that were used to assess the response of transformers to open-phase conditions and provides simulation results for the five transformers that were evaluated.

System Model

A simplified system model was used for all simulations. Figure 2-1 depicts the system model that was used for two-winding transformers. Other models were based on Figure 2-1, with the only modifications being voltage level, load level, transformer connection, and so on.

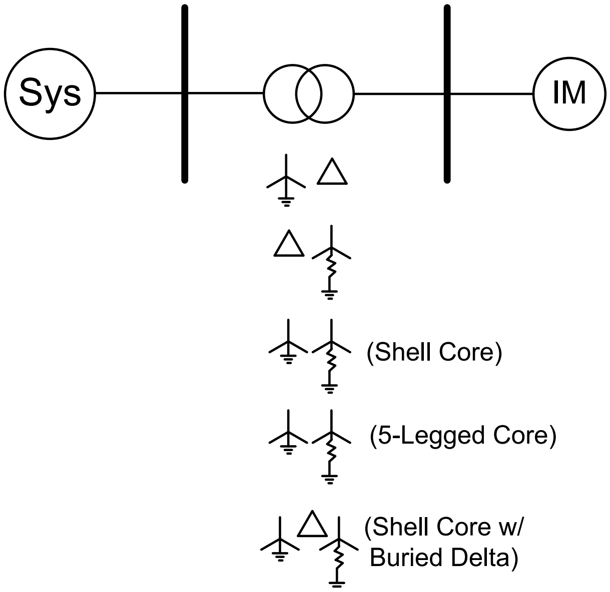

Figure 2-1
Single-line diagram of example system

Source Model

A simplistic source model was used in all simulations. The model consisted of a balanced voltage behind a short-circuit impedance. A damping resistance of 200 ohms was placed in parallel with the short-circuit impedance to provide damping in time-domain simulations using the restructured version of the electromagnetic transients program (EMTP-RV). The frequency-domain model consisted of a balanced voltage behind a short-circuit impedance in series with a short line segment.

Transformer Models

The OpenDSS transformer model is a physically based *n*-phase model. Windings are modeled and connected as they would be in an actual transformer. The transformer is modeled by a primitive Y matrix that embodies all impedances and winding connections. No attempt is made to model the nonlinear portion of the core. A linear magnetizing impedance represents the core within the transformer model. Dugan provides detailed descriptions of the OpenDSS transformer model [2, 3].

Time-domain transformer models are typically categorized in two groups: matrix models and topological-based models [4]. Matrix models are capable of modeling the coupling through air between the phases, but they are unable to model the magnetic coupling between phases due to the core structure. Topological-based models, on the other hand, are capable of modeling the magnetic coupling between phases due to the core, but, in general, they require data that are not readily available. For this study, the winding configurations described by Dugan [2, 3] were used for all time-domain simulations. Comparison with hand calculations using symmetrical component methods validated the accuracy of the EMTP models for assessing the response to an open-phase condition.

Load Models

Dynamic loads were simulated to evaluate the effects of load response to open-phase conditions. Dynamic loads were included in the model as induction machines. In frequency-domain (OpenDSS) simulations, the induction motor was modeled by its positive- and negative-sequence circuits. The machines were connected as ungrounded wye; thus, the zero-sequence impedance was assumed infinite. The positive- and negative-sequence circuits of a squirrel-cage induction machine are provided for reference in Figure 2-2.

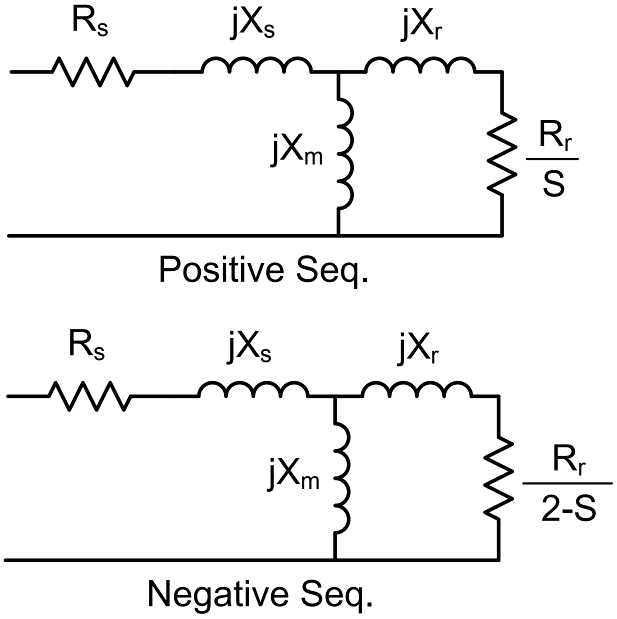

Figure 2-2
Positive- and negative-sequence circuits of a squirrel-cage induction machine

The machine parameters that were used to model the induction machines are provided in Appendix A. The OpenDSS motor model was modeled with symmetrical components; therefore, the mechanical torque is assumed constant in simulations performed in OpenDSS.

For time-domain (EMTP-RV) simulations, the induction machines were modeled using a dq0 model of the machine. The moment of inertia of the rotor and load were combined and modeled as a single rotating mass. The mechanical load of the motor was modeled by its torque-speed characteristics and moment of inertia. Common centrifugal and axial pumps can be modeled by a quadratic torque-speed characteristic [6], as defined in Equation 2-1:

$$\tau_m = K\omega_m^2$$ **Equation 2-1**

Where:

τ_m is the mechanical torque of the load (N•m)

K is a constant of proportionality based on nameplate data

ω_m is the mechanical speed of the motor (rad/sec)

Simulation Results

Simulations using OpenDSS and EMTP-RV were performed for five transformer connections—wye-wye (shell), wye-wye (five-legged), wye-delta, delta-wye, and wye-wye (shell with a buried delta tertiary). Details are provided in Appendix A. Phase A was opened on all simulations as the open-conductor condition. This was a true open phase—that is, there was no connection to ground on either side of the faulted phase. The results of these simulations are provided in the following subsections. The models presented are intended to provide guidance for the comparison of results to similar type transformers.

Two-Winding, Wye-Wye Shell Form

A three-phase shell-form design is depicted in Figure 2-3. Each of the three phases is completely surrounded by core steel. Shell-form transformers are generally >200 MVA. They are often preferred for large generator step-ups and transmission substations because they are generally more durable with respect to through-fault withstand capability.

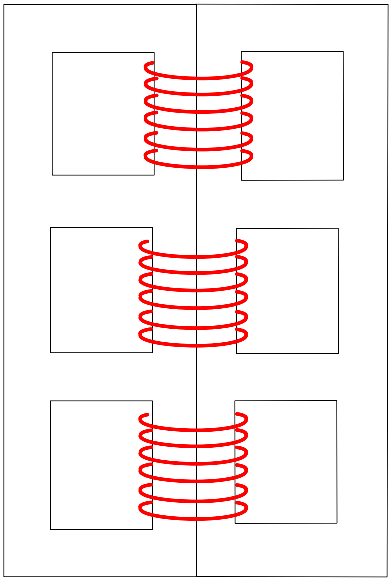

Figure 2-3
Typical three-phase shell-form transformer design

No Load

A simulation was conducted with no load connected to the secondary of the transformer. Table 2-1 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-1
Primary and Secondary Line-to-Neutral Voltages (Shell YY)

	Phase A	Phase B	Phase C
Primary (H)	0 pu	1 pu	1 pu
Secondary (X)	0 pu	1 pu	1 pu

Small Induction Motor Load

An induction motor load equivalent to 10% of the transformer nameplate rating was used to illustrate the effects of an open-phase condition during light loading periods. Table 2-2 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-2
Primary and Secondary Line-to-Neutral Voltages (Shell YY)

	Phase A	Phase B	Phase C
Primary (H)	0.67 pu	0.999 pu	0.998 pu
Secondary (X)	0.67 pu	0.999 pu	0.998 pu

Table 2-3 shows the resulting sequence currents for the primary and secondary sides of the transformer.

Table 2-3
Sequence Currents with 10% Induction Motor Load (Shell YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	5	0	5	0%	100%
Secondary (X)	292	0	292	0%	100%

Large Induction Load

For these simulations, an induction motor load equivalent to 64% of the transformer rating was used to illustrate the effects of an open-phase condition during heavy loading periods. Tables 2-4 and 2-5 provide the resulting voltages at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

The large induction motor simulations are the only simulations in which there was a noticeable discrepancy between the OpenDSS and EMTP results. The OpenDSS model was a sequence model (constant impedance), and the EMTP-RV model was a dq0 model with active feedback to maintain speed (the motor tries to maintain speed by requiring more current from the system); therefore, a large voltage deviation at high current levels explains the differences. However, the results display similar behavior in system response.

Table 2-4
Primary and Secondary Line-to-Neutral Voltages (OpenDSS) (Shell YY)

	Phase A	Phase B	Phase C
Primary (H)	0.57 pu	0.99 pu	0.98 pu
Secondary (X)	0.57 pu	0.96 pu	0.85 pu

Table 2-5
Primary and Secondary Line-to-Neutral Voltages (EMTP) (Shell YY)

	Phase A	Phase B	Phase C
Primary (H)	0.46 pu	0.99 pu	0.99 pu
Secondary (X)	0.46 pu	0.82 pu	0.72 pu

Tables 2-6 and 2-7 provide the resulting sequence currents at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

Table 2-6
Sequence Currents with 64% Induction Motor Load (OpenDSS) (Shell YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	47	0	47	0%	100%
Secondary (X)	2589	0	2589	0%	100%

Table 2-7
Sequence Currents with 64% Induction Motor Load (EMTP) (Shell YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	55	0	55	0%	100%
Secondary (X)	3052	0	3052	0%	100%

Two-Winding, Wye-Wye Five-Legged Core

Many three-phase pad-mount transformers in underground systems, as well as platform-mounted transformers in overhead systems, are five-legged core designs. The core can be a stacked core design, or it can consist of four wound cores, each with a cross-sectional area to carry half the flux (see Figure 2-4).

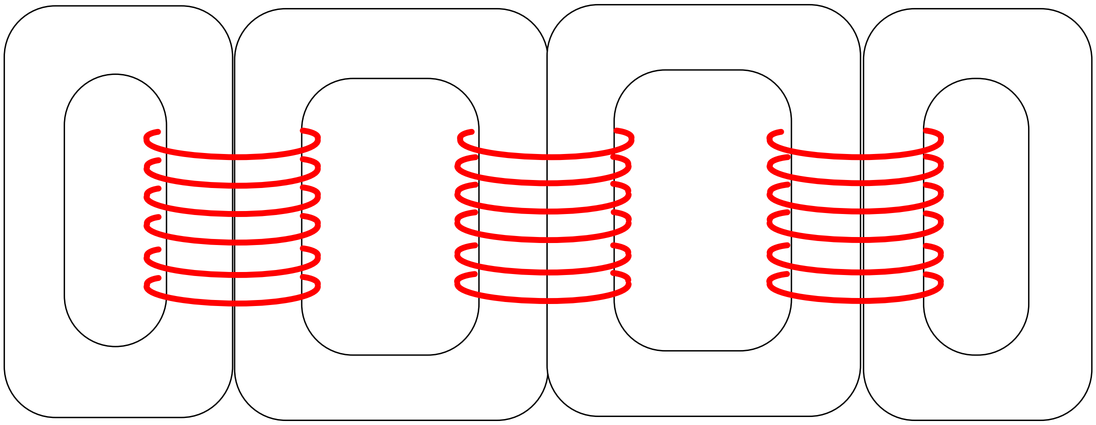

Figure 2-4
Typical five-legged core design—wound cores

As Figure 2-4 shows, the two inner cores have a longer magnetic path than the two outer cores. At the same permeability, the inner cores have a higher reluctance than the outer cores, or a lower inductance. In a typical transformer, the difference in length is approximately 20%. The flux in the inner cores will be approximately 30% higher than in the outer cores; this is the way that the five-legged core was modeled in these simulations, which agrees with measured values such as those described by Loizos et al. [5].

No Load

A simulation was conducted with no load connected to the secondary of the transformer. Table 2-8 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-8
Primary and Secondary Line-to-Neutral Voltages (Five-Legged YY)

	Phase A	Phase B*	Phase C
Primary (H)	0.54 pu	1 pu	1 pu
Secondary (X)	0.54 pu	1 pu	1 pu

* With an open in phase B (inner leg) of the transformer, the voltage on phase B becomes 0.43 pu.

Small Induction Motor Load

An induction motor load equivalent to 10% of the transformer nameplate rating was used to illustrate the effects of an open-phase condition during light loading periods. Table 2-9 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-9
Primary and Secondary Line-to-Neutral Voltages (Five-Legged YY)

	Phase A	Phase B	Phase C
Primary (H)	0.67 pu	0.999 pu	0.998 pu
Secondary (X)	0.67 pu	0.997 pu	0.98 pu

Table 2-10 provides the resulting sequence currents for the primary and secondary sides of the transformer.

Table 2-10
Sequence Currents with 10% Induction Motor Load (Five-Legged YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	5	0	5	0%	100%
Secondary (X)	292	0	292	0%	100%

Large Induction Load

For these simulations, an induction motor load equivalent to 64% of the transformer rating was used to illustrate the effects of an open-phase condition during heavy loading periods.
Tables 2-11 and 2-12 provide the resulting voltages at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

The large induction motor simulations are the only simulations in which there was a noticeable discrepancy between the OpenDSS and EMTP results. The OpenDSS model was a sequence model (constant impedance), and the EMTP-RV model was a dq0 model with active feedback to maintain speed (the motor tries to maintain speed by requiring more current from the system); therefore, a large voltage deviation at high current levels explains the differences. However, the results display similar behavior in system response.

Table 2-11
Primary and Secondary Line-to-Neutral Voltages (OpenDSS) (Five-Legged YY)

	Phase A	Phase B	Phase C
Primary (H)	0.57 pu	0.99 pu	0.98 pu
Secondary (X)	0.57 pu	0.96 pu	0.84 pu

Table 2-12
Primary and Secondary Line-to-Neutral Voltages (EMTP) (Five-Legged YY)

	Phase A	Phase B	Phase C
Primary (H)	0.44 pu	0.99 pu	0.99 pu
Secondary (X)	0.43 pu	0.89 pu	0.82 pu

Tables 2-13 and 2-14 provide the resulting sequence currents at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

Table 2-13
Sequence Currents with 64% Induction Motor Load (OpenDSS) (Five-Legged YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	47	0	47	0%	100%
Secondary (X)	2589	0	2589	0%	100%

Table 2-14
Sequence Currents with 64% Induction Motor Load (EMTP) (Five-Legged YY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	64	0.00	64	0%	100%
Secondary (X)	3513	0.00	3513	0%	100%

Two-Winding, Delta-Wye, Three-Legged Core

This analysis investigated the delta-wye transformer (see Figure 2-5). The delta winding is on the primary side of the transformer (that is, the side where the open phase will be placed). This configuration is modeled with a three-legged core; therefore, core effects are included.

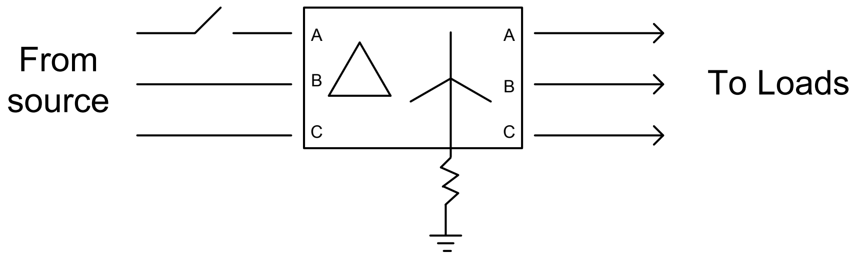

Figure 2-5
Delta-wye transformer

No Load

A simulation was conducted with no load connected to the secondary of the transformer. Table 2-15 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-15
Primary and Secondary Line-to-Neutral Voltages (Three-Legged DY)

	Phase A	**Phase B**	**Phase C**
Primary (H)	0.5 pu	1 pu	1 pu
Secondary (X)	0.5 pu	1 pu	0.5 pu

Small Induction Motor Load

An induction motor load equivalent to 10% of the transformer nameplate rating was used to illustrate the effects of an open-phase condition during light loading periods. Table 2-16 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-16
Primary and Secondary Line-to-Neutral Voltages (Three-Legged DY)

	Phase A	**Phase B**	**Phase C**
Primary (H)	0.64 pu	0.999 pu	0.998 pu
Secondary (X)	0. 89 pu	0.73 pu	0.98 pu

Table 2-17 provides the resulting sequence currents for the primary and secondary sides of the transformer.

Table 2-17
Sequence Currents with 10% Induction Motor Load (Three-Legged DY)

	I_1 (A)	**I_0 (A)**	**I_2 (A)**	**%I_0/I_1**	**%I_2/I_1**
Primary (H)	6	0	6	0%	100%
Secondary (X)	289	0.00	307	0%	106%

Large Induction Load

For these simulations, an induction motor load equivalent to 64% of the transformer rating was used to illustrate the effects of an open-phase condition during heavy loading periods. Tables 2-18 and 2-19 provide the resulting voltages at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

The large induction motor simulations are the only simulations in which there was a noticeable discrepancy between the OpenDSS and EMTP results. The OpenDSS model was a sequence model (constant impedance), and the EMTP-RV model was a dq0 model with active feedback to maintain speed (the motor tries to maintain speed by requiring more current from the system); therefore, a large voltage deviation at high current levels explains the differences. However, the results display similar behavior in system response.

Table 2-18
Primary and Secondary Line-to-Neutral Voltages (OpenDSS) (Three-Legged DY)

	Phase A	Phase B	Phase C
Primary (H)	0.57 pu	0.99 pu	0.98 pu
Secondary (X)	0.79 pu	0.65 pu	0.87 pu

Table 2-19
Primary and Secondary Line-to-Neutral Voltages (EMTP) (Three-Legged DY)

	Phase A	Phase B	Phase C
Primary (H)	0.45 pu	0.99 pu	0.99 pu
Secondary (X)	0.36 pu	0.77 pu	0.41 pu

Tables 2-20 and 2-21 provide the resulting sequence currents at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

Table 2-20
Sequence Currents with 64% Induction Motor Load (OpenDSS) (Three-Legged DY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	47	0	47	0%	100%
Secondary (X)	2584	0	2599	0%	101%

Table 2-21
Sequence Currents with 64% Induction Motor Load (EMTP) (Three-Legged DY)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	64	0	64	0%	100%
Secondary (X)	3417	0	3421	0%	100.1%

Two-Winding, Wye-Delta, Three-Legged Core

This analysis investigated the wye-delta transformer (see Figure 2-6). The wye winding is on the primary side of the transformer (that is, the side where the open phase will be placed). This configuration is modeled with a three-legged core; therefore, core effects are included.

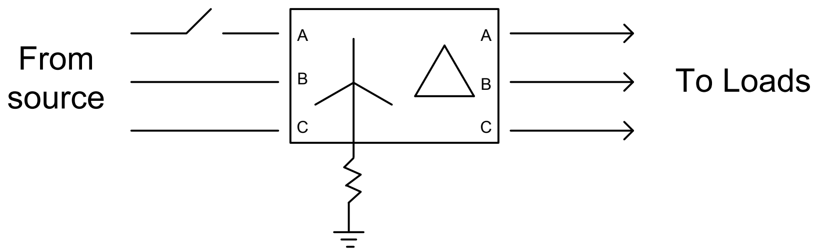

Figure 2-6
Wye-delta transformer

No Load

A simulation was conducted with no load connected to the secondary of the transformer. Table 2-22 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-22
Primary and Secondary Line-to-Neutral Voltages (Three-Legged YD)

	Phase A	**Phase B**	**Phase C**
Primary (H)	1 pu	1 pu	1 pu
Secondary (X)	1 pu	1 pu	1 pu

Small Induction Motor Load

An induction motor load equivalent to 10% of the transformer nameplate rating was used to illustrate the effects of an open-phase condition during light loading periods. Table 2-23 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-23
Sequence Currents with 10% Induction Motor Load (Three-Legged YD)

	Phase A	**Phase B**	**Phase C**
Primary (H)	0.98 pu	0.999 pu	0.998 pu
Secondary (X)	0.99 pu	0.98 pu	0.99 pu

Table 2-24 provides the resulting sequence currents for the primary and secondary sides of the transformer.

Table 2-24
Sequence Currents with 10% Induction Motor Load (Three-Legged YD)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	6	6	0.30	95%	5%
Secondary (X)	330	0.00	16	0%	5%

Large Induction Load

For these simulations, an induction motor load equivalent to 64% of the transformer rating was used to illustrate the effects of an open-phase condition during heavy loading periods. Tables 2-25 and 2-26 provide the resulting voltages at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

The large induction motor simulations are the only simulations in which there was a noticeable discrepancy between the OpenDSS and EMTP results. The OpenDSS model was a sequence model (constant impedance), and the EMTP-RV model was a dq0 model with active feedback to maintain speed (the motor tries to maintain speed by requiring more current from the system); therefore, a large voltage deviation at high current levels explains the differences. However, the results display similar behavior in system response.

Table 2-25
Primary and Secondary Line-to-Neutral Voltages (OpenDSS) (Three-Legged YD)

	Phase A	Phase B	Phase C
Primary (H)	0.87 pu	0.99 pu	0.98 pu
Secondary (X)	0.9 pu	0.86 pu	0.91 pu

Table 2-26
Primary and Secondary Line-to-Neutral Voltages (EMTP) (Three-Legged YD)

	Phase A	Phase B	Phase C
Primary (H)	0.89 pu	0.99 pu	0.99 pu
Secondary (X)	0.94 pu	0.88 pu	0.95 pu

Tables 2-27 and 2-28 provide the resulting sequence currents at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

Table 2-27
Sequence Currents with 64% Induction Motor Load (OpenDSS) (Three-Legged YD)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	54	41	13	77%	24%
Secondary (X)	2974	0.00	704	0%	24%

Table 2-28
Sequence Currents with 64% Induction Motor Load (EMTP) (Three-Legged YD)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	49	38	11	77%	22%
Secondary (X)	2707	0.00	617	0%	23%

Three-Winding, Wye-Wye Shell Form with Buried Delta Tertiary

A three-phase shell-form design is depicted in Figure 2-3. Each of the three phases is completely surrounded by core steel. The configuration studied in this section differs from the shell type studied in the “Two-Winding Wye-Wye Shell Form” section due to the buried delta tertiary, which alters the zero-sequence circuit. The buried delta is modeled with a corner ground.

No Load

A simulation was conducted with no load connected to the secondary of the transformer. Table 2-29 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-29
Primary and Secondary Line-to-Neutral Voltages (Three-Winding YDY Shell)

	Phase A	Phase B	Phase C
Primary (H)	1 pu	1 pu	1 pu
Secondary (X)	1 pu	1 pu	1 pu

Small Induction Motor Load

An induction motor load equivalent to 10% of the transformer nameplate rating was used to illustrate the effects of an open-phase condition during light loading periods. Table 2-30 provides the resulting voltages at the primary and secondary terminals of the step-down transformer.

Table 2-30
Primary and Secondary Line-to-Neutral Voltages (Three-Winding YDY Shell)

	Phase A	Phase B	Phase C
Primary (H)	0.96 pu	0.998 pu	0.997 pu
Secondary (X)	0.96 pu	0.98 pu	0.99 pu

Table 2-31 provides the resulting sequence currents for the primary and secondary sides of the transformer.

Table 2-31
Sequence Currents with 10% Induction Motor Load (Three-Winding YDY Shell)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	6	5.6	0.8	88%	12%
Secondary (X)	327	0	43	0%	13%

Large Induction Load

For these simulations, an induction motor load equivalent to 64% of the transformer rating was used to illustrate the effects of an open-phase condition during heavy loading periods. Tables 2-32 and 2-33 provide the resulting voltages at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

The large induction motor simulations are the only simulations in which there was a noticeable discrepancy between the OpenDSS and EMTP results. The OpenDSS model was a sequence model (constant impedance), and the EMTP-RV model was a dq0 model with active feedback to maintain speed (the motor tries to maintain speed by requiring more current from the system); therefore, a large voltage deviation at high current levels explains the differences. However, the results display similar behavior in system response.

Table 2-32
Primary and Secondary Line-to-Neutral Voltages (OpenDSS) (Three-Winding YDY Shell)

	Phase A	Phase B	Phase C
Primary (H)	0.80 pu	0.99 pu	0.97 pu
Secondary (X)	0.80 pu	0.90 pu	0.91 pu

Table 2-33
Primary and Secondary Line-to-Neutral Voltages (EMTP) (Three-Winding YDY Shell)

	Phase A	Phase B	Phase C
Primary (H)	0.80 pu	0.99 pu	0.99 pu
Secondary (X)	0.80 pu	0.90 pu	0.94 pu

Tables 2-34 and 2-35 provide the resulting sequence currents at the primary and secondary terminals of the step-down transformer using OpenDSS and EMTP-RV, respectively.

Table 2-34
Sequence Currents with 64% Induction Motor Load (OpenDSS) (Three -Winding YDY Shell)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	43	25	18	58%	43%
Secondary (X)	2335	0.00	1005	0%	43%

Table 2-35
Sequence Currents with 64% Induction Motor Load (EMTP) (Three-Winding YDY Shell)

	I_1 (A)	I_0 (A)	I_2 (A)	$\%I_0/I_1$	$\%I_2/I_1$
Primary (H)	51	30	21	58%	42.4%
Secondary (X)	2856	0.00	1214	0%	43%

Summary

The response to an open-conductor condition depends on the transformer construction. Tables 2-36 through 2-39 show the results of the primary and secondary voltages with an open on phase A.

Table 2-36 shows the voltage response to an unloaded transformer. The voltage on all of the transformers' open phase (phase A) falls to or below approximately 50%. The exception of the wye-delta and wye-wye shell with the buried delta tertiary, both of which behave like a three-legged wye-wye core form, as described in the EPRI report *Analysis of Station Auxiliary Transformer Response to Open Phase Conditions* (1025772) [7].

Tables 2-37 through 2-39 show the results of the primary and secondary line-to-neutral voltages with an open on phase A, including the backfeed of the induction machine, which results in a change to the voltage response.

The difference between the models in Tables 2-38 and 2-39 is due to the active feedback in the EMTP-RV model responding differently than the OpenDSS sequence representation of the induction machine model with large deviations in system voltage and high power demand of the induction machine.

Table 2-36
Summary of Primary and Secondary Voltages for No Load

	Primary Voltage (pu)			Secondary Voltage (pu)		
Wye-wye (shell core)	0	1.0	1.0	0	1.0	1.0
Wye-wye* (five-legged core)	0.54	1.0	1.0	0.54	1.0	1.0
Delta-wye (three-legged core)	0.5	1.0	1.0	0.5	1.0	0.5
Wye-delta (three-legged core)	1.0	1.0	1.0	1.0	1.0	1.0
Wye-wye (shell core with buried delta)	1.0	1.0	1.0	1.0	1.0	1.0

* With an open in phase B (inner leg) of the transformer, the voltage on phase B becomes 0.43 pu.

Table 2-37
Summary of Primary Current for a Small Induction Motor Load (10% Transformer Rating)

	Primary Voltage (pu)			Secondary Voltage (pu)		
Wye-wye (shell core)	0.67	0.99	0.99	0.67	0.99	0.99
Wye-wye (five-legged core)	0.67	0.99	0.99	0.67	0.99	0.99
Delta-wye (three-legged core)	0.64	0.99	0.99	0. 89	0.73	0.98
Wye-delta (three-legged core)	0.98	0.99	0.99	0.98	0.98	0.99
Wye-wye (shell core with buried delta)	0.96	0.99	0.99	0.96	0.98	0.99

Table 2-38
Summary of Primary Current for Large Induction Motor Load (64% Transformer Rating); Sequence Motor Model (OpenDSS)

	Primary Voltage (pu)			Secondary Voltage (pu)		
Wye-wye (shell core)	0.57	0.99	0.98	0.57	0.96	0.85
Wye-wye (five-legged core)	0.57	0.99	0.98	0.57	0.96	0.84
Delta-wye (three-legged core)	0.57	0.99	0.98	0.79	0.65	0.87
Wye-delta (three-legged core)	0.87	0.99	0.98	0.9	0.86	0.91
Wye-wye (shell core with buried delta)	0.80	0.99	0.97	0.80	0.90	0.91

Table 2-39
Summary of Primary Current for Large Induction Motor Load (64% Transformer Rating); Active dq0 Motor Model (EMTP-RV)

	Primary Voltage (pu)			Secondary Voltage (pu)		
Wye-wye (shell core)	0.46	0.99	0.99	0.46	0.82	0.72
Wye-wye (five-legged core)	0.44	0.99	0.99	0.43	0.89	0.82
Delta-wye (three-legged core)	0.45	0.99	0.99	0.36	0.77	0.41
Wye-delta (three-legged core)	0.89	0.99	0.99	0.94	0.88	0.95
Wye-wye (shell core with buried delta)	0.80	0.99	0.99	0.80	0.90	0.94

3

CONCLUSIONS

The following conclusions were reached as a result of this research:

- Voltage monitoring on the transformers' primary or secondary terminal alone should be sufficient to detect an open-phase event on wye-wye (shell), wye-wye (five-legged), and delta-wye transformers. Negative-sequence current relaying can protect the motors during an open-phase event when they are loaded from these transformer configurations.
- Care should be taken in using voltage monitoring to detect an open-phase event on wye-wye (shell), wye-wye (five-legged), and delta-wye transformers to avoid unnecessary detection of voltage sags on the transmission that are unrelated to an open-phase event (that is, sufficient time delays are needed). The voltage relaying should be able to discriminate between a total shutdown (loss of all three phases) and a loss-of-phase event (reduction of voltage in one or two phases only.)
- The wye-delta and wye-wye shell with the buried delta tertiary both behave similarly to the three-legged wye-wye core form described in the EPRI report *Analysis of Station Auxiliary Transformer Response to Open Phase Conditions* (1025772) [7]. The existence of a delta winding affects the response of the transformer in a significant way by holding up the secondary voltage during an open-phase condition.
- The machine model can be an important factor in determining the exact response to open-phase conditions. Simulation results indicate that differences can occur between programs depending on the level of detail that is included in the machine model.

Modeling of this condition proved successful; the OpenDSS and EMTP models give similar results. The only difference between the models is due to the active feedback in the EMTP-RV model responding differently than the OpenDSS's sequence representation of the induction machine model.

4
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A

TRANSFORMER AND MOTOR DATA

Representative data for several transformers were obtained from various utilities. These transformers were then normalized to 25 MVA with the same leakage impedances to compare responses. A description of the transformer data is provided as a reference for each of the transformers that were evaluated as part of the study. The zero-sequence impedances for the transformers were matched by adjusting the impedances to the delta winding until the zero-sequence current matched the expected results that should be obtained with the specified zero-sequence impedance from the test report.

Transformers Studied

Wye-Wye Shell Core

230 kV:4.16 kV 25 MVA grounded wye—grounded wye
Percent load loss = 0.2%
Percent no-load loss = 0.5%
Percent I magnetizing = 0.5%
X_{HL} = 10%
Secondary grounding resistance = 20 Ω

Wye-Wye Five-Legged Core

230kV:4.16 kV 25 MVA grounded wye—grounded wye
Percent load loss = 0.2%
Percent no-load loss = 0.5%
Percent I magnetizing = 0.5%
X_{HL} = 10%
Secondary grounding resistance = 20 Ω

Delta-Wye Three-Legged Core

230kV:4.16kV 25 MVA delta—grounded wye
Percent load loss = 0.2%
Percent no-load loss = 0.5%
Percent I magnetizing = 0.5%
X_{HL} = 10%
Secondary grounding resistance = 20 Ω

Wye-Delta Three-Legged Core

230kV:4.16kV 25 MVA delta—grounded wye
Percent load loss = 0.2%
Percent I magnetizing = 0.5%
Percent no-load loss = 0.5%
X_{HL} = 10%

Wye-Wye Shell Core Transformer with Buried Delta Tertiary

230kV:4.16 kV:4.16 kV 25 MVA grounded wye—grounded wye
Connections = H, wye; X, wye; T, delta
Percent load loss = 0.2%
Percent I magnetizing = 0.5%
Percent no-load loss = 0.5%
X_{HL} = 10%
X_{HT} = 25.13%
X_{LT} = 7.85%
Secondary grounding resistance = 20 Ω

Induction Machine Data

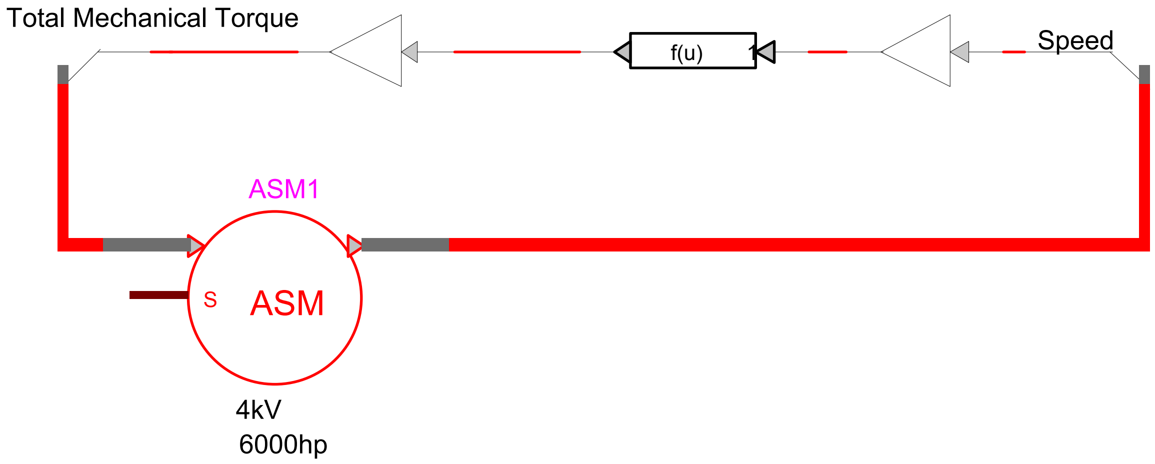

Figure A-1
Induction machine model

All data are presented as per-unit at the rated voltage and power rating determined for each study.

R_s = 0.0045 pu

L_s = 0.075 pu

L_m = 3.23 pu

R_r = 0.0093 pu

L_r = 0.075 pu

H = 5.07 seconds

Poles = 6

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