NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Washington, D.C., Area Low-Voltage Disturbance Event of April 7, 2015

September 2015

RELIABILITY | ACCOUNTABILITY



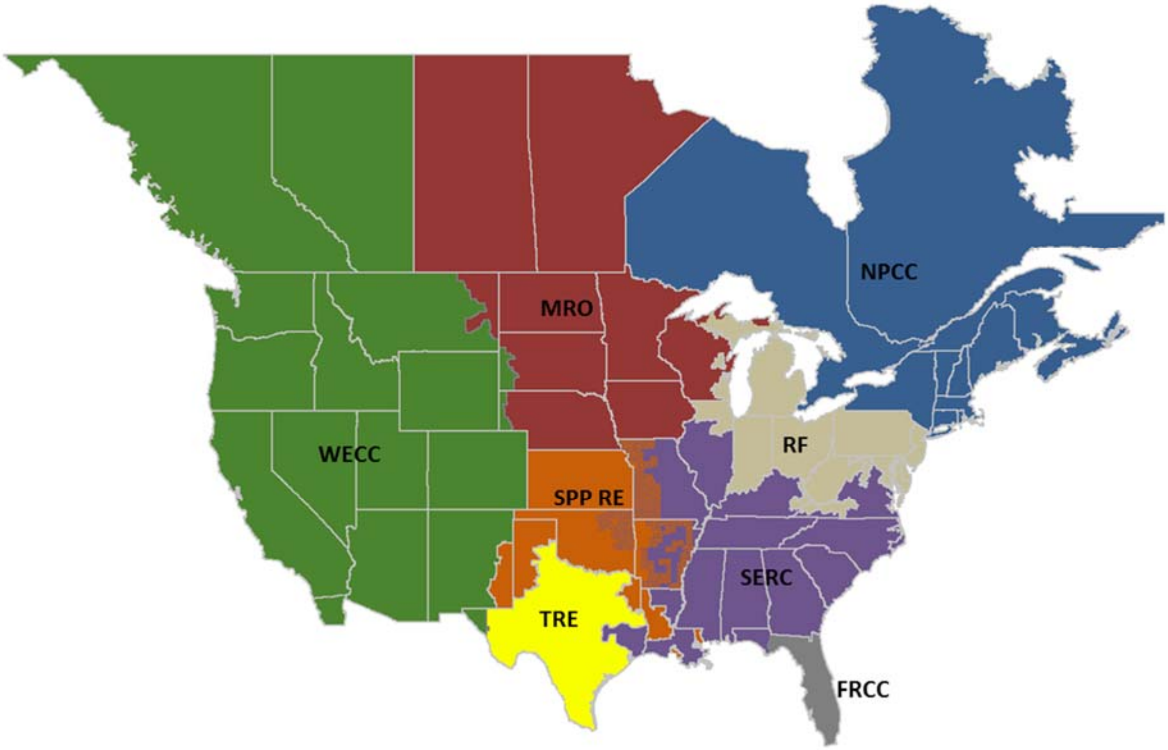

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Table of Contents

Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to ensure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.



The RE boundaries in this map are approximate. The highlighted area between SPP and SERC denotes overlap as some load-serving entities participate in one Region while associated Transmission Owners/Operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP-RE	Southwest Power Pool Regional Entity
TRE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Introduction

This report contains the ERO analysis of the system disturbance that occurred in the Washington, D.C., area on April 7, 2015. It was prepared jointly by ReliabilityFirst (RF) (the RE that oversees this service area) and NERC event analysis teams. To perform the analysis, the teams from NERC and RF merged, capitalizing on the technical expertise of both organizations and RF's detailed knowledge of the area of the disturbance. The entities involved in the disturbance provided data about the event that was key to the successful and timely completion of this analysis.

During the review and analysis of this event, NERC routinely updated FERC on the progress and details of the event analysis process in support of FERC's role as the federal agency responsible for oversight of the ERO in the United States. The causal factors, remediation, and lessons learned from the event were also shared with FERC throughout the process.

This report contains NERC's analysis, technical findings, and recommendations. NERC and RF plan to publish lessons learned from the event to increase industry's understanding of what occurred and possibly mitigate the risk of reoccurrence. The report was prepared in accordance with the NERC Rules of Procedure, Section 807, and its associated Appendix 8, Blackout and Disturbance Response Procedures.

Executive Summary

On April 7, 2015, at 12:39,[1] a fault occurred on a circuit owned by Potomac Electric Power Company (Pepco) that lasted approximately 58 seconds, resulting in approximately 532 MW of customer load lost. While load was restored to most customers in under an hour, the impact of this fault on the Washington, D.C., metropolitan area made this event more visible and noteworthy to the general public.

There was no weather-related activity on the system at the time of the event and no evidence of vandalism, sabotage, or cyber attack. This was an extended fault that occurred on a circuit that was initiated by the failure of a piece of equipment and accompanied by a protection system failure.

Specifically, a C-phase (one of three phases on a high-voltage line) line-to-ground fault occurred on a three-terminal circuit owned by Pepco, spanning the Chalk Point, Ryceville, and Morgantown substations. The fault (commonly known as a short circuit) was due to the failure of a surge arrester (sometimes referred to as a lightning arrestor) on the C-phase of the 230 kV circuit at the Ryceville substation. A surge arrester is a device used on electrical power systems to protect the insulation and conductors of the system from the damaging effects of extremely high voltage, such as that from lightning. Due to the surge arrester failure, there was severe damage to the equipment at the Ryceville substation. The Ryceville substation is jointly owned by Pepco and Southern Maryland Electric Cooperative (SMECO), serving as a connecting station between the two companies' systems.

In response to the short circuit, the appropriate circuit breakers at all three substations correctly tripped. While reclosing in attempt to restore the line back into service according to design, a breaker at the Chalk Point substation failed to reopen as designed, re-energizing the fault and allowing it to become sustained. The fault lasted a total of 58 seconds before being cleared by backup ground protection on two higher-voltage circuits, ultimately de-energizing the entire Chalk Point substation. This sustained fault resulted in the tripping of generators in the local area and a prolonged voltage depression, leading to a total load loss of approximately 532 MW in the Pepco and SMECO service territories.[2]

The voltage depression caused the interruption of service to a small portion of Pepco's commercial and government customers in the Washington, D.C., area. Following the clearing of the fault, approximately 75 MW of load was restored automatically by customer systems within five minutes, with the restoration reaching approximately 160 MW within 30 minutes.[3] Nearly all lost load was restored by 13:25, with the remaining load being restored by 14:21.

Findings and Recommendations

Two independent protection system failures at Chalk Point[4] were found to have caused the protracted (58-second) clearing of the fault between Ryceville and Chalk Point.

- The failure of line relay system No. 1 (LR1) was due to a loose connection between the auxiliary relay coil cutoff trip and the breaker contact string at Chalk Point.
- The failure of line relay system No. 2 (LR2) was an intermittent electrical discontinuity in the auxiliary relay coil circuit, which occurred when the Chalk Point breaker reclosed into fault.

---

[1] All times have been documented in EDT 24-hour format for clarity and consistency.

[2] SMECO experienced 87 MW of load loss, which is included in the 532 MW total.

[3] Restoration efforts required some customers to manually intervene and reengage their systems with the Pepco distribution system.

[4] There are two completely separated and redundant protection systems on the Chalk Point – Ryceville –Morgantown 230 kV line.

Further analysis resulted in one corrective action to address the issues with LR1, two corrective actions to address the issues with LR2, and a recommendation to perform a review of the overall relay design at the Chalk Point station.

In response to this event, the following actions were taken and recommendations given:

- Pepco has evaluated and modified the Chalk Point line LR2 trip auxiliary relay circuit design. This was completed on May 23, 2015.
- The NERC Event Analysis (EA) team recommends that Pepco evaluate the design and redundancy of breaker failure (stuck breaker), transformer phase overcurrent, and transformer ground overcurrent protection schemes to ensure adequate reliability to prevent future similar events.
- In order to reduce exposure of extra-high-voltage (EHV) transformers to possible damage from prolonged through-faults and to add a layer of defense in depth, the NERC EA team recommends that the NERC System Protection and Controls Subcommittee (SPCS) of the NERC Planning Committee evaluate potential guidelines on backup, time-delayed ground overcurrent, and phase protection.
- This event primarily impacted load that separated from the electrical system, automatically and by design, in response to the sustained low-voltage condition resulting from the delayed clearing of the fault. Evolving load characteristics and models, as well as the behavior of loads in response to abnormal system conditions, are areas for further study by NERC.

NERC and RF are currently working with Pepco and PJM to produce lessons learned for the industry through the NERC EA Subcommittee. Industry will benefit from the lessons learned by learning how to improve protection systems and testing procedures.

Table 1: Quick Facts About the Disturbance	
Date & Time	April 7, 2015, at 12:39:03 EDT
NERC Event Category	**Category 2f** – Unintended loss of 300 MW or more of firm load for more than 15 minutes
Entities Involved	Transmission Owners/Operators: • PJM • Pepco • BG&E Distribution Providers • Pepco • SMECO Generation Owners/Operators: • Exelon Nuclear • NAES Corporation-Brandywine Balancing Authority: PJM Reliability Coordinator: PJM
Load Loss	• Pepco: 445 MW • SMECO: 87 MW

Table 1: Quick Facts About the Disturbance	
Initiating Cause	Failure of the C-phase surge arrester located on the Chalk Point – Ryceville – Morgantown 230 kV line
Root Cause & Contributing Causes	• **Primary Effect 1:** The failure of the LR1 relay scheme was the result of a loose connection in the trip auxiliary relay coil cutoff 52a contact string for Chalk Point 230 kV breaker 2C. • **Primary Effect 2:** The failure of the LR2 relay scheme was the result of an intermittent electrical discontinuity in the auxiliary relay coil circuit occurring when Chalk Point breaker 2C reclosed into the fault at Ryceville.
Generation Lost	• Brandywine Power Facility's combined-cycle unit (205 MW gross, 202 MW net) • Calvert Cliffs nuclear Unit 1 (932 MW gross, 896 MW net) • Calvert Cliffs nuclear Unit 2 (918 MW gross, 883 MW net)
System Recovery	• All load was restored within 2 hours. • Area Control Error (ACE) recovered in 6 minutes and 44 seconds. • All transmission elements[5] were returned to service within 6.5 hours. • Brandywine generation was returned to service in about 1 hour. • Calvert Cliffs nuclear units were returned to service within 2 days. • The damaged Chalk Point – Ryceville 230 kV line was returned to service in 16 days.

---

[5] Except for the damaged Chalk Point – Ryceville 230 kV line.

Background and Method of Analysis

This section describes the impacted area, entities involved, and approach the event analysis team used to complete its analysis.

Impacted Area

The impact of this disturbance was limited to portions of Washington, D.C., and the peninsular portion of Maryland, south and east of the city. The area, shown in Figure 1, is bordered to the west by the Potomac River and to the east by the Chesapeake Bay. The disturbance caused a low-voltage excursion on the distribution system, which impacted some load in the greater Washington, D.C., metropolitan area.

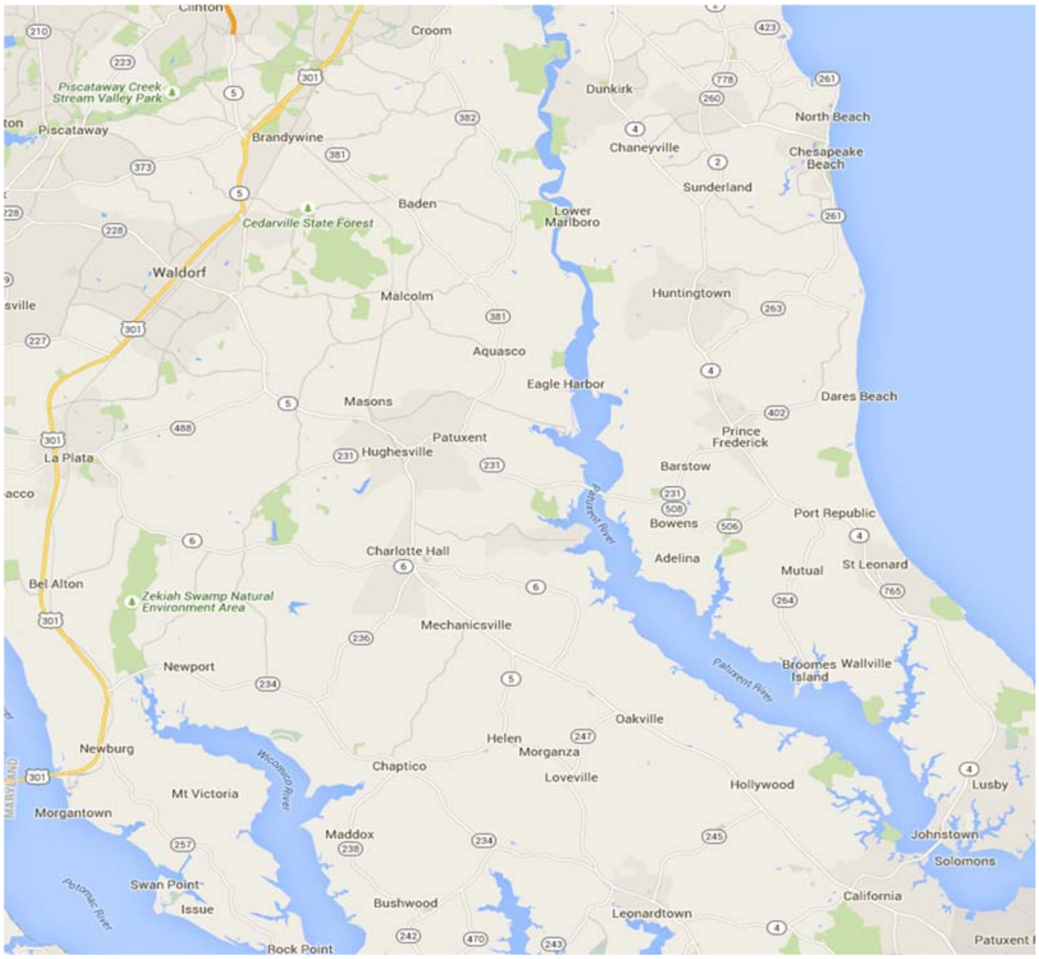


Figure 1: Geographic Area of Disturbance

Entities Involved

PJM

PJM Interconnection coordinates the movement of electricity through all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. PJM dispatches approximately 185,600 MW of generating capacity over 59,700 miles of transmission lines. PJM has 48,327 miles of ac transmission above 100 kV, which includes 2,200 miles of 765 kV; 4,504 miles of 500 kV; 17,268 miles of 200–345 kV; and 24,355 miles of 115–161 kV. PJM has 150 interconnection points.

PJM is the Transmission Operator (TOP) and Transmission Service Provider (TSP) for these facilities, though it does not own or physically operate them. PJM performs the Balancing Authority (BA) functions and is the Market Operator and Reliability Coordinator (RC) for its area. The organization uses security-constrained economic dispatch to match generation with load and to maintain line loading within safe operating limits.

Pepco

Pepco provides wholesale and retail electric service to approximately 815,000 residential and commercial customers in Washington, D.C., and Montgomery and Prince George's counties in Maryland. Pepco owns approximately 141 miles of 500 kV transmission lines, 747 miles of 230 kV transmission lines, 72 miles of 138 kV transmission lines, and 38 miles of 115 kV transmission lines. Pepco is a subsidiary of Pepco Holdings, Inc. (PHI), a holding company comprised of Pepco, Atlantic City Electric Company, Delmarva Power and Light Company, and Pepco Energy Services.

Pepco is registered on the NERC Compliance Registry as a Distribution Provider (DP), Load-Serving Entity (LSE), and Transmission Owner (TO) in RF.

SMECO

SMECO is an electric distribution cooperative headquartered in Hughesville, Maryland. SMECO serves approximately 156,000 customers in the southern Maryland counties of Calvert, Charles, Prince George's, and St. Mary's. SMECO's core business is to provide electric service to residential and commercial customers. SMECO has four 69 kV and three 230 kV interconnection points with Pepco. SMECO has 90.4 miles of 230 kV configured in a radial manner to serve load and also has 364 miles of 69 kV transmission. The SMECO 230 kV interconnection points are at three substations: Aquasco, Ryceville, and Hawkins Gate.

SMECO is registered on the NERC Compliance Registry as a DP and LSE. PJM is the TOP, BA, and RC for SMECO. Pepco is the TSP that supplies power to the SMECO distribution area interconnection points and is also the PJM-designated Local Control Center (LCC), performing delegated TOP tasks.

Brandywine Power Facility

Brandywine Power Facility is the generation facility at Panda substation and is owned by is owned by KMC Thermo, LLC. (formerly owned by Panda Energy Corporation). Panda substation is located in Brandywine, MD, and is the connection point for the Brandywine Power Facility, a 230 MW[6] generation facility.

NAES Corporation-Brandywine, the Generator Operator (GOP) for the Brandywine generators, is registered as a GOP in the NERC Compliance Registry within RF.

BG&E

Baltimore Gas and Electric Company (BG&E) is based in Baltimore, MD, and serves more than 1.2 million business and residential electric customers. BG&E's territory covers over 2,300 square miles and BG&E operates approximately 1,300 miles of transmission lines. BG&E is a subsidiary of Exelon Corporation.

BG&E is registered on the NERC Compliance Registry as a DP, LSE, and TO in RF.

Exelon Nuclear

Exelon Nuclear is an operating unit of Exelon Generation Company and a second-tier subsidiary of Exelon Corporation (Exelon). Exelon Nuclear is responsible for the day-to-day operation and management of Exelon Generation Company's nuclear generating stations, including Calvert Cliffs.

---

[6] Net MW summer capacity rating according to the EIA Form 860.

Exelon is one of the nation's largest electric companies with more than 19,000 employees. Exelon's family of companies includes energy generation, power marketing, transmission, and energy delivery. Exelon is headquartered in Chicago, IL.

Exelon Nuclear is registered on the NERC Compliance Registry as a Generator Owner (GO) and GOP in RF.

ERO Event Analysis Process

The *ERO Event Analysis Process*[7] was used to conduct this event analysis. The process is a structured and consistent approach to performing event analyses in North America. Through the EA process, the ERO Enterprise strives to develop a culture of reliability excellence that is an aggressive self-critical review and analysis of operations, planning, and critical infrastructure protection (CIP) processes.

The *ERO EA Process* presents a method for addressing event analysis, provides a robust lessons learned process, and facilitates communication and information exchange among registered entities, NERC, and the REs. The *ERO EA Process* also serves as a learning opportunity for industry. Through the process, insight and guidance is provided by the identification and dissemination of valuable information to owners, operators, and users of the BPS, who can use that information to improve the reliability of the BPS.

ERO Sequence of Event Analysis Technique

The determination of an accurate sequence of events is critical to understanding the nature of the event. In the analysis of Washington, D.C., Area Low-Voltage Disturbance Event, the NERC and RF event analysis team used multiple data sources to identify and determine what took place during the event using information from phasor measurement unit (PMU), digital fault recorder (DFR), and supervisory control and data acquisition (SCADA) data. Each of these sources has its inherent differences, so by using all three, an accurate timeline can be assembled.

ERO System Modeling Technique

As part of the ERO EA process, the Power System Simulator for Engineering (PSS/E) powerflow and dynamics program was used. System models of the events are simulated as they occurred to develop voltage profiles of the impacted area as well as to determine the wide-area impacts of the disturbance.

Forensic Analysis

In order to determine the factors that caused the incident, a forensic analysis was conducted of the damaged and faulty equipment. The resulting information aided in determining the initial cause, as well as how and why certain system conditions not visible through data occurred.

---

[7] http://www.nerc.com/pa/rrm/ea/Pages/EA-Program.aspx.

Disturbance Description

Disturbance Overview

Initiating Event

The initiator of this disturbance was an electrical and physical failure of the C-phase 230 kV surge arrester and subsequent fault in the Pepco portion of the Ryceville substation (Ryceville substation is jointly owned by Pepco and SMECO). At approximately 12:39, a C-phase-to-ground fault occurred on the transmission line at the Ryceville substation. The C-phase surge arrester experienced a rapid electrical breakdown of its internal metal-oxide varistor (MOV) stack insulation capabilities, which likely was caused by moisture intrusion due to a premature seal failure, causing the MOV stack to go into "thermal runaway," which caused a single-phase-to-ground fault.

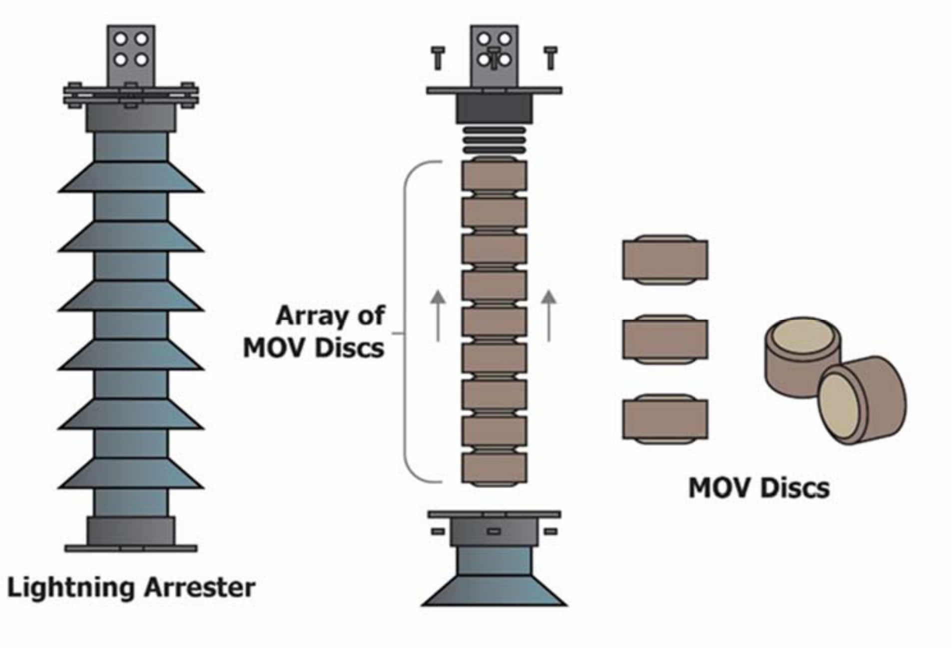


Figure 2. Lightning (Surge) Arrester Shown Whole and Dissected into Parts to Illustrate Composition

The surge arrester is a device used on electrical power systems to protect the insulation and conductors of the system from the damaging effects of lightning. When a lightning surge (or switching surge, which is very similar) travels along the power line to the arrester, the current from the surge is diverted through the arrester in most cases to earth (ground). Lightning that strikes the electrical system introduces millions of volts that may damage transmission lines and can also cause severe damage to transformers and other electrical or electronic devices.

The A-phase surge arrester was severely damaged, and both the B-phase and C-phase surge arresters were completely destroyed. They were found on the ground in several small pieces under the A-frame structure that supports the lines to Chalk Point. Only their bases remained attached to the A-frame. There was evidence of burning and arcing at the base of both the B-phase and C-phase arresters.

Figure 3 shows the pitting and arcing on the A-frame structure, and the B-phase and C-phase arrester bases showed burning and thermal stress. This damage is consistent with the DFR readings of fault current exceeding 6,000 amps.

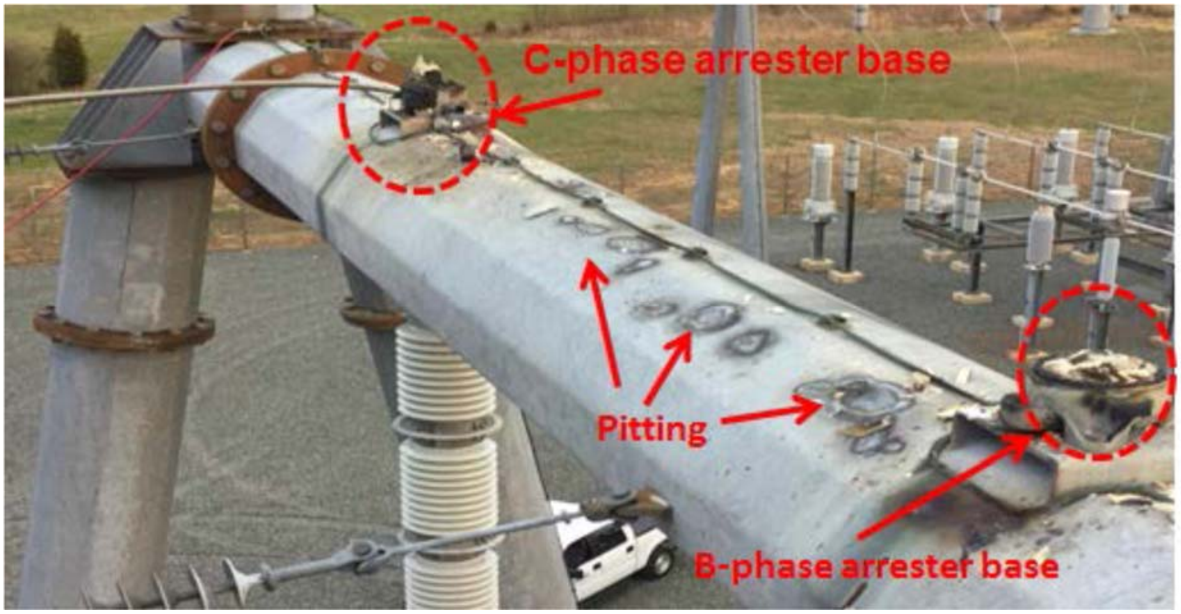


Figure 3: C-phase and B-phase Surge Arresters

Burning and pitting was seen on the top of the 230 kV A-frame structure, particularly near the B-phase and C-phase surge arresters. There was also burning and pitting on the inside of the upper portion of the centermost A-frame structure, nearest the remains of the A-phase surge arrester. No damage appeared on the line capacitor-coupled potential device (CCPD) located on the C-phase, nor in the vicinity of where the C-phase physically connects to the A-frame underneath the failed A-phase underhung insulator stack.

The A-phase underhung insulator was damaged and fell onto the disconnect switch below the A-frame. The A-phase motor-operated disconnect (MOD) switch insulator and bus bar were damaged by the fallen underhung insulator. The A-phase dead-end insulator burned through at the Y-clevis connection and fell into a field outside the substation. The static wire attached to the top center of the A-frame structure broke at its connection to the structure and also dropped into the field outside the substation.

Forensic Analysis Results

There was a significant amount of physical damage at the Ryceville substation to the A-frame dead-end structure and connected equipment. All three surge arresters were damaged beyond repair. The A-phase conductor and the static wire that became disconnected from the A-frame during the fault fell into the field adjacent to the substation outside the fence line.

The destroyed surge arresters were verified to be appropriate for their application at this substation. An analysis of the performance history of this make and model of surge arrester revealed no prior reported problems across industry. The most recently performed inspection was in March 2015, in accordance with the two-month cycle implemented for this substation. An annual thermal imaging inspection was performed in January 2015 with no reported abnormalities. No evidence of external tampering, modification, or sabotage was found. Individuals nearby during the event stated that there was no suspicious activity.

The internal components of the destroyed surge arresters were scattered around the ground below the A-frame. The C-phase arrester components showed clear signs of burning and thermal stress consistent with an electrical failure. The A-phase arrester components showed no noticeable signs of excess thermal stress or burning, which supports the conclusion that the A-phase arrester failed mechanically when the A-phase conductor broke free of the A-frame structure and fell to the ground outside the substation (the top of the arrester has a nontension connection to the conductor, which went into tension and snapped the arrester when the normal conductor tension was released as the dead-end insulator burned through at the Y-clevis, as described earlier). Figure 4 shows the internal disks from both the C-phase (left) and A-phase (right) arresters.

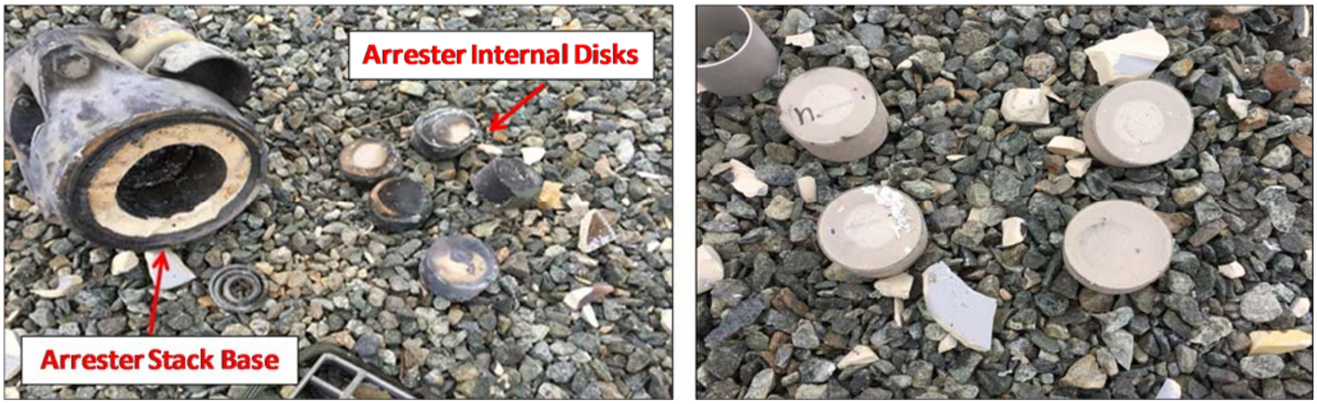


Figure 4: Internal MOV Disks from C-phase (left) and A-phase (right) Arresters

In addition to the damaged arresters, the underhanging insulator for the A-phase was broken off from the A-frame structure, as shown in Figure 5.

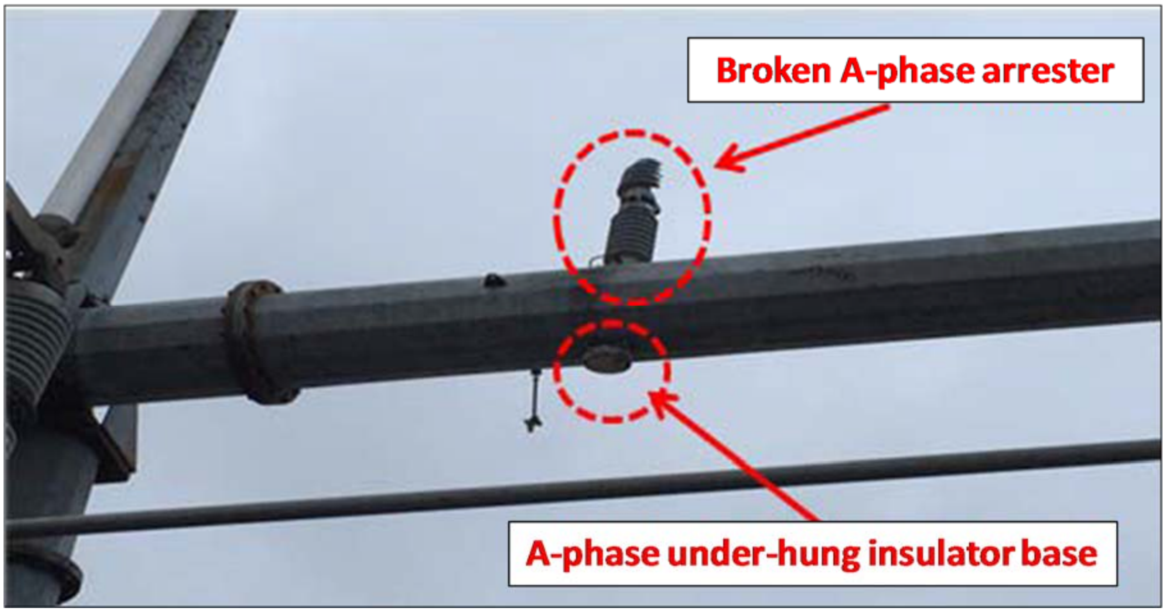


Figure 5: Damaged A-phase Surge Arrester and Underhung Insulator

The insulator, still attached to the conductor, was found outside the substation as it had pulled away from the A-frame structure when the normal tension in the conductor released as the insulator burned through. There was evidence of burning at the Y-clevis end where the insulator was connected to the A-frame structure, as shown in Figure 6.

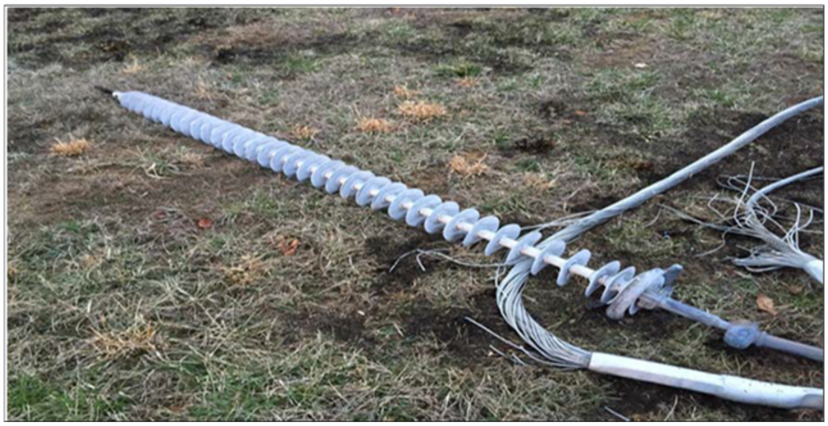


Figure 6: A-phase Dead-End Insulator outside Ryceville Substation

Since the undamaged surge arresters on the adjacent line were of the same make, model, and vintage, Pepco chose to replace them as well. They were then examined for any sign of premature aging or deterioration to evaluate potential causes of the failed arresters. No issues were found with those arresters.

Phases of the Disturbance

The disturbance can be broken into three major primary effects:

1. Initial fault and reclosing
2. Generation tripping
3. Clearing of the fault

Initial Fault and Reclosing

Initial Conditions

Prior to the disturbance, no abnormalities existed within the system aside from scheduled maintenance of several nearby circuits, transformers, and buses. These maintenance outages were analyzed and found to be inconsequential to the cause of the outage. All generators supplying energy to the system were running as expected given the relatively light load and market conditions at the time. No irregularities in equipment had been revealed in previous scheduled inspections of related equipment.

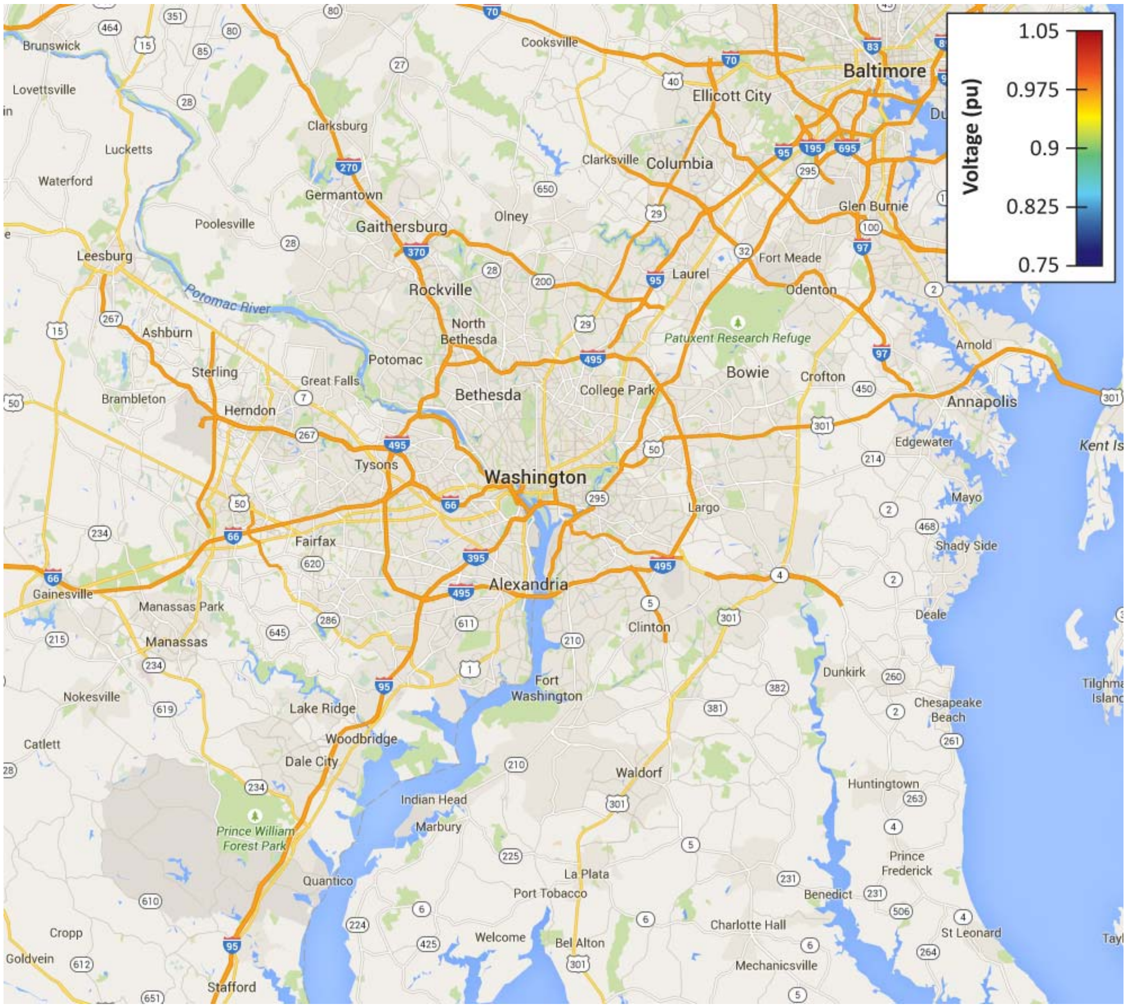


Figure 7. Pre-Disturbance Voltage Levels were Normal[8]

---

[8] If the actual system voltage profile using a powerflow simulation program to create gradient picture was illustrated here, the entire footprint would be bright orange to red in color as shown in the scale; that bright orange to red gradient was removed from this graphic for clarity.

Initiating Event

The event that initiated the loss of power was the electrical and physical failure of a C-phase surge arrester, which destroyed the arrester, damaged several adjacent components, and caused a short circuit in the Pepco portion of the Ryceville substation. Following the arrester failure, an electrical arc to the A-frame structure formed because damaged and destroyed components were no longer able to hold the energized conductor in an appropriate position. This free flow of electricity from the arcing line to the A-frame structure caused a single-phase-to-ground fault. The resulting short circuit caused large amounts of power to flow toward the fault from connected substations at Chalk Point and Morgantown, which resulted in the prolonged voltage drop throughout the area.

Breaker Tripping in Relation to Fault

Due to this fault, as designed, breakers at the Chalk Point, Ryceville, and Morgantown stations opened automatically to de-energize the line, preventing further equipment damage or spreading of the disturbance. From a design perspective, these breakers intentionally attempt to reclose after a short delay to automatically restore the line from brief system abnormalities, such as momentary faults or surges in voltage that historically account for a majority of faults. The breakers are designed to reclose once and reopen immediately if the fault is still present. One of the Chalk Point breakers, however, did not reopen after it reclosed to check for the fault's persistence.

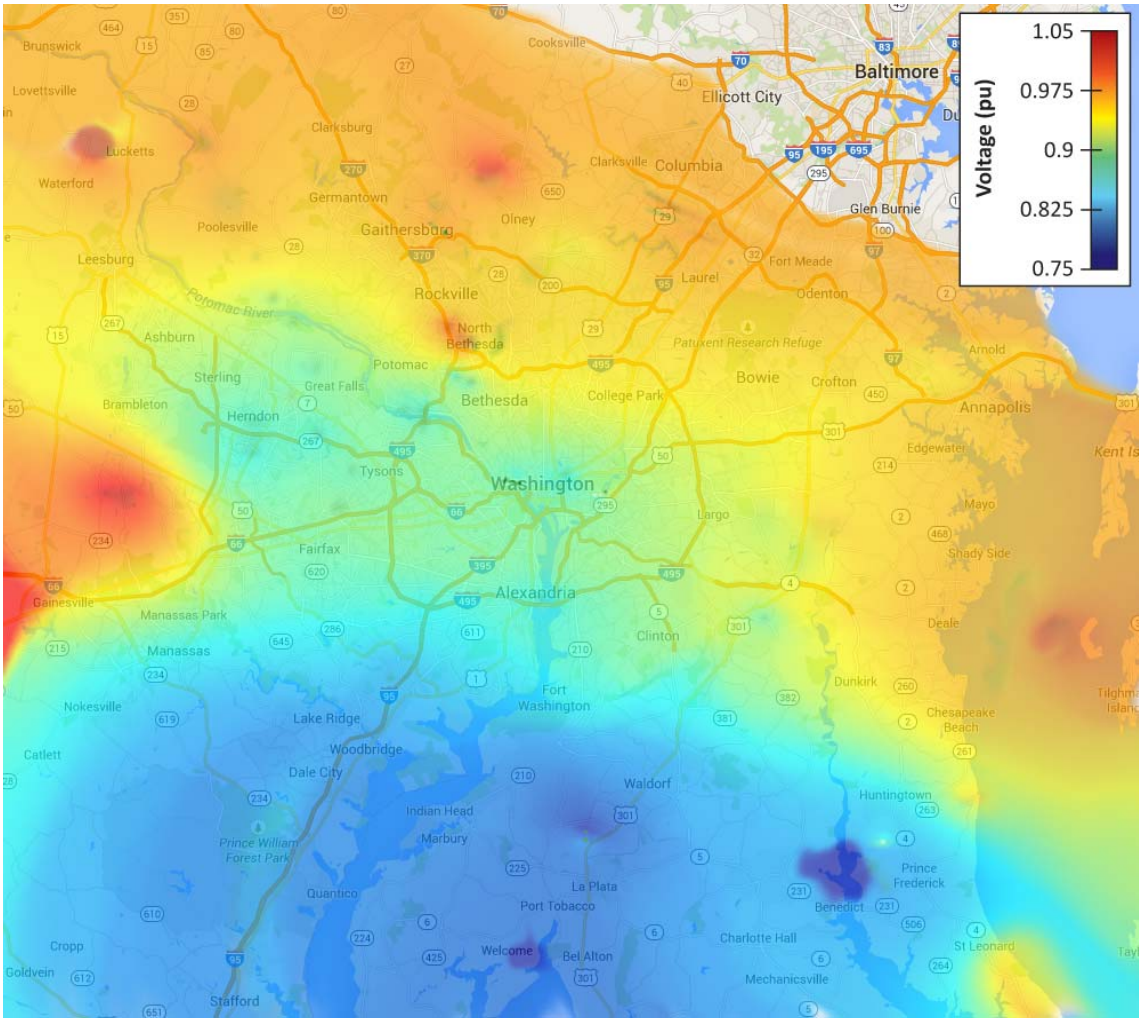


Figure 8. Noticeable Depression in Voltage due to Chalk Point Breaker Remaining Closed

Two-Phase-to-Ground Fault

Following the re-energizing of the circuit from Chalk Point with the C-phase fault still present, arcing resumed at the Ryceville substation and migrated to the adjacent B-phase line approximately 0.75 seconds after the Chalk Point breaker reclosed into the fault. That arcing caused a mechanical failure of the surge arrestor on the B-phase line, causing it to arc to the C-phase and the A-frame support structure. At this point the fault became a two-phase-to-ground fault, which led to a further voltage drop in the surrounding areas.

The generating units at Brandywine Power Facility, as well as the breakers on inactive generators located at the Chalk Point station, tripped as designed to prevent equipment damage. The topology of Chalk Point and Morgantown, with their generators offline and their respective scheduled maintenance outages, were contributory to the severity of the disturbance.

Three-Phase-to-Ground Fault

Approximately seven seconds after the fault migrated to the B-phase of the line, the continued arcing and ionized air around the fault migrated to the A-phase line, creating a three-phase-to-ground fault. This evolution of the fault caused even greater voltage degradation within the surrounding area. Approximately eight seconds after the evolution to a three-phase fault, Calvert Cliffs generating Units 1 and 2 began to shut down, as designed, in response to the severely low voltages, for nuclear safety and to prevent possible equipment damage.

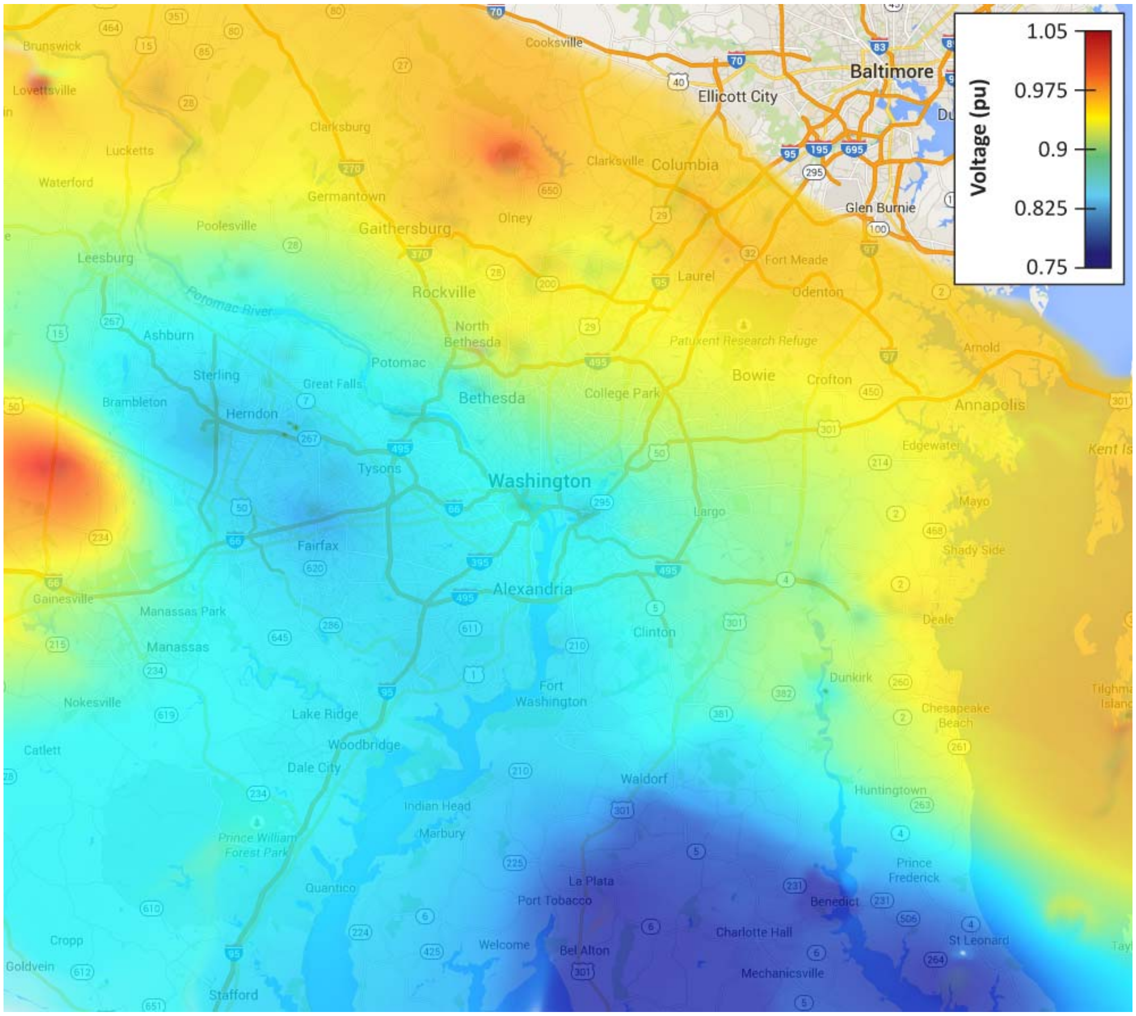


Figure 9: Further Voltage Depression Following Brandywine and Calvert Cliffs Generator Trips

Fault Migrates to Adjacent Circuit

Approximately 12 seconds after becoming a three-phase fault, the fault spread to the adjacent circuit’s C-phase, which is supported by the opposite side of the same A-phase structure at Ryceville substation. This adjacent circuit’s protection systems responded as designed, with all associated breakers tripping at Chalk Point, Ryceville, and Morgantown. Each breaker then correctly reclosed to test the line and reopened immediately, as designed.

Generator Trips

Brandywine Combined-Cycle Generation

Approximately 20 seconds after the Chalk Point breaker reclosed into the fault, Brandywine combined-cycle generation tripped offline. The relays on the generator step-up (GSU) transformers on the three generators at the Brandywine plant[9] detected ground current caused by the two-phase-to-ground fault at Ryceville. Those relays correctly tripped the Brandywine generators to protect them from equipment damage. The Brandywine plant was carrying a total of 202 MW at the time of the trip.

Calvert Cliffs

The two generators at Calvert Cliffs came offline differently because of design differences between the units. The prolonged voltage degradation to each unit's auxiliary equipment service buses initiated the tripping sequences of the generators; both units responded as designed. Unit 1 was immediately shut down for loss of the auxiliary power supply to the generator exciter system, which correctly forced the high-voltage breakers to immediately trip.

Unit 2, which uses a different type of exciter system, tripped the nuclear reactor due to extremely low voltage on its auxiliary equipment service buses. The generating unit then ramped down the power output, eventually tripping the high-voltage breakers on reverse power relay action.

Clearing of the Fault

At approximately 48 seconds after the Chalk Point breaker reclosed into the fault, the current flowing through B-phase and arcing at Ryceville substation caused the phase to burn open, halting the flow of fault current on B-phase. The fault had evolved back to a two-phase-to-ground fault. The imbalanced current of the two-phase-to-ground fault allowed backup relays on the 500 kV circuits connected to Chalk Point to detect the fault and trip those circuits.

At this point the faulted circuit became disconnected from the system and fully de-energized, extinguishing the fault. The fault existed for just over 58 seconds, from the Chalk Point breaker reclosing into the fault until it was finally extinguished by operation of the 500 kV backup relays.

---

[9] Brandywine is a 2x1 combined-cycle plant with two combustion turbines and a heat recovery steam unit.

Loss-of-Load Analysis

This disturbance impacted approximately 532 MW of load, 445 MW of which was native Pepco load (approximately 13 percent of their total load at the time of the disturbance), and 87 MW of which was SMECO load (about 28 percent of SMECO total load at the time of the disturbance) that is served from the Pepco transmission system (based on 310 MW SMECO system load prior to the event). Numerous federal, state, and local government facilities and commercial customers were impacted. Figure 10 shows Pepco's net system load, including SMECO load, from 12:00 to 17:00 EDT, on April 7, 2015.

Pepco Load Impacts

The extended fault on the 230 kV line caused a corresponding low-voltage condition on the local distribution systems in the area, including downtown Washington, D.C. Voltages at individual customer meter points may have been lower or higher than those recorded at Pepco substations.

This event primarily impacted Pepco customers at commercial facilities and government buildings whose customer-owner internal electrical protective equipment tripped, by design, in response to the low-voltage condition from the event described above. During a protracted low-voltage condition, building electrical systems will generally transfer to their backup systems, where such systems are installed and functional. These backup systems, which usually consist of an uninterruptible power supply and emergency generator, are typically designed to serve only critical loads (e.g., elevators, emergency lighting, and safe shutdown power for certain equipment) rather than the normal electrical needs of the entire building.

Only a small area of southwest Washington, D.C., (Wards 2 and 6) experienced a power outage as a direct result of any Pepco circuit breaker operations. All other impacted customers experienced outages as a result of the operation of their own internal equipment, as described above.

Typical residential customers have simpler protection systems than a commercial building or government facility; this simpler residential protection does not isolate the customer in response to an undervoltage condition, as a commercial or government customer would. Therefore, residential customers should not have experienced a sustained outage in the same manner as a large customer with undervoltage protection on their customer-owned equipment.

While the exact amount of megawatts of customer load lost was directly measurable from Pepco's metering, it is challenging to determine the exact number of customers represented by this 532 MW. Pepco does not necessarily have access to the data from customer-owned, behind-the-meter equipment. In addition, no one else has a comprehensive understanding of the many organizational and societal decisions that ultimately impacted loads that took place in the time immediately following the disturbance.

SMECO Load Impacts

SMECO lost 87 MW of load (74,086 customers) due to the loss of supply from the Pepco transmission system at the Morgantown, Chalk Point, and Ryceville delivery points. SMECO restored over 60 percent of its impacted load via SCADA, restoring 53.5 MW (39,743 customers) within 20 minutes and another 32.1 MW (30,376 customers) by 13:21, 42 minutes after the disturbance. The final 1.7 MW of load (3,967 customers) were restored by manual switching at 14:21.

System Restoration

Post-Disturbance System Status

Immediately following the system disturbance, the Pepco and PJM systems were stable, and no exceptional actions outside of normal emergency operating procedures were needed to maintain reliability. In response to the frequency and area control error (ACE) deviations, PJM deployed 100 percent synchronous reserves across its BA footprint and coordinated for and received 900 MW of emergency power from Northeast Power Coordinating Council (NPCC) entities.

Equipment Restoration

Following the disturbance, PJM, Pepco, and SMECO executed a deliberate and orderly process to evaluate system conditions and restore the system to a more reliable state. This process included dispatching field personnel to involved substations to inspect facilities and verify the condition of equipment prior to re-energization. With the exception of the Calvert Cliffs Units 1 and 2 nuclear generating units, and the damaged Chalk Point – Ryceville circuit, equipment restoration efforts were generally uncomplicated and completed by that evening. Units at Calvert Cliffs were restored to operation on April 9, 2015. Repair of damaged equipment at Ryceville substation was completed and the equipment returned to service by May 23, 2015.

Load Restoration

As previously mentioned, this disturbance impacted approximately 532 MW of load, 445 MW of native Pepco load (approximately 13 percent of their total load), and 87 MW on SMECO load (approximately 28 percent of their total load) that is served from the Pepco transmission system. All load was restored by 14:21 EDT, just under two hours after the start of the disturbance.

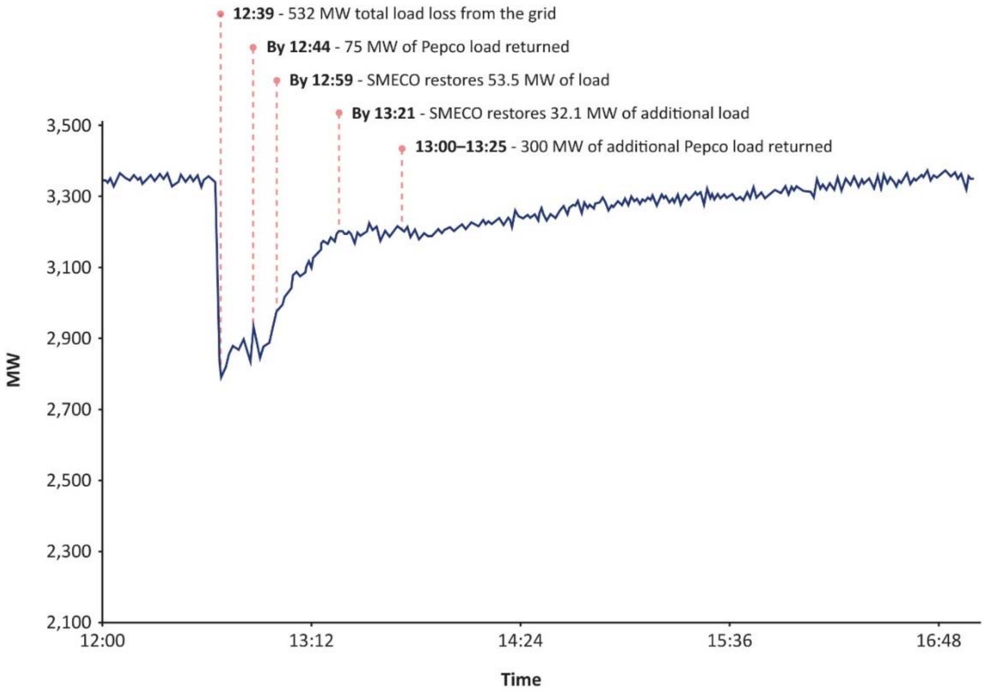


Figure 10: Pepco Net System Load (Includes SMECO Load), April 7, 2015[10]

This event primarily impacted Pepco customers at commercial facilities and government buildings whose customer-owner internal electrical protective equipment tripped, by design, in response to the severe low-voltage

---

[10] Pepco load data.

conditions. During a protracted low-voltage condition, building electrical systems will generally transfer to their backup systems where such systems are installed and functional.

In order to restore service to its normal configuration, each individual facility had to transfer from its backup system to Pepco's electric distribution system (this transfer also includes restoring noncritical loads that are not served by the backup system). In some cases, this is done automatically and was performed within minutes of the event. By 12:44, approximately 75 MW of load had returned to the system, most of which probably represents customers whose service was automatically transferred back to Pepco's electric distribution system.

In other instances, transferring a building's load back to Pepco's electric distribution system required a manual process. Although manual transfers are not complicated, they are dependent on trained and authorized electricians or electrical service personnel being available to respond and perform the necessary switching operations on the customer equipment. The location and activity of customer facility electricians at the time of the disturbance affected the speed of manual restoration switching, which could have extended the outage for those customers while customer facility electricians responded. Between 13:00 and 13:25, about 300 MW of additional Pepco load was restored, most of which represents customers whose service required manual processes for restoration. This brought the total amount of load restored to 375 MW (about 84 percent of the total Pepco load impacted).

The remaining 70 MW of impacted Pepco load did not appear to return to the system. This is probably due to load patterns changing for the remainder of the afternoon in response to organizational decisions and the normal load changes of the 87 percent of Pepco's load that was NOT impacted by this disturbance.

PJM Area Control Error Recovery

During the fault on the Chalk Point – Ryceville 230 kV line, PJM lost 1,958 MW of generation from its Balancing Authority Area, including the Brandywine Power Facility combined-cycle plant and Calvert Cliffs Units 1 and 2.

PJM's ACE dropped 1,981 MW as a net result of the generation and apparent load loss. In response to the frequency and ACE deviations, PJM deployed 100 percent synchronous reserves across its BA footprint and entered into a Simultaneous Activation of Reserve Event with 900 MW of assistance brought in from the Northeast. PJM ACE recovered to 0 MW in six minutes and 44 seconds. Eastern Interconnection frequency and PJM ACE are shown in Figure 11.

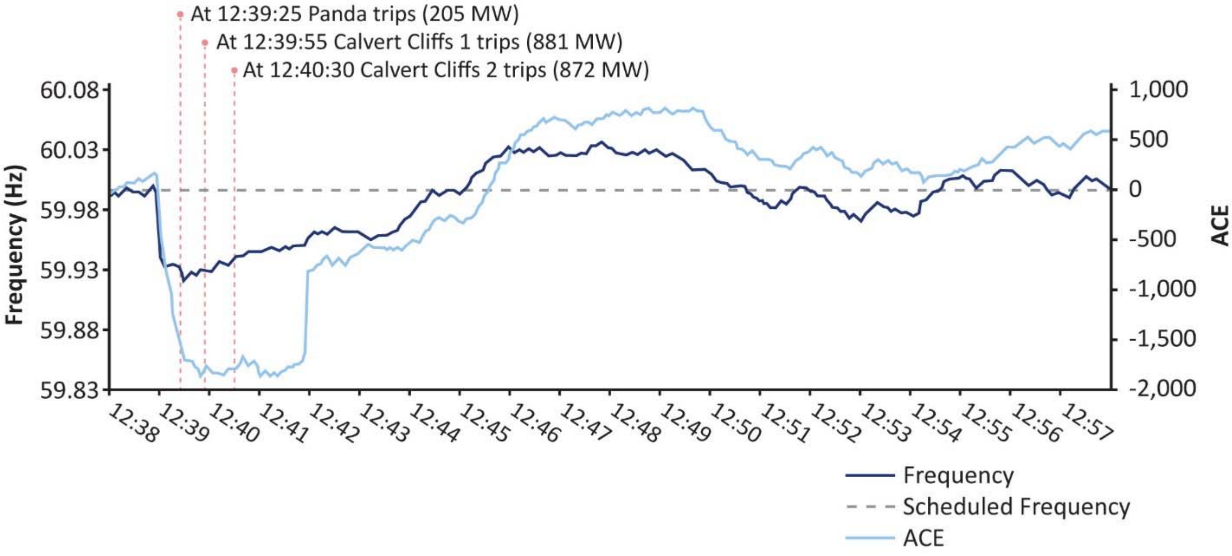


Figure 11: Eastern Interconnection Frequency and PJM ACE Recovery

Analysis & Resolutions

Protection System Performance

This section provides insight into the performance of the involved facilities' protection systems. These protection systems are designed to protect both equipment and the grid by recognizing and isolating short circuits or other undesired conditions quickly and with minimum impact to the larger system.

Protection System Overview

The Chalk Point – Ryceville circuit has two fully independent and redundant protection systems, referred to as LR1 and LR2. Each system has its own completely independent direct current (dc) systems, dc sources, instrument transformers, trip coils, and communication systems.

The Chalk Point breaker is set to reclose after a delay when the substation bus side of the breaker is energized and the transmission line is de-energized (hot bus/dead line condition) and after a shorter delay when both the substation bus and transmission line are energized (hot bus/hot line condition). The Morgantown breaker is set to reclose after a delay for hot bus/dead line conditions and after a shorter delay for hot bus/hot line conditions. The Ryceville breaker is set to reclose after a delay upon receiving a signal from either Morgantown or Chalk Point. Both Chalk Point and Morgantown have local breaker failure protection systems that will open all breakers needed to disconnect the failed breaker from the system in case it fails to open when needed to isolate a fault.

Additionally, in accordance with PJM Manual 07, Sections 1 and 7, all 500 kV involved circuits have time-delayed ground overcurrent protection set to operate at not greater than 600 amps, to serve as backup protection.

Performance During Fault Conditions

When the initial fault occurred, all breakers at the Chalk Point, Morgantown, and Ryceville substations tripped as designed to isolate the fault. At Morgantown, additional breakers associated with reserve station service transformers unexpectedly tripped shortly before the breakers associated with the faulted circuit tripped.

The first reclosing attempt occurred at Morgantown approximately 2.5 seconds after the initial opening and sooner than the designed delay. The LR1 system detected the fault and again tripped the breaker immediately as intended; the LR2 system did not respond to this close-into-fault condition. Post-event testing revealed an issue with the reclosing relay's timer that caused the reclosing attempt sooner than intended, and the relay was subsequently replaced.

The Chalk Point breaker reclosed after a delay, as designed. The LR1 system detected the fault after reclosing and attempted to send a signal to the auxiliary relays to trip the breaker. However, due to an open circuit in the control wiring, the auxiliary relays failed to receive the trip signal so the breaker never attempted to trip. Testing performed post-event suggested that the LR2 relay also detected the fault and attempted to send a trip signal to the auxiliary relays. However, during the disturbance the auxiliary tripping relays did not operate, so the breaker never attempted to trip. Since the breaker tripping relays and the breaker failure initiate signal were connected to the same auxiliary relay that did not operate, the local breaker failure protection system failed to initiate and disconnect the breaker from the system when it failed to trip. Pepco and an independent contractor performed extensive testing on the LR2 system following the event; neither were able to recreate or otherwise explain the failure of the auxiliary relays to operate.

The Ryceville breaker reclosed after a delay, as designed, and tripped immediately upon reclosing. The control circuit at Ryceville is designed to communicate with the Chalk Point protection systems, and this communication occurred as designed from Ryceville to Chalk Point during the fault.

Approximately 1.5 seconds after the Chalk Point breaker reclosed into the fault, Brandywine Power Facility tripped offline due to neutral overcurrent. Shortly after that, additional breakers at Chalk Point connecting generators (which were offline at the time) also tripped due to the same phase imbalance. Both these trips occurred as designed and intended, to protect equipment from imbalanced phase currents.

Upon evolving into a three-phase fault, system voltage levels dropped low enough to cause the Calvert Cliffs Units 1 and 2 nuclear reactors to automatically initiate a shutdown due to low voltage on their auxiliary buses. Unit 1's high-voltage breakers tripped immediately by design to disconnect the unit from the grid following the loss of power to its excitation system. Unit 2 began to ramp down its output to a point when it would begin to motor off the system and cause the reverse power relays to trip its high-voltage breakers, according to design.

As the fault evolved to include the C-phase of the adjacent parallel circuit at Ryceville substation, that circuit's protection systems all operated as designed and intended. The Chalk Point substation breakers opened first, followed closely by the Morgantown and Ryceville substation breakers. The Chalk Point breaker then reclosed by design to test the circuit for a persistent fault, and reopened immediately.

At approximately 48 seconds after the Chalk Point breaker reclosed into the fault, the current flowing through B-phase and arcing at Ryceville substation caused the phase to burn open, halting the flow of fault current on B-phase. The fault had evolved back to a two-phase-to-ground fault. The imbalanced current of the two-phase-to-ground fault allowed backup relays on the 500 kV circuits connected to Chalk Point to detect the fault and trip those circuits. At this point, the faulted circuit became disconnected from the system and fully de-energized, extinguishing the fault. The fault existed for just over 58 seconds, from the Chalk Point breaker reclosing into the fault until it was finally extinguished by operation of the 500 kV backup relays.

Protection System Observations

Analysis of the protection system performance yielded two observations with broader industry relevance. These observations deal with design enhancements to the auxiliary trip circuitry and the breaker failure initiate (BFI) circuitry.

Auxiliary Trip Circuit Open Paths

An analysis of the auxiliary tripping circuitry revealed an opportunity for improvement for the LR1 circuit design, shown in Figure 12. The reliability of this tripping circuit can be improved by changing the 52a contacts from a series to a parallel connection.

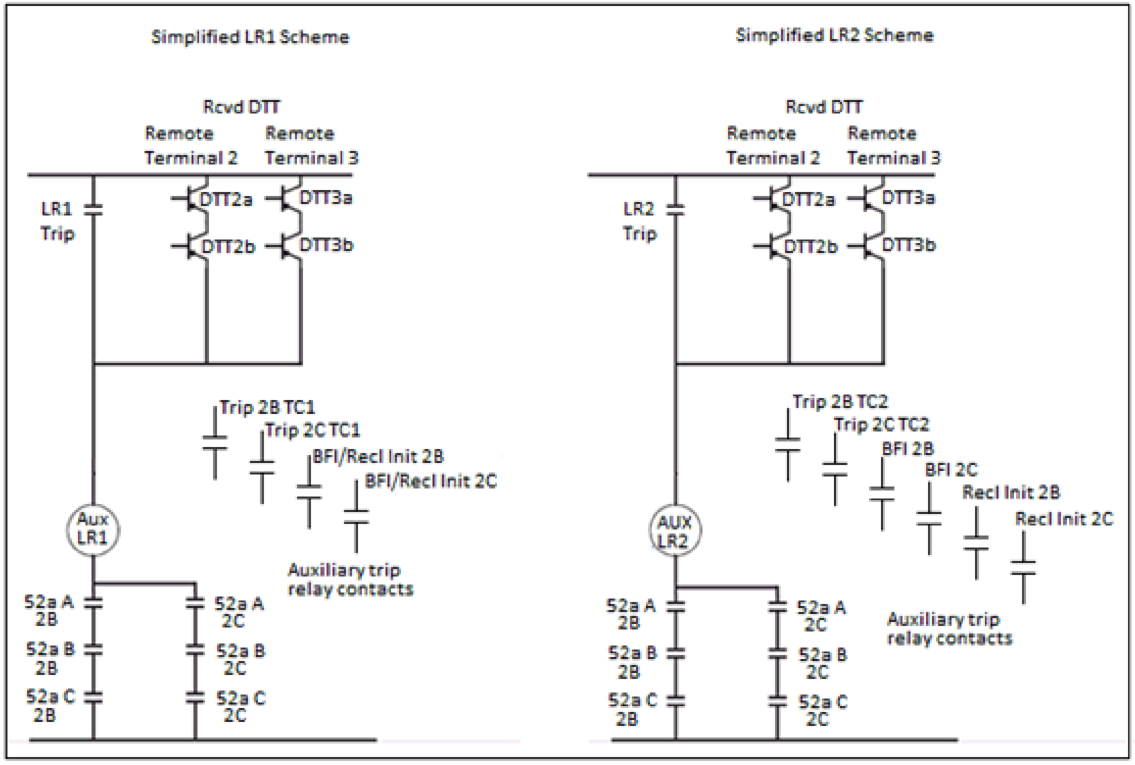


Figure 12: Chalk Point Dual Redundant Relay Systems

Breaker Failure Initiate Originating from Trip Auxiliary Relay

A local breaker failure protection system should be immune to potential failures of the auxiliary relay circuitry to the greatest extent possible. To improve reliability, some alternatives to having the BFI signal originate from the auxiliary relays include:

- Use a separate contact from the protective relay to provide the BFI signal.
- Use a dedicated auxiliary relay for breaker failure initiate if a separate contact is not available on the protective relay.
- Connect the protective relay trip contact directly to a breaker failure relay input if the breaker failure relay will accommodate a voltage input.

Appendix 1 – PJM Requirement for Ground Fault Protection

The following passages are excerpts from the PJM Manual-07, Rev 0, 11/16/11, Sections 1 and 7.

Section 1: Applicability
This document establishes the minimum design standards and requirements for the protection systems associated with the bulk power facilities within PJM. The facilities to which these design standards apply are generally comprised of the following:

- all 100 MVA and above generators connected to the BES facilities
- all 200 kV and above transmission facilities
  - all transmission facilities 100 kV to 200 kV critical to the reliability of the BES as defined by PRC-023-1 and determined by PJM System Planning
    - PJM System Planning will also investigate the criticality of equipment (generators, buses, breakers, transformers, capacitors and shunt reactors) associated with the PRC-023-1 determined lines.

General principles of applicability include:

1. Compliance with NERC Transmission Planning Standards TPL-001-1 through TPL-004-1 and the associated Table 1, as may be amended from time to time, is mandatory.
2. Where a protection system does not presently meet the requirements of NERC Transmission Planning Standards TPL-001-1 through TPL-004-1 and the associated Table 1, action shall be taken by the facility owner to bring the protection system(s) into compliance.
3. Adherence to applicable NERC and Regional reliability standards is mandatory; however, the PJM requirements set forth in this document are in some cases more restrictive than the applicable NERC or Regional reliability standards.

A protection system is defined as those components used collectively to detect defective power system elements or conditions of an abnormal or dangerous nature, to initiate the appropriate control circuit action, and to isolate the appropriate system components. All new projects approved after January 1, 2012, shall conform to these design standards. It is recognized that some facilities existing prior to the adoption of these requirements do not conform. It is the responsibility of the facility owners to consider retrofitting those facilities to bring them into compliance as changes or modifications are made to those facilities.

Section 7: Line Protection
7.4: Restricted Ground Fault Protection
A scheme must be provided to detect ground faults with high fault resistance. The relay(s) selected for this application must be set at 600 primary amperes or less, provided that this setting is greater than the maximum-line zero-sequence load unbalance. These relays may serve as the overreaching, non-communications-assisted ground tripping function.

This section outlines the requirements for the protection of lines at system voltages above 200 kV and as defined in Manual, Section 1 - Applicability.

Appendix 2 – Glossary of Terms and Acronyms

Glossary of Terms and Acronyms	
Acronym	**Definition**
ACE	Area Control Error
BA	Balancing Authority
BFI	Breaker Failure Initiate
BG&E	Baltimore Gas and Electric Company
CCPD	capacitor-coupled potential device
CIP	Critical Infrastructure Protection
DFR	Digital Fault Recorder
DP	Distribution Provider
DUTT	Direct Underreaching Transfer Trip
EA	Event Analysis
EMS	Energy Management System
ERAG	Eastern Interconnection Reliability Analysis Group
ERO	Electric Reliability Organization
FERC	Federal Energy Regulatory Commission
GCB	Gas Circuit Breakers
GO	Generator Owner
GOP	Generator Operator
GSU	Generator Step-up transformer
LCC	Local Control Center
LLG	Line to line to ground fault
LSE	Load Serving Entity
MMWG	Multiregional Modeling Working Group
MOD	Motor-operated disconnect switch
MOV	Metal Oxide Varistor
MW	Megawatt
NERC	North American Electric Reliability Corporation
NPCC	Northeast Power Coordination Council
NRC	U.S. Nuclear Regulation Commission
OCB	Oil Circuit Breakers
Pepco	Potomac Electric Power Company
PHI	Pepco Holdings Incorporated
PMU	Phasor measurement unit

Glossary of Terms and Acronyms	
Acronym	**Definition**
POTT	Permissive Overreaching Transfer Trip
pu	Per Unit
RC	Reliability Coordinator
RF	ReliabilityFirst
RTO	Regional Transmission Organization
SAR	Simultaneous Activation of Reserve Event
SCADA	Supervisory Control and Data Acquisition
SER	Sequence of Event Recording
SLG	Single line to ground fault
SMECO	Southern Maryland Electric Cooperative
TO	Transmission Owner
TOP	Transmission Operator
TOR	Trip on reclose