ARIZONA PUBLIC SERVICE COMPANY

ROOT CAUSE OF FAILURE REPORT FOR THE JUNE 14, 2004 GRID DISTURBANCE

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EXECUTIVE SUMMARY

At 07:40:55.747 on June 14, 2004, the Western Area Power Authority 230kV Liberty (LBX) to Westwing (WW) line faulted. The event cascaded into a grid disturbance and resulted in the tripping of all three Palo Verde reactors, Redhawk Steam Turbine 1 and Combustion Turbines 1A and 2A, and Arlington Station, and disruption of service to approximately 20,440 APS customers, and approximately 35,000 Tucson Electric Power customers. Due to the nature of the event, Arizona Public Service Company (APS) deemed that a Root Cause Analysis, to determine the failure cause of the grid disturbance (i.e., why the 230kV system did not contain the fault) and to craft corrective actions to prevent recurrence, was appropriate.

Root cause analysis includes five phases. While there is some overlap between phases, efforts are made to keep them as distinct as possible. These phases are:

1. Data Collection: Collect and organize data, develop a problem description and chronology of events, and identify the effects.

2. Assessment: Analyze data to determine how and why the events happened.

3. Correction: Develop, review, and implement corrective actions.

4. Inform: Explain/discuss the results of the root cause analysis, including corrective actions, with management and personnel involved in the event, or others as necessary to prevent recurrence of similar events.

5. Follow-up: Determine if corrective action have been effective in resolving the problems.

This paper will address items 1 through 4.

The investigation has concluded that the root cause was a failure of a Westinghouse AR relay, style number 606B017A09A, manufactured in October, 1974. The relay was used in the trip schemes of breakers WW1022 and WW1126. The AR relay acts as a contact multiplier in the relay protective schemes. As noted in Westinghouse's Installation, Operations, and Maintenance Instructions, "The AR relay is a four-pole auxiliary type relay, especially designed for ultra high speed circuit breaker tripping duty in protective schemes." It further notes that "The AR relay is well suited for bus arrangements where more than one breaker must be tripped."

Subsequent to the event, it was found that two of the contacts in the AR relay for the protective scheme for WW1022 had not made contact when the fault began on the LBX - WW 230kV line. Because of the failed AR relay, WW1022 not only did not operate to isolate the line fault, but the signal that WW1022 had not opened ("breaker failure") was also not initiated, since both signals utilized the same contacts.

As an interim corrective action, APS T&D replaced the defective relay. In addition, redundant AR relays were installed on the two schemes within the Westwing 230kV switchyard that used a single AR to pass trip signals to multiple breakers (WW1022 /WW1126, and WW1726/WW1822). While installing and testing the redundant AR relay in the WW1726/WW1822 scheme, it was noted that

one contact on the existing AR relay also did not make up. A new relay was installed.

The root cause analysis employed a barrier analysis approach. Four failed, degraded, or missing barriers were identified. They are:

- AR relay for WW1022 breaker failed to actuate;
- Functional testing did not detect the failure of the AR relay;
- A lack of redundancy in transmitting the necessary tripping signals; and
- A lack of backup protection on the 525kV transformers.

As corrective actions, APS will:

1. Add redundant AR relays in the protective schemes for the Deer Valley – Westwing 230kV line and the Liberty – Westwing 230kV line (Complete: Reference W219277);

2. Add back-up relaying on the three 525/230kV transformers at Westwing substation (T10 Complete: Reference W220156, T4 Complete: Reference W223285), the two 525/230kV transformers at the Yavapai substation (Complete: reference W220367), and the 525/69kV transformer at the North Gila substation (Complete: Reference W220372) (Note: Westwing transformer T7 already has back-up protection – Reference G-32901, Rev. 11 and Westwing transformer T1 will have back up relaying incorporated during rebuilding in spring of 2005);

3. Functional test all AR relays installed in relay protective schemes, to ensure each of the four contacts fully close; (Estimated completion date: 2/28/2005)

4. Require that all periodic functional testing ensure that all contacts and elements within tripping circuits, that are practical to access, are tested; (Estimated completion date: 2/28/2005)

5. Return the two failed AR relays to ABB (current product supplier) for bench testing to determine if setting attributes (contact pressure, spring tension, etc.) are in compliance with manufacturer's specifications; (Estimated completion date: 2/28/2005)

6. Review all other protective schemes for switchyards 230kV or higher to determine if they need to be upgraded to prevent single failure consequences (Estimated completion date: 4/30/2005); and

7. Complete upgrades to tripping schemes identified in Action 6. (Estimated completion date: 12/31/2006)

ROOT CAUSE INVESTIGATION

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BACKGROUND

The Westwing 230kV switchyard is located west of the Loop 303 on Hatfield Road northeast of Sun City West. It is also adjacent to the Westwing 525kV switchyard. The 230kV switchyard is supplied by the three 525kV/230kV transformer banks in the Westwing 525kV switchyard, as well as the Raceway (APS), Surprise (APS), Agua Fria (SRP), Deer Valley (SRP), Liberty (WAPA), and Pinnacle Peak (WAPA) 230kV lines. The 230kV switchyard also supplies the APS 69kV switchyard via two ties. Except for one of the 230kV to 69kV ties, which utilizes a single protective breaker, all other connections within the Westwing 230kV switchyard utilize a breaker-and-a-half scheme.

ROOT CAUSE ANALYSIS METHOD

Root cause analysis includes five phases. While there is some overlap between phases, efforts are made to keep them as distinct as possible. These phases are:

1. Data Collection: Collect and organize data, develop a problem description and chronology of events, and identify the effects.
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This paper will address items 1 through 4.

DATA COLLECTION

- APS, SRP, and WAPA digital fault recorder data from 6/14/2004 through 6/16/2004 was obtained.
- APS Energy Management System (EMS) data from 6/14/2004 through 6/16/2004 was obtained.
- Outage Information System (OIS) data for Liberty – Westwing line, 1993 - present
- Drawing G-32901 Rev. 11, Westwing 500kV Switchyard Transformer Bays 7, 10, 13 & 16 One Line Diagram
- Drawing G-33410 Rev. 15, Westwing 230kV Switchyard PCB WW1022, 1126, 1222 Fail Prot DC Schematic
- Drawing G-33434 Rev. 9, Westwing 230kV Switchyard WAPA 230kV Liberty Line Relaying Schematic
- Drawing G-33451 Rev. 14, Westwing 230kV Switchyard 230kV WAPA Liberty

Line & West Bus Tie PCB WW1022 DC Schematic

- Drawing G-33453 Rev. 16, Westwing 230kV Switchyard 230kV WAPA Liberty & Pinn Pk Line PCB WW1126 DC Schematic

- Drawing G-33463 Rev. 19, Westwing 230kV Switchyard PCB1726 Deer Valley Line D.C. Schematic

- Westinghouse Installation, Operation, and Maintenance Instruction Manual I.L. 41-759H, September 1978, Type AR High Speed Auxiliary Relay

- ABB Instruction Leaflet 41-759.2D, May 1999, Type ARS Auxiliary Relay High Speed

- INPO OE8495, Relay Sensitivity Results in Loss of Offsite Power

- INPO OE9846, Failures of Westinghouse Type AR Auxiliary Relays

- INPO Equipment Performance and Information Exchange

During the investigation, the following timeline was reconstructed:

June 14, 2004

07:40 - Westwing - Liberty 230kV Line (faulted line)

Elements affected during the event and restoration efforts:

525kV:
Arlington - Hassayampa 525kV Line
Devers - Palo Verde 525kV Line
Hassayampa - Palo Verde 525kV Line #1
Hassayampa - Palo Verde 525kV Line #2
Hassayampa - Palo Verde 525kV Line #3
Mead – Perkins - Westwing 525kV Line
Moenkopi - Yavapai 525kV Line
Navajo - Westwing 525kV Line
Palo Verde - Rudd 525kV Line
Palo Verde - Westwing 525kV Line #1
Palo Verde - Westwing 525kV Line #2
Yavapai – Westwing 525kV Line

345kV:
South - Westwing 345kV Line

230kV:
Agua Fria - Westwing 230kV Line
Deer Valley - Westwing 230kV Line
Glen Canyon – Sigurd 230kV Line
Pinnacle Peak - Westwing 230kV Line
Pinnacle Peak East 230kV Transfer Breaker
Raceway - Waddell 230kV Line
Raceway - Westwing 230kV Line
Surprise - Westwing 230kV Line

69kV:
Coconino - Winslow 69kV Line
Flying E - Wickenburg 69kV Line
Hedgepeth Hills - Westwing 69kV Line
McMicken - Morristown 69kV Line
McMicken - Surprise 69kV Line
McMicken - Westwing 69kV Line
Morristown - Wickenburg 69kV Line
Rio Vista - Westwing 69kV Line
Westbrook – Westwing 69kV Line
White Spar - Wickenburg 69kV Line

Transformers:
McMicken 69/12.47kV Transformer #3
Raceway 230/69kV Transformer #8
Surprise 230/69kV Transformer #4
Westwing 525/230kV Transformer #1
Westwing 525/230kV Transformer #4
Westwing 525/345kV Transformer #7
Westwing 525/230kV Transformer #10
Westwing 230/69kV Transformer #11
Westwing 230/69kV Transformer #14

Generation:
Arlington
Palo Verde Unit-1
Palo Verde Unit-2
Palo Verde Unit-3
Redhawk Steam Turbine 1
Redhawk Combustion Turbine 1A
Redhawk Combustion Turbine 2A

Substations:
DOE ED4
Flying E
McMicken
Morristown
Patton
Wickenburg

Note: During a 6/15/2004 post event analysis meeting between APS, SRP, and WAPA protective

relaying department personnel, it was noted that SRP's time stamps differed from APS' time stamps by as much as 40 milliseconds. SRP could not explain the deviation at that time. All timestamps obtained from non-APS sources are noted below.

07:40:55.747 - **Fault #1 inception**, Fault #1 type = C-N, Fault #1 cause = Phase down (broken bells) on LBX-WW Line, Fault #1 location = Tower #73 (between Union Hills and Beardsley), Fault #1 magnitude = Phase C – 18,060 amps; Neutral – 18,240 amps
Note: Westwing 525/230kV Transformers T1, T4 & T10 were on-line and providing fault current for Fault #1.

At Westwing, the Liberty line relays operated properly and issued a trip signal. Incorporated in this scheme is a Westinghouse high-speed "AR" auxiliary tripping relay that is used to "multiply" that trip signal toward both trip coils of two breakers (WW1022 & WW1126). The "AR" relay failed (partially) and issued the trip signal to breaker WW1126 only. Since the trip signal was never successfully issued to WW1022, breaker failure for WW1022 was also never initiated (this would have cleared the Westwing 230kV West bus and isolated the fault). Therefore, the "remote" ends of all lines feeding into the 525kV and 230kV yards were required to trip to isolate the fault.

07:40:55.814 4.0 cycles after fault #1 inception; WW1126 opened (LBX / PPX 230kV crossover breaker)

07:40:55.822 4.5 cycles after fault #1 inception; LBX1282 opened (Westwing 230kV Line)

07:40:56.115 22.1 cycles after fault #1 inception; AFX732 & AFX735 opened (Westwing 230kV Line)

07:40:56.122 22.5 cycles after fault #1 inception; YP452 & YP852 opened (Westwing 525kV Line)

07:40:56.136 23.3 cycles after fault #1 inception; WW1426 & WW1522 opened (Agua Fria 230kV Line)

07:40:56.142 23.7 cycles after fault #1 inception; WW856 & WW952 opened (Yavapai 525kV Line)

07:40:56.165 25.1 cycles after fault #1 inception; DV322 & DV722 & DV962 opened (Westwing 230kV Line)

07:40:56.172 25.5 cycles after fault #1 inception; WW1726 & WW1822 opened (Deer Valley 230kV Line)

07:40:56.196 26.9 cycles after fault #1 inception; RWYX482 & RWYX582 & RWYX782 opened (Westwing 230kV Line) (Waddell 230kV Line) (Raceway 230/69kV Transformer #8)

07:40:56.247 Fault #1 magnitude = Phase C – 15,420 amps; Neutral – 15,490 amps

07:40:56.515 46.1 cycles after fault #1 inception; WW1222 opened (Pinnacle Peak 230kV Line)

t = unknown Surprise Lockout "L" operated; (Surprise 230/69kV Transformer #4 Differential & B/U Over-Current)

07:40:56.548 48.1 cycles after fault #1 inception; SC622 & SC922 & SC262 opened (Surprise 230/69kV Transformer #4)

07:40:57.549 108.1 cycles after fault #1 inception; SC1322 opened (Westwing 230kV Line)

07:40:57.800 123.2 cycles after fault #1 inception; RWP-CT2A opened (Redhawk Combustion Turbine 2A)

07:40:57.807 123.6 cycles after fault #1 inception; RWP-ST1 opened (Redhawk Steam Turbine 1)

07:40:57.814 124.0 cycles after fault #1 inception; RWP-CT1A opened (Redhawk Combustion Turbine 1A)

07:40:58.339 155.5 cycles after fault #1 inception; RIV762 opened (Westwing 69kV Line)

07:40:58.372 157.5 cycles after fault #1 inception; HH762 opened (Westwing 69kV Line)

t = unknown Westwing Lockout "AK" operated; (Westwing 230/69kV Transformer #11 Differential & B/U Over-Current)

07:40:59 (EMS) WW2026 & WW2122 opened; (Westwing 230/69kV Transformer #11 - High Side)

07:40:59.272 211.5 cycles after fault #1 inception; WK362 opened (Westwing 69kV Line)

07:40:59.489 224.5 cycles after fault #1 inception; HAAX935 & HAAX938 opened (Arlington -

Hassayampa 525kV Line) (Time stamp provided by SRP)

07:41:00 (EMS) WW862 & WW962 & WW1362 opened; (Westwing 230/69kV Transformer #11 - Low Side)

07:41:00.374 TEP South terminal opened (Westwing 345kV Line) (Time stamp provided by TEP)

07:41:00.392 278.7 cycles after fault #1 inception; WW752 opened (South 345kV Line)

07:41:01.982 Fault #1 type changed = B-C-N

07:41:02.144 383.8 cycles after fault #1 inception; PSX832 closed auto (Perkins Cap-Bank Bypass) (Time stamp provided by SRP)

07:41:02.154 Fault #1 type changed = C-N

07:41:02.799 Fault #1 type changed = B-C-N

07:41:03.966 493.1 cycles after fault #1 inception; SC562 opened (McMicken 69kV Line)

07:41:05.373 577.6 cycles after fault #1 inception; MQ562 opened (McMicken 69kV Line)

07:41:07.849 12.102 seconds after fault #1 inception; HAAX922 & HAAX925 opened (Palo Verde 525kV Line #2) (Time stamp provided by SRP)

07:41:07.851 12.104 seconds after fault #1 inception; PLX972 & PLX975 opened (Hassayampa 525kV Line #2) (Time stamp provided by SRP)

07:41:07.859 12.112 seconds after fault #1 inception; HAAX932 opened (Palo Verde 525kV Line #1) (Time stamp provided by SRP)

07:41:07.875 12.128 seconds after fault #1 inception; PLX982 & PLX985 opened (Hassayampa 525kV Line #3) (Time stamp provided by SRP)

07:41:07.876 APS recorder at Redhawk indicates that all three PLX-HAAX lines have opened

07:41:07.878 12.131 seconds after fault #1 inception; HAAX912 & HAAX915 opened (Palo Verde 525kV Line #3) (Time stamp provided by SRP)

07:41:07.880 12.133 seconds after fault #1 inception; PLX942 & PLX945 opened (Hassayampa 525kV Line #1)

07:41:08.104 Fault #1 type changed = A-B-C-N

07:41:10.445 14.698 seconds after fault #1 inception; NV1052 & NV1156 opened (Westwing 525kV Line)

07:41:10.456 14.709 seconds after fault #1 inception; WW556 & WW652 opened (Navajo 525kV Line)

07:41:12 (EMS) WW424J opened (Westwing 230kV West Bus Reactor)

07:41:18.900 Fault #1 magnitude: Phase A – 12,400 amps; Phase B – 16,750 amps; Phase C – 15,790 amps; Neutral – 1,469 amps

07:41:20.005 24.258 seconds after fault #1 inception; PLX992 opened (Devers 525kV Line) (PLX995 out-of-service at this time) (Time stamp provided by SRP)

07:41:20.113 24.366 seconds after fault #1 inception; PLX932 & PLX935 opened (Rudd 525kV Line) (Time stamp provided by SRP)

07:41:20.145 24.398 seconds after fault #1 inception; RUX912 & RUX915 opened (Palo Verde 525kV Line) (Time stamp provided by SRP)

07:41:20.864 25.117 seconds after fault #1 inception; PLX912 & PLX915 opened (Westwing 525kV Line #1) (Time stamp provided by SRP)

07:41:20.873 25.126 seconds after fault #1 inception; WW1456 & WW1552 opened (Palo Verde 525kV Line #2)

07:41:20.874 25.127 seconds after fault #1 inception; WW1156 & WW1252 opened (Palo Verde 525kV Line #1)

07:41:20.895 25.148 seconds after fault #1 inception; PLX922 & PLX925 opened (Westwing 525kV Line #2) (Time stamp provided by SRP)

07:41:21:200 Fault #1 magnitude: Phase A – 4,770 amps; Phase B – 5,605 amps; Phase C – 5,527 amps; Neutral – 1,166 amps

07:41:23 (DOE) Sigurd terminal opened (Glen Canyon 230kV Line) (Open ended at Sigurd due to overload)

07:41:23.848 28.101 seconds after fault #1 inception; PLX988 opened (Palo Verde Unit 3) (Time stamp provided by SRP)

07:41:24.280 System Frequency = 59.514 Hz (Measured at APS Reach Substation)

07:41:24.641 28.894 seconds after fault #1 inception; PLX918 opened (Palo Verde Unit 1) (Time stamp provided by SRP)

07:41:24.652 28.905 seconds after fault #1 inception; PLX938 opened (Palo Verde Unit 2) (Time stamp provided by SRP)

07:41:25 (DOE) ED4-122 & ED4-322 opened; (DOE ED4 Substation) Tripped on under-frequency (Note frequency low at 07:41:24.280)

07:41:25 (EMS) ML142, ML542, ML1042 & ML1442 opened (Moon Valley 12kV Feeders) Tripped on under-frequency (Note frequency low at 07:41:24.280)

07:41:25.722 MEX794 closed auto; (Mead Cap Bank bypass) (Time stamp provided by DOE)

07:41:34:300 Fault #1 magnitude: Phase A – 4,160 amps; Phase B – 4,355 amps; Phase C – 4,118 amps; Neutral – 957 amps

07:41:34.300 Fault #1 magnitude (at Mead terminal): Phase A – 1,608 amps; Phase B – 1,871 amps; Phase C amps – 1,605 amps; Neutral – 43 amps (Time stamp provided by DOE)

07:41:34.615 38.868 seconds after fault #1 inception; MEX1092 & MEX1692 opened (Mead - Perkins - Westwing 525kV Line)
Fault #1 cleared

07:42:22.773 System Frequency = 59.770 Hz (Measured at APS Reach Substation)

07:44:19 (EMS) APS issued close command to YP452; (WW / T1 ring breaker)
07:44:21.018 Close successful

07:44:49 (EMS) APS issued close command to WW952; (Yavapai 525kV Line)
Execute failure

07:45:12 (EMS) APS issued close command to WW952; (Yavapai 525kV Line)
Execute failure

07:49:14 (EMS) YU1342 closed locally; (Yucca Gas Turbine #3)

07:49:47 (EMS) YU1442 closed locally; (Yucca Gas Turbine #4)

07:50:07 (EMS) YU1142 closed locally; (Yucca Gas Turbine #1)

07:50:29 (EMS) HAAX932 closed by SRP; (Palo Verde 525kV Line #1)

07:50:30 (EMS) YU1242 closed locally; (Yucca Gas Turbine #2)

07:50:45 (EMS) HAAX935 closed by SRP; (PLX1 / ALX crossover breaker)

07:53:30 (DOE) Sigurd terminal closed (Glen Canyon 230kV Line)

07:54:55.728 LBX1282 closed by DOE; (Westwing 230kV Line)
Fault #2 inception, Fault #2 type = A-B-C-N, Fault #2 cause = Phase down (broken bells) on LBX-WW Line, Fault #1 location = Tower #73 (between Union Hills and Beardsley)
Note: Westwing 525/230kV Transformers did not provide fault current for Fault #2.

07:54:55.835 6.4 cycles after fault #2 inception; LBX1282 opened (Westwing 230kV Line)
Fault #2 cleared

07:57:11 (EMS) WP-CC5-CTB closed locally; (West Phoenix Combined Cycle #5 Combustion Turbine B)

08:02:57 (EMS) SG-CT3 closed locally; (Saguaro Combustion Turbine #3)

08:03:59 (EMS) APS issued close command to WW1222; (Pinnacle Peak 230kV Line)
08:03:59.764 Close successful
Fault #3 inception, Fault #3 type = A-B-C-N, Fault #3 cause = Phase down (broken bells) on LBX-WW Line, Fault #1 location = Tower #73 (between Union Hills and Beardsley)
Note: Westwing 525/230kV Transformers did not provide fault current for Fault #3.

08:03:59.809 2.7 cycles after fault #3 inception; WW1222 opened (Pinnacle Peak 230kV Line)
Fault #3 cleared

08:04:41 (EMS) OC262 closed locally; (Ocotillo Gas Turbine #1)

08:06:03 (DOE) DOE issued close command to ED4-122; (DOE ED4 Substation)
Execute failure; (Later determined to be a failed close coil in the breaker.)

08:06:30 (DOE) DOE issued close command to ED4-122; (DOE ED4 Substation)
Execute failure

08:07:20 (EMS) APS issued open command to WW526; (T4 / SC 230kV crossover breaker)
Open successful

08:07:37 (EMS) APS issued open command to WW622; (Surprise 230kV Line)
Open successful

08:09:22 (EMS) APS issued open command to WW1322; (T1 230kV breaker)
Open successful

08:09:51 (EMS) PLX942 closed by SRP; (Hassayampa 525kV Line #1) Energizing the Palo Verde 525kV East bus

08:10:10 (EMS) APS issued open command to WW256; (T1 / NB 525kV crossover breaker)
Open successful

08:10:31 (EMS) HAAX922 closed by SRP; (Palo Verde 525kV Line #2)

08:10:40 (EMS) YU262 closed locally; (Yucca Steam Turbine #1)

08:10:43 (EMS) HAAX925 closed by SRP; (PLX2 / WB 525kV crossover breaker)

08:10:50 (EMS) APS issued close command to WW1222; (Pinnacle Peak 230kV Line)
Execute failure

08:10:55 (EMS) HAAX912 closed by SRP; (Palo Verde 525kV Line #3)

08:11:07 (EMS) HAAX915 closed by SRP; (PLX3 / HQX 525kV crossover breaker)

08:11:14 (EMS) APS issued close command to WW1222; (Pinnacle Peak 230kV Line)
Execute failure

08:11:33 (EMS) HAAX938 closed by SRP; (ALX 525kV Line)
All Hassayampa switchyard breakers now closed

08:11:35 (EMS) PLX972 closed by SRP; (Hassayampa 525kV Line #2)

08:11:53 (EMS) PLX982 closed by SRP; (Hassayampa 525kV Line #3)

08:13:04 (EMS) WP1466 closed locally; (West Phoenix Gas Turbine #2)

08:14:21 (EMS) SG812 closed locally; (Saguaro Gas Turbine #1)

08:14:33 (EMS) PLX912 closed by SRP; (Westwing 525kV Line #1)

08:15:03 (EMS) APS issued close command to WW1252; (Palo Verde 525kV Line #1)
08:15:05.575 Close successful
Fault #4 inception, Fault #4 type = A-B-C-N, Fault #4 cause = Phase down (broken bells) on LBX-WW Line, Fault #1 location = Tower #73 (between Union Hills and Beardsley)
Fault #4 magnitude = Phase A – 10,270 amps; Phase B – 11,130 amps; Phase C – 10,580 amps; Neutral – 258 amps
Note: Westwing 525/230kV Transformers T4 & T10 were on-line and providing fault current for Fault #4.

08:15:05.633 3.5 cycles after fault #4 inception; WW1252 & PLX912 opened (Palo Verde 525kV Line #1)
Fault #4 cleared

08:15:34 (EMS) APS issued open command to WW1052; (T10 525kV breaker)
Open successful

08:15:48 (EMS) APS issued open command to WW1756; (PSX / NB 525kV crossover breaker)
Open successful

08:16:03 (EMS) APS issued open command to WW1652; (Perkins 525kV Line)
Open successful

08:17:39 (EMS) PLX912 closed by SRP; (Palo Verde 525kV Line #1)

08:17:50 (EMS) APS issued close command to WW1252; (Palo Verde 525kV Line #1)
Close successful energizing the Westwing 525kV North bus

08:18:14 (EMS) APS issued open command to WW1622; (Raceway 230kV Line)
Open successful

08:18:22 (EMS) PLX922 closed by SRP; (Westwing 525kV Line #2)

08:18:31 (EMS) APS issued close command to WW1552; (Palo Verde 525kV Line #2)
Close successful

08:19:22 (EMS) SG2312 closed locally; (Saguaro Gas Turbine #2)

08:19:24 (EMS) OC922 closed locally; (Ocotillo Gas Turbine #2)

08:20:55 (EMS) APS issued open command to WW2422; (T14 230kV breaker)
Open successful

08:21:27 (EMS) APS issued open command to WW422; (T4 230kV breaker)
Open successful

08:21:28 (EMS) APS issued close command to WW952; (Yavapai 525kV Line)
Close successful

08:21:36 (EMS) APS issued open command to WW226; (T10 / EB crossover breaker)
Open successful

08:21:38 (EMS) RWP-CT2A closed locally; (Redhawk Combustion Turbine 2A)

08:21:44 (EMS) APS issued close command to YP852; (WW / T3 ring breaker)
Close successful

08:21:44 (EMS) RWP-CT1A closed locally; (Redhawk Combustion Turbine 1A)

08:21:46 (EMS) APS issued open command to WW122; (T10 230kV breaker)
Open successful

08:22:56 (EMS) APS issued close command to NV1052; (Westwing 525kV Line)
Close successful

08:23:13 (EMS) APS issued close command to WW652; (Navajo 525kV Line)
Close successful

08:24:25 (DOE) DOE issued close command to ED4-322; (DOE ED4 Substation)
Close successful

08:24:58 (EMS) WP1666 closed locally; (West Phoenix Gas Turbine #1)

08:25:04 (EMS) APS issued close command to ML1442;
Close successful

08:25:14 (EMS) APS issued close command to ML1042;
Close successful

08:25:25 (EMS) APS issued close command to ML142;
Close successful

08:25:27 (EMS) NV1156 closed locally; (WW / ST3 525kV crossover breaker)

08:25:37 (EMS) APS issued close command to ML542;
Close successful

08:28:30 (EMS) DBN101 closed locally; (Desert Basin Gas Turbine #1)

08:28:57 (EMS) RUX912 closed by SRP; (PLX / T3A ring breaker)

08:29:19 (EMS) RUX915 closed by SRP; (PLX / T1A ring breaker)

08:30:35 (EMS) PLX932 closed by SRP; (Rudd 525kV Line)

08:31:40 (EMS) PLX928 opened by SRP; (Palo Verde X01 Transformer 525kV breaker)

08:31:50 (EMS) APS issued close command to WW256; (T1 / NB 525kV crossover breaker)
Close successful energizing Westwing 525kV South bus, T1 & T4

08:32:29 (EMS0 APS issued close command to WW1322; (T1 230kV breaker)
08:32:33.375 Close successful
Fault #5 inception, Fault #5 type = A-B-C-N, Fault #5 cause = Phase down (broken bells) on LBX-WW Line, Fault #1 location = Tower #73 (between Union Hills and Beardsley), Fault #5 magnitude = Phase A – 13,290 amps; Phase B – 13,780 amps; Phase C – 13,320 amps; Neutral – 409 amps
Westwing 230kV bus voltages (measured phase to neutral) = Phase A – 24,420 volts; Phase B – 22,880 volts; Phase C – 22,380 volts (should be 132,791 volts nominally)

Note: Westwing 525/230kV Transformer T1 was on-line and providing fault current to Fault #5. This is the fault the local media captured on video.

08:32:33.742 22.0 cycles after fault #5 inception; YP452 & YP852 opened (Westwing 525kV Line)

08:32:33.743 22.1 cycles after fault #5 inception; WW952 opened (Yavapai 525kV Line)

08:32:33.749 22.4 cycles after fault #5 inception; MK652 & MK952 opened (Yavapai 525kV Line)

08:32:33.768 23.6 cycles after fault #5 inception; YP252 & YP952 opened (Moenkopi 525kV Line)

08:32:41.100 Fault #5 magnitude = Phase A – 11,210 amps; Phase B – 12,790 amps; Phase C – 12,230 amps; Neutral – 985 amps
Westwing 230kV bus voltage (measured phase to neutral) = Phase A – 45,240 volts; Phase B – 31,950 volts; Phase C – 29,330 volts (should be 132,791 volts nominally).

08:32:46.032 WS562 opened on over-load; (Coconino 69kV Line)

08:32:48 (EMS) RWP-CT1A opened; (Redhawk Combustion Turbine 1A)

08:32:48 (EMS) RWP-CT2A opened; (Redhawk Combustion Turbine 2A)

08:32:51 (EMS) APS issued open command to WW1322; (T1 230kV breaker)
08:32:53.121 19.746 seconds after fault #5 inception;
Open successful
Fault #5 cleared

08:32:55 (EMS) PPE1822 opened; (Pinnacle Peak East 230kV Transfer breaker) Tripped on over-voltage (The over-voltage element is enabled because PPE1822 can spare PPE1622 which is the 230kV Capacitor Bank.) (The PPE1622 relay also had an over-voltage operation at this time but PPE1622 was open.)

08:36:29 (EMS) PLX925 closed by SRP; (WW2 / TX01 525kV crossover breaker) Energizing Palo Verde auxiliary transformer X01

08:36:59 (EMS) PLX948 opened by SRP; (Palo Verde X02 Transformer 525kV breaker)

08:37:03 (EMS) PLX998 opened by SRP; (Palo Verde X03 Transformer 525kV breaker)

08:37:23 (EMS) PLX928 closed by SRP; (Palo Verde X01 Transformer 525kV breaker) Energizing Palo Verde 525kV West bus

08:41:14 (EMS) PLX945 closed by SRP; (HAAX1 / TX02 525kV crossover breaker)

08:41:20 (EMS) RWP-CT2A closed locally; (Redhawk Combustion Turbine 2A)

08:41:39 (EMS) PLX948 closed by SRP; (Palo Verde X02 Transformer 525kV breaker)

08:41:55 (EMS) WW1023 opened locally

08:42:10 (EMS) WW1021 opened locally

08:42:28 (EMS) RWP-CT1A closed locally; (Redhawk Combustion Turbine 1A)

08:43:04 (EMS) FA742 closed; (Fairview Gas Turbine #1)

08:43:10 (EMS) RWP-CT2A opened; (Redhawk Combustion Turbine 2A)

08:44:15 (EMS) WB962 opened on over-load; (White Spar 69kV Line)

08:44:43 (EMS) PLX998 closed by SRP; (Palo Verde X03 Transformer 525kV breaker)

08:44:53 (EMS) APS issued close command to WB962; (White Spar 69kV Line)
Close successful

08:45:16 (EMS) WB962 opened on over-load; (White Spar 69kV Line)

08:46:26 (EMS) APS issued close command to WW1322; (T1 230kV breaker)
Close successful energizing the Westwing 230kV West bus

08:47:06 (EMS) APS issued close command to SC562; (McMicken 69kV Line)
Execute failure

08:47:35 (EMS) APS issued close command to YP452; (WW / T1 525kV ring breaker)
Close successful

08:47:48 (EMS) APS issued close command to WW952; (Yavapai 525kV Line)
Close successful

08:48:59 (EMS) APS issued close command to SC622; (ES / T4 230kV crossover breaker) Execute failure (due to lockout at Surprise Substation)

08:49:56 (EMS) APS issued close command to SC622; (ES / T4 230kV crossover breaker) Execute failure (due to lockout at Surprise Substation)

08:50:28 (EMS) RWP-CT2A closed locally; (Redhawk Combustion Turbine 2A)

08:50:37 (EMS) APS issued close command to SC562; (McMicken 69kV Line) Close successful

08:50:43 (EMS) APS issued close command to WW1622; (Raceway 230kV Line) Close successful

08:50:50 (EMS) APS issued close command to MK652; (NP / YP 525kV ring breaker) Close successful

08:51:09 (EMS) APS issued close command to YP252; (MK / T1 525kV ring breaker) Close successful

08:51:13 (EMS) APS issued open command to MQ162; (Wickenburg 69kV Line) Open successful

08:51:13 (DOE) DOE issued close command to RWYX482; (WAX / WWW 230kV ring breaker) Execute failure

08:51:22 (EMS) APS issued close command to YP952; (MK / WW 525kV ring breaker) Close successful

08:51:27 (EMS) YP952 opened; (MK / WW 525kV ring breaker)

08:51:34 (EMS) APS issued close command to MQ562; (McMicken 69kV Line) Close successful

08:51:59 (DOE) DOE issued close command to RWYX482; (WAX / WW 230kV ring breaker) Close successful

08:52:14 (DOE) DOE issued close command to RWYX582; (WAX / T8 230kV ring breaker) Execute failure

08:52:15 (EMS) APS issued close command to MK952; (FC / YP 525kV ring breaker) Close successful

08:52:59 (EMS) APS issued close command to MQ162; (Wickenburg 69kV Line) Close successful

08:53:09 (EMS) MQ162 opened; (Wickenburg 69kV Line)

08:53:19 (DOE) DOE issued close command to RWYX782; (WW / T8 230kV ring breaker) Execute failure

08:53:43 (EMS) APS issued close command to WW1726; (DV / RWYX 230kV crossover breaker) Close successful

08:53:45 (EMS) APS issued open command to WB162; (Morristown 69kV Line) Open successful

08:53:57 (EMS) APS issued close command to MQ162; (Wickenburg 69kV Line) Close successful

08:54:00 (EMS) APS issued close command to WW1822; (Deer Valley 230kV Line) Close successful energizing the Westwing 230kV East bus

08:55:02 (EMS) APS issued open command to WB562; (Flying E 69kV Line) Open successful

08:55:12 (EMS) APS issued close command to WB162; (Morristown 69kV Line) Close successful

08:55:59 (EMS) APS issued close command to DV722; (PPX / WW 230kV ring breaker) Close successful

08:56:02 (EMS) APS issued close command to FE362; (Eagle Eye 69kV Line) Close successful

08:56:20 (EMS) APS issued close command to WB562; (Flying E 69kV Line) Close successful

08:56:24 (EMS) APS issued close command to DV322; (ALX / WW 230kV ring breaker) Close successful

08:57:02 (EMS) APS issued close command to DV962; (230/69 Transformer #6)
Close successful

08:57:27 (EMS) APS issued close command to WB962; (White Spar 69kV Line)
Close successful

08:57:29 (EMS) WP-CC4-CT closed locally; (West Phoenix Combined Cycle #4 Combustion Turbine)

08:59:14 (EMS) APS issued open command to WW1262; (RIV / T11 69kV ring breaker)
Open successful

08:59:23 (EMS) APS issued open command to WW1662; (RIV / T14 69kV ring breaker)
Open successful

09:00:14 (EMS) RWP-ST2 closed locally; (Redhawk Steam Turbine 2)

09:00:43 (EMS) APS issued close command to WW2026; (T11 / WB 230kV crossover breaker)
No response

09:01:31 (EMS) APS issued close command to WW2026; (T11 / WB 230kV crossover breaker)
No response

09:03:18 (EMS) APS issued close command to WW2026; (T11 / WB 230kV crossover breaker)
No response

09:03:53 (EMS) WP6142 & WP6146 closed locally; (West Phoenix Combined Cycle #1)

09:04:34 (EMS) APS issued close command to WW2122; (T11 230kV breaker)
No response

09:04:53 (EMS) APS issued close command to WW2422; (T14 230kV breaker)
Close successful

09:05:48 (EMS) APS issued close command to WW1662; (RIV / T14 69kV ring breaker)
Close successful

09:06:18 (EMS) APS issued close command to RIV762; (Westwing 69kV Line)
Close successful

09:06:49 (EMS) APS issued close command to WW2122; (T11 230kV breaker)
No response

09:07:01 (EMS) APS issued close command to WW622; (Surprise 230kV Line)
Close successful

09:07:30 (EMS) RWP-ST1 closed locally; (Redhawk Steam Turbine 1)

09:08:39 (EMS) APS issued close command to SC922; (WW / T4 230kV ring breaker)
Execute failure

09:08:56 (EMS) APS issued close command to SC922; (WW / T4 230kV ring breaker)
Execute failure

09:08:57 (EMS) APS issued close command to WW1262; (MCM / T14 69kV ring breaker)
Close successful

09:09:09 (EMS) APS issued close command to WW862; (MCM / T11 69kV ring breaker)
Execute failure

09:09:20 (EMS) APS issued close command to SC1322; (WW / T12 230kV ring breaker)
Execute failure

09:09:34 (EMS) APS issued close command to SC1322; (WW / T12 230kV ring breaker)
Close successful

09:09:36 (EMS) APS issued close command to WW862; (MCM / T11 69kV ring breaker)
Execute failure

09:10:10 (EMS) DBN-ST closed locally; (Desert Basin Steam Generator)

09:14:52 (EMS) APS issued close command to WW752; (WW / T7 525kV breaker)
Close successful

09:14:57 (EMS) WW752 opened; (WW / T7 525kV breaker)

09:16:00 (EMS) APS issued close command to WW856; (YP / T7 525kV crossover breaker)
Close successful

09:16:20 (EMS) APS issued close command to WW752; (WW / T7 525kV breaker)
Close successful

09:17:09 (EMS) APS issued close command to HH762; (Westwing 69kV Line)
Close successful

09:19:11 (EMS) PLX975 closed by SRP (HAAX2 / WB 525kV crossover breaker)

09:19:42 (EMS) APS issued close command to YP852; (WW / T3 525kV ring breaker)
Close successful

09:19:58 (EMS) APS issued close command to YP952; (YP T1 / T3 525kV ring breaker)
No response

09:21:04 (EMS) APS issued close command to YP952; (YP T1 / T3 525kV ring breaker)
Execute failure

09:22:04 (EMS) PSX922 opened by SRP; (Perkins phase-shifter bypass)

09:22:20 (EMS) APS issued close command to WW1756; (NB / PSX 525kV crossover breaker)
Close successful

09:22:54.705 PSX922 closed by SRP (Perkins phase-shifter bypass) (Time stamp provided by SRP)

09:23:04 (EMS) PSX922 opened by SRP: (Perkins phase-shifter bypass)

09:23:44 (EMS) APS issued close command to WS562; (Coconino 69kV Line)
Close successful

09:23:48 (EMS) APS issued close command to WW1652; (Perkins 525kV Line)
Close successful

09:24:15 (EMS) WP6242 & WP6246 closed locally; (West Phoenix Combined Cycle #2)

09:27:10.649 DOE closed MEX1692; (PSX / T1 525kV ring breaker) (Time stamp provided by DOE)

09:27:36 (DOE) DOE closed MEX1092; (PSX / MPX 525kV ring breaker)

09:27:44 (EMS) APS issued close command to PPE1822; (Pinnacle Peak East 230kV transfer breaker)
Close successful

09:30:04 (EMS) PSX832 opened by SRP; (Perkins Cap Bank bypass)

09:32:51 (EMS) APS issued open command to FE362; (Eagle Eye 69kV Line)
Open successful

09:39:01 (EMS) DBN201 closed locally; (Desert Basin Gas Turbine #2)

09:47:21 (EMS) WP-CC4-ST closed locally; (West Phoenix Combined Cycle #4 Steam Turbine)

09:48:05 (EMS) WP6342 & WP6346 closed locally; (West Phoenix Combined Cycle #3)

09:48:58 (EMS) APS issued close command to WW1052; (WW / T10 525kV breaker)
Close successful

09:49:13 (EMS) APS issued close command to WW1156; (WW / T10 PLX1 525kV crossover breaker)
Close successful

09:49:44 (EMS) APS issued close command to WW122; (WW / T10 230kV breaker)
Close successful

09:50:06 (EMS) APS issued close command to WW226; (WW / T10 EB 230kV crossover breaker)
Close successful

09:50:38 (EMS) APS issued close command to WW556; (NV / T4 525kV crossover breaker)
Close successful

09:51:14 (EMS0 APS issued close command to WW422; (WW / T4 230kV breaker)
Close successful

09:52:15 (EMS) APS issued close command to WW526; (WW / T4 SC 230kV crossover breaker)
Close successful

09:59:15 (EMS) RWP-CT1B closed locally; (Redhawk Combustion Turbine 1B)

09:59:17 (EMS) RWYX782 closed by DOE; (WW / T8 230kV ring breaker)

09:59:27 (EMS) PLX910 opened locally; (Palo Verde Unit 1 MOD)

10:00:20 (EMS) RWYX582 closed by DOE; (WAX / T8 230kV ring breaker)

10:02:33 (EMS) PLX915 closed by SRP; (ST1 / WW1 525kV crossover breaker)

10:02:53 (EMS) PLX918 closed by SRP; (ST1 / 525kV breaker)

10:03:38 (EMS) APS issued close command to WW1222; (Pinnacle Peak 230kV Line)
Close successful

10:06:00 (EMS) Westwing Lockout "AK" reset locally; (WW 230/69kV Transformer #11 Differential & B/U Over-Current)

10:07:34 (EMS) Surprise Lockout "L" reset locally; (SC 230/69kV Transformer #4 Differential & B/U Over-Current)

10:08:37 (EMS) APS issued close command to SC622; (ES / T4 230kV ring breaker)
Close successful

10:09:00 (EMS) APS issued close command to SC262; (SC / T4 69kV breaker)
Close successful

10:09:37 (EMS) APS issued close command to WW2122; (WW / T11 230kV breaker)
Close successful

10:09:42 (EMS0 APS issued close command to SC922; (WW / T4 230kV ring breaker)
Close successful

10:10:16 (EMS) APS issued close command to WW2026; (WW / T11 WB 230kV crossover breaker)
No response

10:10:21 (EMS) APS issued close command to WK362; (Westwing 69kV Line)
Close successful

10:10:30 (EMS) APS issued close command to WW2026; (WW / T11 WB 230kV crossover breaker)
Close successful

10:11:25 (EMS) APS issued close command to WW1362; (WW / T11 HH 69kV ring breaker)
Close successful

10:11:40 (EMS) APS issued close command to WW962; (WW / T11 MCM 69kV ring breaker)
Close successful

10:11:59 (EMS) APS issued close command to WW862; (WW / T11 MCM 69kV ring breaker)
Close successful

10:16:45 (EMS) RWP-CT2B closed locally; (Redhawk Combustion Turbine 2B)

10:21:52 (EMS) APS issued close command to WW1456; (PLX2 / SB 525kV crossover breaker)
Close successful

10:32:39 (EMS) PLX980 opened locally; (Palo Verde Unit 3 MOD)

10:37:40 (EMS) PLX985 closed by SRP; (ST3 / HAAX3 525kV crossover breaker)

10:39:33 (EMS) PLX988 closed by SRP; (ST3 525kV breaker)

11:01:53 (EMS) PLX930 opened locally; (Palo Verde Unit 2 MOD)

11:31:12 (EMS) WW1022 opened; (Liberty 230kV Line) Tripped due to low-gas while taking a gas sample for analysis

11:39:47 (EMS) PLX938 closed by SRP; (ST2 525kV breaker)

11:44:37 (EMS) PLX935 closed by SRP; (ST2 / RUX 525kV crossover breaker)

14:30 (approx.) APS System Protection contacted APS Substation Maintenance with suspected cause of failure to trip on WW1022

15:42:19 (EMS) APS issued close command to YP952; (YP T1 / T3 525kV ring breaker)
Close successful (Closing delayed due to breaker problems)

16:00 (approx.) APS Substation Maintenance contacted APS System Protection with confirmation that the failed component was found

17:58:55 (EMS) APS issued close command to WW424J; (Westwing 230kV West Bus Reactor)
Close successful

20:01:27 (EMS) PLX992 closed by SRP; (Devers 525kV Line)

June 15, 2004

16:31:00 (DOE) DOE opened MEX794; (Mead Cap Bank bypass)

June 16, 2004

14:39:00 (DOE) DOE closed ED4-122; (DOE ED4 Substation) (Returned to service after replacing close coil in breaker.)

19:15:37 (EMS) DOE closed LBX1282 (Westwing 230kV Line)

19:16:08 (EMS) APS issued close command to WW1126 (LBX / PPX 230kV cross-over breaker) Close successful returning the Liberty - Westwing 230kV Line to service

19:53:51 (EMS) SRP closed AFX732 (Westwing 230kV Line)

19:54:15 (EMS) SRP closed AFX735 (WW / T4 230kV cross-over breaker)

19:54:39 (EMS) APS issued close command to WW1522 (AFX 230kV Line)
Close successful

19:55:13 (EMS) APS issued close command to WW1426 (AFX / T1 230kV cross-over breaker) Close successful returning the Agua Fria – Westwing 230kV Line to service

June 24, 2004

10:35:09 (EMS) APS closed WW1022 locally (Liberty 230kV Line)

ANALYSIS

The initial event occurred at 07:40:55.747 on June 14, 2004. SRP (the maintenance agent for the Liberty – Westwing line) has concluded that the initiating event was the failure of an insulator at Tower #73 on the Liberty – Westwing 230kV line. An eyewitness reported that they saw a large bird, possibly a heron, take flight from the line shortly before seeing and hearing an arc. SRP surmised that "streaming" from the heron, which is a conductive liquid sometimes discharged prior to flight, got between the phase conductor and the tower causing a flashover. This phenomenon is well documented in IEEE papers (see, for example, J. T. Burnham, Bird Streamer Flashover on FPL Transmission Lines, IEEE Transactions on Power Delivery, Vol. 10, No. 2, April 1995). Digital Fault Recorder (DFR) data subsequently determined that the original fault was C phase to neutral. For the Liberty – Westwing 230kV line, C phase is the top conductor.

During troubleshooting at the Westwing 230kV switchyard, it was noted that breaker WW1022 had remained closed. A sample of the SF_6 gas was requested to be taken from breaker WW1022. During this evolution, sufficient gas was released to actuate the low SF_6 gas trip. It was noted that the breaker tripped upon receipt of the signal. Therefore, troubleshooters concluded that the breaker's mechanism and trip coils were not defective and began further investigation to determine the failure of WW1022 to open. The relay technicians, in concert with Protective Metering and Automated Control engineers traced through the schematic and, after bench testing, confirmed that contacts within the AR relay for the protective scheme of WW1022 had not closed when the fault began on the Liberty - Westwing 230kV line. Because of the failed AR relay, WW1022 did not operate to isolate the line fault, and the signal that WW1022 had not opened ("breaker failure") was also not initiated, since both signals utilized the same contacts.

Numerous structured methods exist to assist root cause evaluators in the investigation of equipment failures and human error events. For this particular investigation, the team utilized a "Barrier Analysis" approach. A Barrier Analysis considers the physical and administrative barriers that should or could have prevented an unwanted event and determines if those barriers were missing or inadequate. A Barrier Analysis has three important elements:

1. Target - This is the item of value that was in harms way

2. Hazard - This is the energy that must be separated from the Target

3. Barriers - The physical entities and/or administrative controls between the Hazard and the Target. Some Barriers

may be ineffective, degraded, or nonexistent.

In defining the "Target" for this evaluation, the "Harm" that was caused was the 525kV system ended up isolating the fault rather than the fault being isolated within the 230kV Westwing switchyard. The "Hazard" is the fault on the Liberty-Westwing 230kV line. The "Target" is the 525kV system. The following failed, degraded, or non-existent Barriers have been identified:

- AR relay for WW1022 failed to actuate;
    - It was determined that two contacts on 94/AR on drawing G-33434 Rev. 9 (contacts 10–1 and 2–3) did not close resulting in the prevention of the Zone 1 fault signal and breaker failure signal from opening WW1022 (Reference G-33451 Rev. 14). The remaining two contacts (4-5 and 6–7) were found to have "made". Therefore, the line fault was not isolated from the Westwing 230kV West Bus. The fault was able to affect the Westwing 525kV switchyard through the 525/230kV transformers.
- Functional testing did not detect the failed AR relay;
    - Functional testing is typically performed to ensure that the relay changes state (open to close and close to open) within the manufacturer's specification. When testing, only one set of contacts have been connected to the timer, as all four contacts are "ganged" together in the operating mechanism and therefore, move together. Typically, contacts 2-3 have been chosen for the test. In the case of WW1022, it is not know if contacts 10-1 have not been closing for some time, or if they failed to close at the same time as contacts 2-3 failed. The last functional test was performed in 2000 and was next due in 2006. It is not known at this time what has caused two of the four contacts to no longer close. Visual observation does not detect any change. The degraded condition was verified through bench testing. The relays will be brought back to ABB Coral Springs, Florida for testing.
- Lack of redundancy in transmitting the necessary tripping signals; and
    - Although the Westinghouse manual describes the AR relay as "well suited for bus arrangements where more than one breaker must be tripped", when the AR relay in question failed, the configuration of the circuitry at the time of the event (Reference drawings G-33410 Rev. 15, G-33434 Rev. 9, G-33451 Rev. 14, and G-33453 Rev. 16) was insufficient to clear the fault within the 230kV system. The event was discussed with the WECC Reliability Subcommittee and it was concluded that no WECC criteria was violated. However, consequences of the event have been reviewed by APS and it has been concluded that defense against single failures should be provided for all 230kV and higher voltage applications. It was also concluded that additional relaying protection should be provided such that faults in lower voltage systems do not result in the clearing of lines in the higher voltage systems.
- Lack of over-current protection on the 525kV transformers.

- Currently, APS does not utilize transformer backup protection on the 525kV to lower voltage transformers. APS does not normally install backup protection on 525kV transformers, reportedly due to past trouble with tripping on inrush current. Had backup protection been installed on the three 525/230kV transformers at Westwing, it is anticipated that the three transformers would have tripped and isolated the fault from the 525kV EHV system.

The investigation has concluded that the root cause was a failure of a Westinghouse AR relay, style number 606B017A09A, manufactured in October, 1974. The AR relay acts as a contact multiplier in the relay protective schemes. For the AR relay in question, it provided contacts for the protective schemes for breakers WW1022 and WW1126. (Reference drawings G-33410 Rev. 15, G-33434 Rev. 9, G-33451 Rev. 14, and G-33453 Rev. 16) As noted in Westinghouse's Installation, Operations, and Maintenance Instructions, "The AR relay is a four-pole auxiliary type relay, especially designed for ultra high speed circuit breaker tripping duty in protective schemes." It further notes that "The AR relay is well suited for bus arrangements where more than one breaker must be tripped."

The current practice, during functional testing of AR relays, does not check the proper operation of all contacts. It is recommended that all future functional testing of all tripping circuits include verification of operation of all contacts, when practicable.

A review of the technical manual currently in use by relay technicians (Westinghouse Installation, Operation, and Maintenance Instruction Manual I.L. 41-759H, September 1978, Type AR High Speed Auxiliary Relay) was compared with the current technical manual (ABB Instruction Leaflet 41-759.2D, May 1999, Type ARS Auxiliary Relay High Speed). Note that the Type ARS relay is composed of one or two Type AR relays. The only difference in the acceptance check or the calibration portions of the manuals was for the contact pressure when the relay is supplied with two normally open and two normally closed contacts. The relays in question have four normally open contacts and the instructions are unchanged.

It is further noted that the relay schemes in question were not single failure proof. An abbreviated review of other protection schemes within the Westwing 525kV yard notes that the bus differential scheme is also three electromechanical relays that are not redundant. Therefore, failure of a single relay, in the presence of the corresponding single phase to ground fault, would require the fault to be cleared by the lines entering the Westwing substation. It is believed that this type of protection exists in other substations within the system. It is recommended that a review of 230kV and higher switchyards be performed to identify all other protection schemes that are vulnerable to single failure consequences.

As an interim corrective action, APS T&D installed redundant AR relays on the two schemes within the Westwing 230kV switchyard that used a single AR to pass trip signals to multiple breakers (WW1022 /WW1126, and WW1726/WW1822). While installing and testing the redundant AR in the WW1726/WW1822 scheme, it was also noted that one contact on the existing AR relay also did not make up. A new relay was installed.

APS has reviewed industry operating experience and determined that the expected failure rate for this type of normally de-energized relay is approximately 0.06 in 1,000,000 hours[1,2]. Current APS T&D

[1] IEEE 500 - 1984, *Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Station*s

[2] WCAP-14129, Revision 2-NP-A, *Reliability Assessment of Westinghouse Type AR Relays Used as SSPS Slave Relays*

practice is to functional test AR relays every six years. However, the focus of the testing has been to assure contact opening and closing speed. As a result, the testing typically only verifies that one set of contacts opens and closes. It has also been noted that typically functional tests are conducted utilizing existing battery charger output voltage rather than 80% of rated battery voltage. The later would ensure that the relays are functional at the minimum battery output voltage. A Doble industry query was sent and it was determined that 83% of responders use the nominal battery voltage. Due to the complexity of testing at reduced voltage, it is not recommended that this enhancement be incorporated.

Industry operating experience and EPIX data was also provided by the Palo Verde Nuclear Generating Station. A review noted no similarities to the failure mechanism present in the Westwing AR relays. (Reference OEs 8495, 9846, and 17957.)

Currently, there are over 100 AR relays used in protective schemes in APS' system. MAXIMO Work Orders have been written to functional check each of the four contacts in each AR relay. In addition, the pickup voltage has also been asked to be recorded.

CORRECTIVE ACTIONS

As corrective actions, APS will:

1. Add redundant AR relays in the protective schemes for the Deer Valley – Westwing 230kV line and the Liberty – Westwing 230kV line (Complete: Reference W219277);

2. Add back-up relaying on the three 525/230kV transformers at Westwing substation (T10 Complete: Reference W220156, T4 Complete: Reference W223285), the two 525/230kV transformers at the Yavapai substation (Complete: Reference W220367), and the 525/69kV transformer at the North Gila substation (Complete: Reference W220372) (note: Westwing transformer T7 already has back-up protection – Reference G-32901, Rev. 11);

3. Functional test all AR relays, installed in relay protective schemes, to ensure each of the four contacts fully close; (Estimated completion date: 12/31/2004)

4. Require that all periodic functional testing ensure that all contacts and elements within tripping circuits, that are practical to access, are tested; (Estimated completion date: 2/28/2005)

5. Return the two failed AR relays to ABB (current product supplier) for bench testing to determine which setting attributes (contact pressure, spring tension, etc.) are no longer in compliance with manufacturer's specifications; (Estimated completion date: October 15, 2004)

6. Review all other protective schemes for switchyards 230kV or higher to determine if they need to be upgraded to prevent single failure consequences (Estimated completion date: 12/31/2004); and

7. Complete upgrades to tripping schemes identified in Action 6. (Estimated completion date: 12/31/2005)

CONCLUSIONS

The root cause of the June 14, 2004 system disturbance was the failure of an AR relay in the protective scheme of breaker WW1022. The relay failure resulted in the breaker not tripping to isolate the fault on the Liberty – Westwing 230kV line. Further, the relay failure also prevented a "breaker failure" signal to be sent that would have isolated the problem within the Westwing 230kV yard. As a result, the fault was sensed by the 525kV system and multiple breakers responded. Failed barriers within protective scheme design and the relay testing program have been identified. Corrective actions to prevent

recurrence have been identified and will be monitored for effectiveness.

LIST OF AR RELAYS FLAGSTAFF SUBSTATIONS					
SUBSTAION	**BREAKER**	**TRIP COILS**	**PANEL**	**DESIGNATION**	**FUNCTION**
COCONINO	CQ462	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ562	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ665	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ666	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ862	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ962	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ1062	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ1162	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ1262	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ1362	N/A	11ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ622	N/A	8ER	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
COCONINO	CQ522	N/A	2WF	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
MOENKOPI	N/A	N/A	7W	94-2/AR	MK-ELD GENERATOR DUMP TO NAVAJO
MOENKOPI	N/A	N/A	7W	94-3/AR	NV-CYX GENERATOR DUMP TO FOUR CORNERS
MOENKOPI	N/A	N/A	7W	94-4/AR	NV-CYX & MK-ELD GENERATOR DUMP TO FOUR CORNERS
MOENKOPI	N/A	N/A	8SF	94/AR	MK-NV GENERATOR DUMP TO NAVAJO
MOENKOPI	N/A	N/A	7SF	94-5/AR	MK-YP GENERATOR DUMP TO NAVAJO
MOENKOPI	MK556	TC-1	3NR	62X/AR1	BREAKER FAIL INITIATE
MOENKOPI	MK556	TC-2	3NR	62Y/AR2	BREAKER FAIL INITIATE
MOENKOPI	MK652	TC-1	3NR	62X/AR1	BREAKER FAIL INITIATE
MOENKOPI	MK652	TC-2	3NR	62Y/AR2	BREAKER FAIL INITIATE
MOENKOPI	MK856	TC-1	4NR	62X/AR1	BREAKER FAIL INITIATE
MOENKOPI	MK856	TC-2	4NR	62Y/AR2	BREAKER FAIL INITIATE
MOENKOPI	MK952	TC-1	4NR	62X/AR1	BREAKER FAIL INITIATE
MOENKOPI	MK952	TC-2	4NR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	N/A	N/A	8NC	94-1/AR	NV-CYX GENERATOR DUMP TO PLANT
NAVAJO	N/A	N/A	8NC	94-2/AR	CYX-MCX GENERATOR DUMP TO PLANT
NAVAJO	N/A	N/A	8NC	94/AR	NV-CYX GENERATOR DUMP TO MOENKOPI
NAVAJO	N/A	N/A	7NC	94/AR-MK	NV-MK GNERATOR DUMP TO PLANT
NAVAJO	N/A	N/A	7NC	94-1/AR-MK	MK-YP GENERATOR DUMP TO PLANT
NAVAJO	N/A	N/A	8NC	94/AR-ELD	MK-ELD GENERATOR DUMP TO PLANT
NAVAJO	N/A	N/A	8NF	94/AR-WW	NV-WW GENERATOR DUMP TO PLANT
NAVAJO	NV1052	TC-1	5SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1052	TC-2	5SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1156	TC-1	5SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1156	TC-2	5SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1156	TC-1	5SR	11TX/AR	TRIP FROM PLANT
NAVAJO	NV1156	TC-2	5SR	12TX/AR	TRIP FROM PLANT
NAVAJO	NV1252	TC-1	5SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1252	TC-2	5SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1252	TC-1	5SR	12TX/AR	TRIP FROM PLANT
NAVAJO	NV1252	TC-2	5SR	11TX/AR	TRIP FROM PLANT
NAVAJO	NV1352	TC-1	6SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1352	TC-2	6SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1456	TC-1	6SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1456	TC-2	6SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1456	TC-1	6SR	14TX/AR	TRIP FROM PLANT
NAVAJO	NV1456	TC-2	6SR	15TX/AR	TRIP FROM PLANT
NAVAJO	NV1552	TC-1	6SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1552	TC-2	6SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1552	TC-1	6SR	15TX/AR	TRIP FROM PLANT

NAVAJO	NV1552	TC-2	6SR	14TX/AR	TRIP FROM PLANT
NAVAJO	NV1652	TC-1	7SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1652	TC-2	7SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1756	TC-1	7SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1756	TC-2	7SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1756	TC-1	7SR	17TX/AR	TRIP FROM PLANT
NAVAJO	NV1756	TC-2	7SR	18TX/AR	TRIP FROM PLANT
NAVAJO	NV1852	TC-1	7SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV1852	TC-2	7SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV1852	TC-1	7SR	18TX/AR	TRIP FROM PLANT
NAVAJO	NV1852	TC-2	7SR	17TX/AR	TRIP FROM PLANT
NAVAJO	NV2056	TC-1	8SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV2056	TC-2	8SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV2056	TC-1	8SR	20TX/AR	TRIP FROM PLANT
NAVAJO	NV2056	TC-2	8SR	21TX/AR	TRIP FROM PLANT
NAVAJO	NV2152	TC-1	8SR	62X/AR1	BREAKER FAIL INITIATE
NAVAJO	NV2152	TC-2	8SR	62Y/AR2	BREAKER FAIL INITIATE
NAVAJO	NV2152	TC-1	8SR	21TX/AR	TRIP FROM PLANT
NAVAJO	NV2152	TC-2	8SR	20TX/AR	TRIP FROM PLANT
ROUND VALLEY	RV822	ONE TRIP COIL	4N	94AR	TRANSFER TRIP RECEIVE FROM SELIGMAN
SANDVIG	SV562	N/A	8B	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
SANDVIG	SV962	N/A	7B	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
WILLOW LAKE	WL722	TC-1	4N	62X/AR	BREAKER FAILE INITIATE

LIST OF AR RELAYS CHOLLA SUBSTATIONS					
SUBSTATION	**BREAKER**	**TRIP COILS**	**PANEL**	**DESIGNATION**	**FUNCTION**
CHOLLA	CH842	N/A		8TXAR	TRIP FROM 345 YARD
CHOLLA	CH1242	N/A		12TX/AR	TRIP FROM 345 YARD
CHOLLA	CH1342	N/A		13TX/AR	TRIP FROM 345 YARD
CHOLLA	CH762	N/A	10NR	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
CHOLLA	CH962	N/A	10NR	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
CHOLLA	CH1062	N/A	10NR	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
CHOLLA	CH1162	N/A	10NR	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
CHOLLA	CH1262	N/A	10NR	SBF-1 RELAY	BREAKER FAIL RELAY TRIPS LOCKOUTS
CHOLLA	CH222	TC-1 TC-2 NA			
CHOLLA	CH322	TC-1 TC-2 NA			
CHOLLA	CH522	TC-1 TC-2 NA			
CHOLLA	CH622	TC-1 TC-2 NA			
CHOLLA	CH822	TC-1 TC-2 NA			
CHOLLA	CH1222	TC-1 TC-2 NA			
CHOLLA	CH132	TC-1 TC-2	3S 4S	AR AR	POTT AUX PLC POTT AUX MW
		TC-1 TC-2	3S	94/FC1 AR	BREAKER TRIP
		TC-1 TC-2	5SR	94/TT FC1	RECEIVE TRANSFER TRIP FROM FOUR CORNERS
		NA	4S	FC1/AR1 FC1/AR2	FOUR CORNERS DROP KEYING
		TC-1 TC-2	3S	62X/86X 62Y/86Y	BREAKER FAIL INITIATE FC UNIT DROP KEYING
		TC-1	4S	SBF-1 RELAY	RETRIP BREAKER TRIP LOCKOUT
CHOLLA	CH332	TC-1 TC-2 NA	1S	3TX/AR	TRIP FROM 500 YARD LOCKOUTS
CHOLLA	CH532	TC-1 TC-2 NA	11S 12S	MW AR PLC AR	POTT AUX MW POTT AUX PLC
			11S	FC2/AR1 FC2/AR2	FOUR CORNERS DROP KEYING
			5SR	94TT/FC2	RECEIVE TRANSFER TRIP FROM FOUR CORNERS
			11S	SBF-1 RELAY	TRIPS LOCKOUT
CHOLLA	CH632	TC-1 TC-2 NA			
CHOLLA	CH732	TC-1 TC-2	4SR	62X/86X 62Y/86Y	BREAKER FAIL INITIATE
		TC-1	4SR	SBF-1 RELAY	RETRIP BREAKER TRIP LOCKOUT
CHOLLA	CH832	TC-1 TC-2	1N	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
CHOLLA	CH932	TC-1 TC-2	8S	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
			9S	T/AR	FOUR CORNERS DROP KEYING
		TC-1 TC-2	9S	T/AR1 T/AR2	FOUR CORNERS DROP KEYING
		TC-1 TC-2	8S	9TX1 9TX2	TRIP FROM 500 YARD LOCKOUTS

CHOLLA	CH1032	TC-1 TC-2	2S	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1 TC-2	2S	10/TX1 10/TX2	TRIP FROM 500 YARD LOCKOUTS
CHOLLA	CH152	TC-1 TC-2	1NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
CHOLLA	CH256	TC-1 TC-2	1NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	1NR	2TX/AR	TRIP FROM 345 YARD
CHOLLA	CH352	TC-1 TC-2	2NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	2NR	3TX/AR	TRIP FROM 345 YARD
CHOLLA	CH452	TC-1 TC-2	2NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	2NR	4TXG/AR	TRIP FROM PLANT
CHOLLA	CH556	TC-1 TC-2	3NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	3NR	5TXG/AR	TRIP FROM PLANT
		TC-1	3NR	5TX/AR	TRIP FROM 345 YARD
CHOLLA	CH652	TC-1 TC-2	3NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	3NR	6TX/AR	TRIP FROM 345 YARD
CHOLLA	CH1052	TC-1 TC-2	5NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
CHOLLA	CH1156	TC-1 TC-2	6NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	6NR	11TXG/AR	TRIP FROM PLANT
CHOLLA	CH1252	TC-1 TC-2	6NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	6NR	12TXG/AR	TRIP FROM PLANT
CHOLLA	CH1456	TC-1 TC-2	6NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	6NR	14TXG/AR	TRIP FROM PLANT
CHOLLA	CH1552	TC-1 TC-2	7NR	62X/AR1 62Y/AR2	BREAKER FAIL INITIATE
		TC-1	7NR	15TXG/AR	TRIP FROM PLANT

Total Identified AR Relays in the Metro Area		
Substation	**Function**	**No. of Relays**
Cactus	230kv OC Line (3 relays)	3
Cactus	230kv PP Line (3 relays)	3
Deer Valley	230kv WW Line	1
Lincoln Street	LS 322 L1	1
Lincoln Street	LS 322 L2	1
Lincoln Street	LS 622 L1	1
Lincoln Street	LS 622 L2	1
Lincoln Street	LS 822	1
Ocotillo 230	OC 322 L1	1
Ocotillo 230	OC 322 L2	1
Ocotillo 230	OC 422 L1	1
Ocotillo 230	OC 422 L2	1
Ocotillo 230	OC1122	1
Pinnacle Peak 230	PP 122 L1	1
Pinnacle Peak 230	PP 122 L2	1
Pinnacle Peak 230	PP1122	1
Sunnyslope	230kv ME Line L1	1
Sunnyslope	230kv ME Line L2	1
West Phoenix	230/69 #14 Xfmr	1
West Phoenix	230/69 #16 Xfmr	1
Westwing	230kv Deer Valley Line	2
Westwing	230kv DOE Liberty Line	2

Substation	**Breaker**	**Trip Coils**	**Panel**	**Designation**	**Function**
Cocopah	CY362 & CY1142	N/A	6B	94-1/AR	Yucca Line
Cocopah	CY362 & CY342	N/A	7B	94-2/AR	10th Street Line
North Gila	NG556	N/A	5B	SBF-1	Breaker Failure
North Gila	NG652	N/A	6B	SBF-1	Breaker Failure
North Gila	NG856	N/A	8B	SBF-1	Breaker Failure