Analysis of Undervoltage Load Shedding Event at Philadelphia, Mississippi

Meyer Kao
Tennessee Valley Authority

Gary Kobet
Tennessee Valley Authority

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Abstract

This paper describes a voltage collapse event that occurred on August 4th, 2003 in TVA's Philadelphia, Mississippi service area. During this one hour event, which included three voltage collapse events (and a few near misses close to the edge), the 161kV bus voltage at TVA's Philadelphia substation swung from 98kV to 192kV. This 300MVA load area is fed by three 161kV source lines. One line was out for maintenance when another line faulted. This began the chain of events that led to a fast voltage collapse. Undervoltage load shedding relays subsequently operated and dropped 170MVA of load. Bus voltages then overshot, up to 120% of nominal, due to excessive reactive support from the capacitor banks. A sequence of event (SOE) recorder and digital fault recorders were used to analyze this extended event. Solutions and recommendations were submitted to the operating organization to prevent future undervoltage events.

This paper will present the chronological event of the voltage collapse in the Philadelphia MS area. This paper will also address the decisions that were made leading to the vulnerable position, and ultimately voltage collapse. Subsequent recommendations and solutions were proposed to prevent future occurrences of these type events.

Introduction

The Tennessee Valley Authority (TVA) is the largest public power producer in the United States. TVA has over 30,000 megawatts of generation, providing electrical power to the Tennessee Valley service area spanning over portion of seven states. TVA owns over 17,000 miles of transmission line covering over 80,000 square miles. All of the generation, interchange of power, and system dispatching are coordinated and controlled from Chattanooga, TN. The operation and maintenance of TVA's transmission system are divided into 15 geographical offices.

Background

Back in the late 1970s, TVA's Mississippi service area was identified as one load center that could experience a voltage collapse under certain contingencies. The West Point, Mississippi service area (which includes Philadelphia) is mostly a load area with the nearest base load generation more then 100 miles away. It is due to the lack of dynamic real and reactive support in this area that would lead to the voltage collapse under certain contingency. For the loss of the 500/161/13kV intertie bank at West Point 500 kV substation, there was a high probability of voltage collapse during severe loading condition. See figure 1 for the system configuration in the West Point Mississippi area.

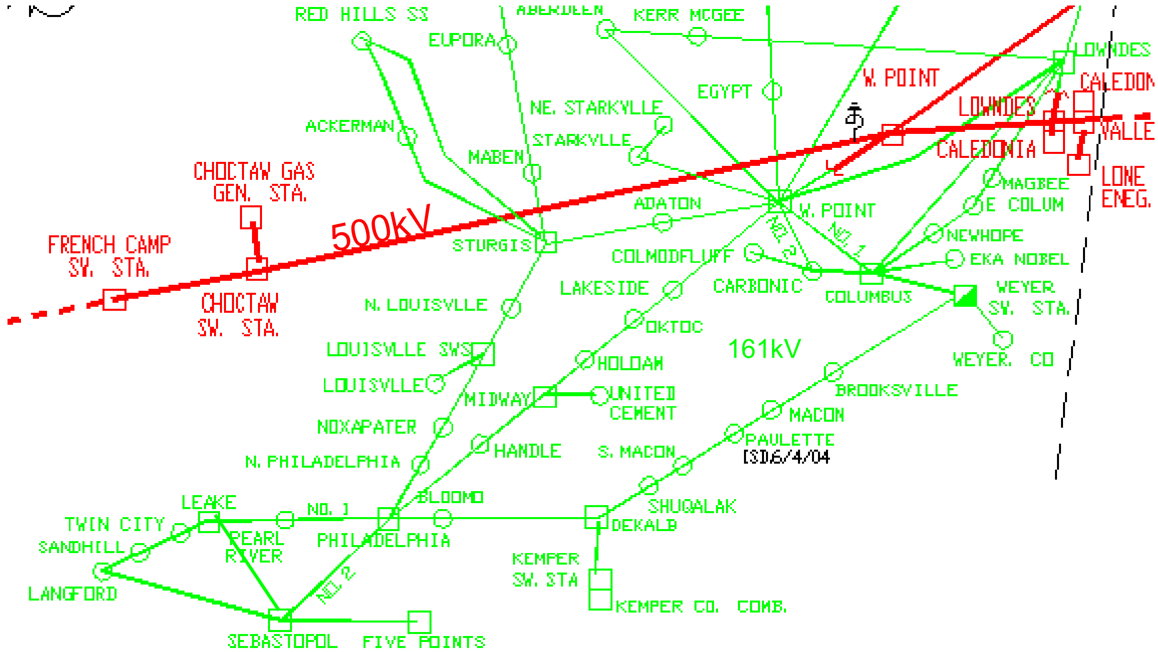


Figure 1 - West Point MS Service Area

An undervoltage load shedding (UVLS) scheme was implemented to prevent a total blackout in this load area and preserve some vital loads. The relays were installed to trip the same auxiliary relays/loads tripped by the existing underfrequency load shedding relaying. UVLS is in service at the substations listed in the Table 1 below:

Table 1 - Undervoltage Load Shedding Settings

Substation	Volts	% of Nominal	Steps	Cycles	Trips	Approximate load
West Point	103	87%	Dev 62LS-1	45	Switches both 161kV cap banks on	168MVAR
			Dev 62LS-2	NO LONGER USED		
			Dev 62LS-3	75	46kV and 13kV load	78MW
Columbus	103	87%	Dev 62LS-1	60	Chemical plant	160MW
			Dev 62LS-2	90	46kV and 13kV load	60MW
East Columbus	103	87%	Dev 62LS-1	105	69kV load	79MW
Dekalb	103	87%	Dev 62LS-1	105	46kV feeders	52MW
Louisville	103	87%	Dev 62LS-1	105	161kV feeders	37MW
Philadelphia	103	87%	Dev 62LS-1	90	161kV radial load	150MW
			Dev 62LS-2	105	46kV and 13kV load	56MW
Sturgis	103	87%	Dev 62LS-1	105	69kV load	6MW

The time delay of 45 to 105 cycles is necessary to prevent false operation for faults on the 161 kV lines. Time delays coordinate with zone 2 and zone 3 of the distance relays on the 161 kV line terminals. (Further details concerning the design of the scheme can be found in reference 2.)

It should be noted that the problem for which the scheme was installed (loss of the West Point 500/161kV intertie bank) was largely solved with the installation of a second 500/161kV intertie bank at Lowndes Substation, north of Columbus, Mississippi. However, it was decided that the UVLS scheme should remain in-service for the case where both intertie banks were out of service. Admittedly, this should be a rare double contingency occurrence. But, as this paper demonstrates, there were other benefits of the scheme that were unforeseen.

Sequence of Events

A sequence of events (SOE) has been included as an appendix. It is recommended the reader use this SOE, with the single-line diagram provided on the next page, to grasp the events that took place. The following discussion is ordered using the main headers in the SOE:

Outline

- Preliminary events 8/2 through 8/3
    - Recurring fault on Dekalb-Weyerhaeuser 161kV line
    - Scheduled outage on Louisville-Noxapater 161kV line section
- Initial Voltage Collapse 8/4
- First Operator Intervention; Second Voltage Collapse
- Second Operator Action; Third Voltage Collapse
- Third Operator Action; Fourth Voltage Collapse
- Fourth Operator Action; Fifth Voltage Collapse
- Load Restoration
- Area Transmission System Restoration
- Cause of Fault Located on Dekalb-Shuqualak 161kV line section

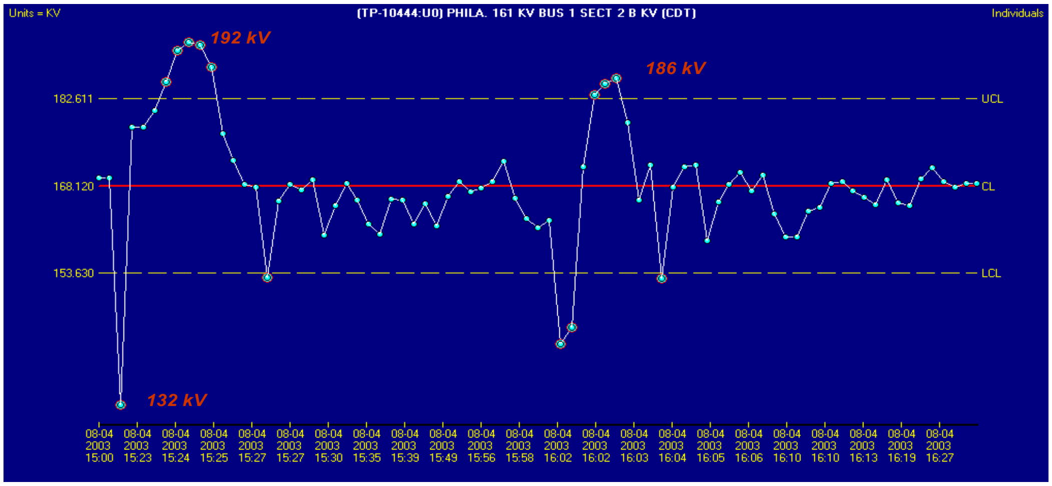
Discussion that follows will follow the outline. Conclusions are provided at the end of the paper.

The voltage profile of the Philadelphia 161kV bus over the entire sequence is shown in Figure 2.

Preliminary Events

Figure 3 shows a simple single line diagram of the area of interest. The Sturgis, West Point, and Columbus buses are sources. The Kemper plant connected to Dekalb has approximately 400MVA worth of gas turbine peaking generation. It is important to note that the plant was off-line on the day of the disturbance. The remaining buses are strictly load buses.

Philadelphia Bus Voltage Profile
8/04/2003 15:00:00 – 18:00:00



Data sampled at every 4 seconds
Actual voltage collapses are more severe

Figure 2 - Philadelphia 161kV Bus Voltage 8-4-2003 1500-1800

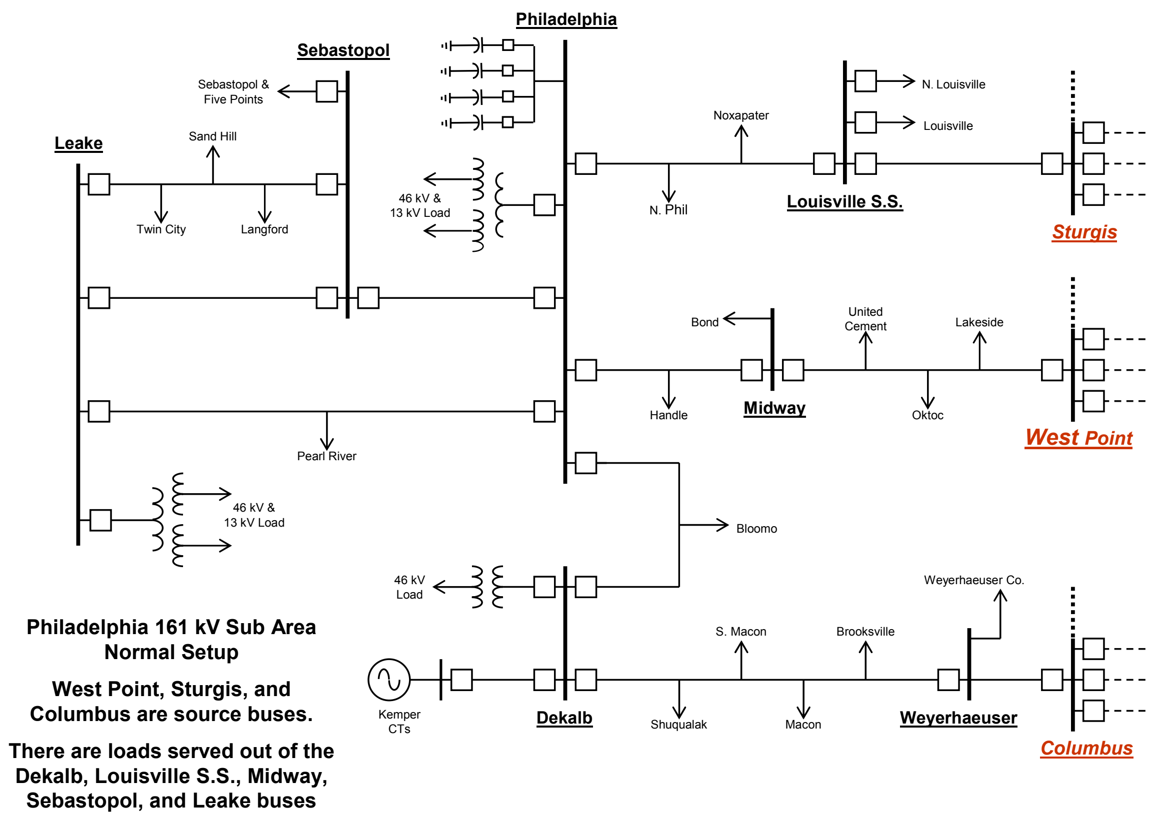


Figure 3 - Philadelphia Area Transmission System

On Saturday, August 2, 2003, at 18:23:38, an A-phase-to-ground fault occurred on the Dekalb-Weyerhaeuser 161kV line. The fault was successfully cleared in about 4 cycles, and automatic reclosing was successful. The same fault (verified by digital fault recorder (DFR) shots) recurred at 18:26:42, again with successful automatic reclosing (reclosing reset timers are set for 90 seconds). Since these were only momentary interruptions to the tap stations, the transmission operator recorded both operations in the log, planning to call the field line crew in Monday morning to inspect the line.

On Sunday, August 3, 2003, at 15:58:36, the same A-phase-to-ground fault recurred. This time, however, all three attempts at automatic reclosing failed, and the line terminal breakers locked out. The third attempt was part of a line sectionalizing scheme, with the motor operated disconnect (MOD) on the Weyerhaeuser side of South Macon tap open. The system dispatcher attempted a remote test close, which was unsuccessful. Each load tap has disconnect switches on either side of the tap. The line crew from West Point was dispatched. At Shuqualak, the line crew opened the disconnect on the Weyerhaeuser side of the tap. The system dispatcher successfully tested the line from Dekalb. Since the fault was intermittent and since the line section between Shuqualak and South Macon tap was isolated, the logical conclusion was that the fault must be between the isolated section or on the South Macon tap itself. The dispatcher then remotely opened the MOD on the Dekalb side of the South Macon tap and closed the MOD on the other side of the tap. The system dispatcher then successfully closed the breaker at Weyerhaeuser picking up all the taps on the line. The line crew inspected the 5+ miles section of this line and (correctly) could not find the problem. This section was then later placed back in to service to tie through this line back to the source bus.

Initial Voltage Collapse; Recurring Fault on Dekalb-Weyerhaeuser

On August 4th, there was a scheduled outage for the line section between the Louisville Switching Station and the Noxapater tap. The purpose of the outage was to replace a couple of old wood poles in a swampy area. This pre-arranged outage was approved for the morning four (4) hour period. A special crane was brought in for this purpose. There is only one crane of this type in the TVA's west area and its usage has to be coordinated between field offices. The chief dispatcher had been on vacation over the weekend and was unaware of the disturbances the 2 prior days. With this outage, only 2 source lines were left feeding approximately 290 MVA of load. Of this 290MVA, Table 2 shows the loads affected by this disturbance.

Table 2. Loads Affected by Disturbance

Element(s)	MW	MVAR	MVA
Philadelphia breakers 888 & 944	116	18	118
Philadelphia 46 & 13kV yard	30	7	31
Dekalb breakers 424 & 444	20	6	21
Taps on Weyerhaeuser-Dekalb 161kV line	38	6	39
TOTAL	204	37	207

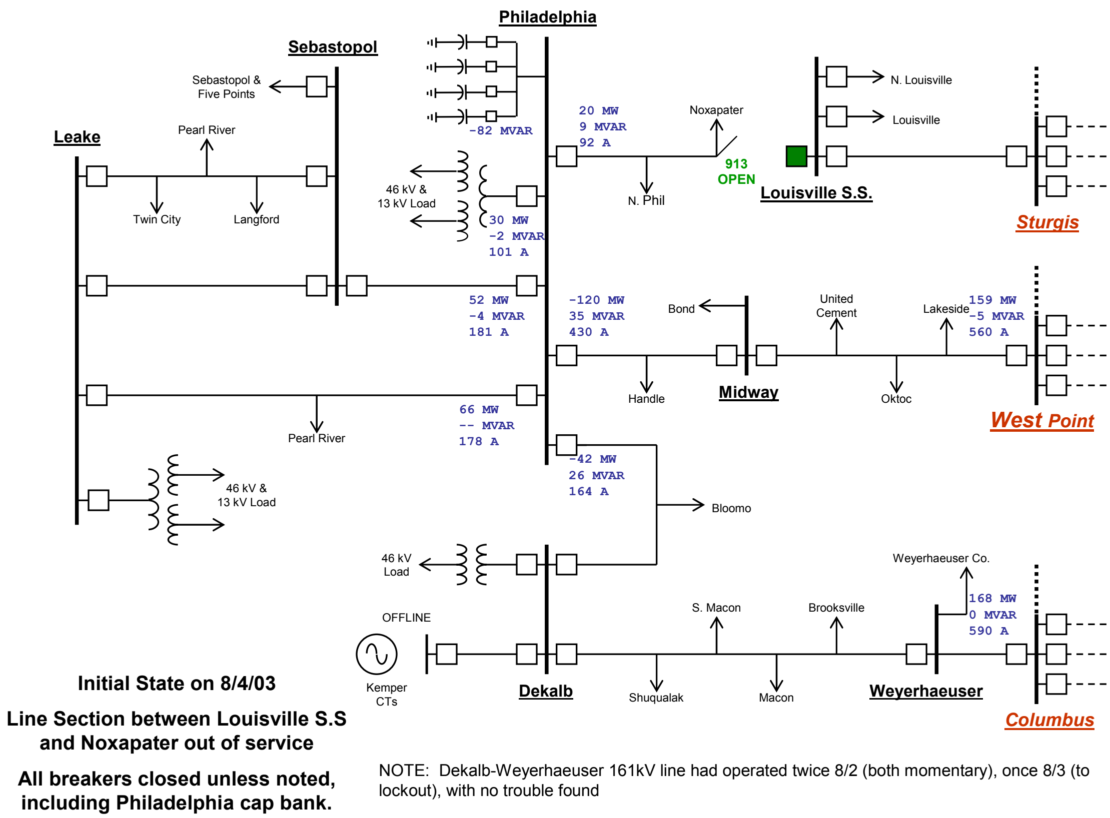


Figure 4 - Louisville S.S to Noxapater Section Out. Loading at 8-4-03, 15:00

Prior to the initial fault, all four 161 kV capacitor banks (total about 80MVAR) at Philadelphia were switched on and in manual control. Kemper generation was offline.

After learning of the events of the previous two days, and receiving a fault location from System Protection & Analysis that the fault was actually between Dekalb and Shuqualak, the chief dispatcher requested the field line crew perform an aerial inspection of the Dekalb-Shuqualak line section.

At 15:22:49, the same fault that had occurred the 2 prior days returned. The line crew reportedly saw the flash and thought lightning had struck the line. Breakers at Dekalb and Weyerhaeuser tripped to clear this fault. At this point, the line from West Point substation was the only source line feeding the all the load. Prior to the first reclosing at Dekalb's Weyerhaeuser breaker, the loading on the Philadelphia's Midway/West Point breaker was -197 MW+j95 MVAR.

The first reclose attempt at Dekalb on the Weyerhaeuser breaker was a blind reclose 1.5 seconds after the initial trip. In closing this breaker, 4 tap loads, Shuqualak, South Macon, Macon, and Brooksville are being picked up. Figures 5 and 6 show the Philadelphia 161kV bus voltage and Dekalb 161kV line currents at Philadelphia. Figures 7 and 8 show the Dekalb 161 kV bus voltage and Weyerhaeuser line currents at Dekalb.

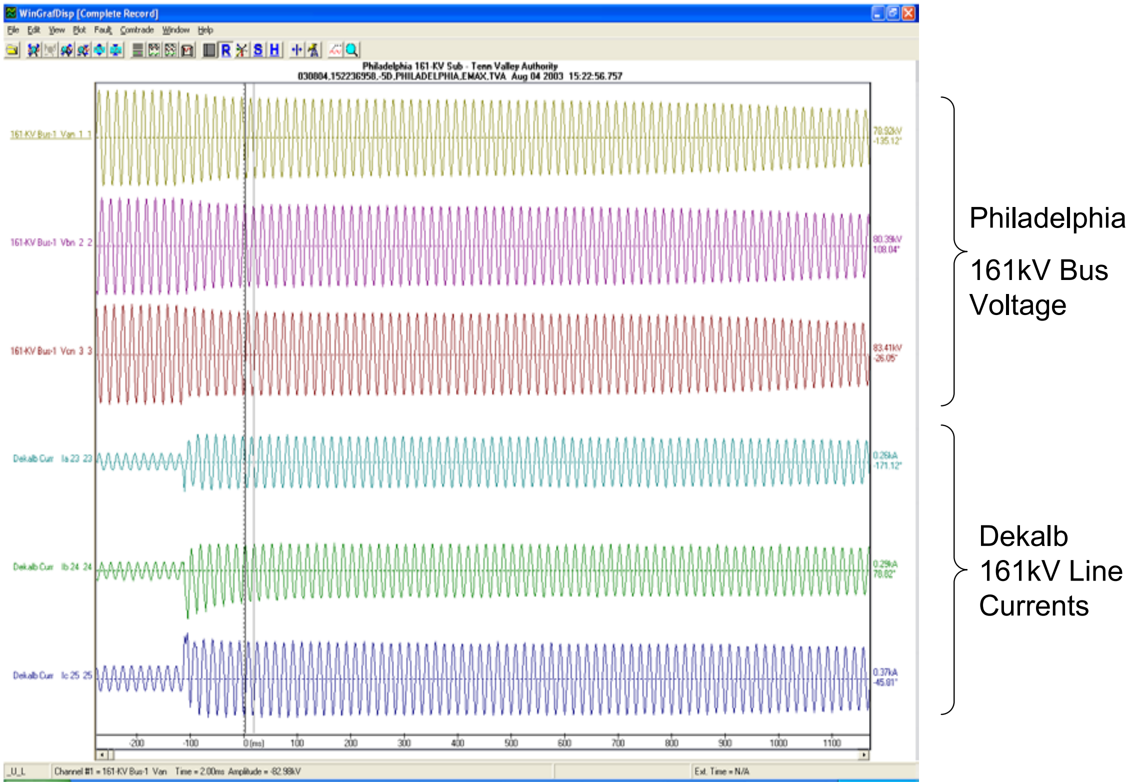


Figure 5 - Philadelphia Substation 161kV Bus Volts and Dekalb Line Current

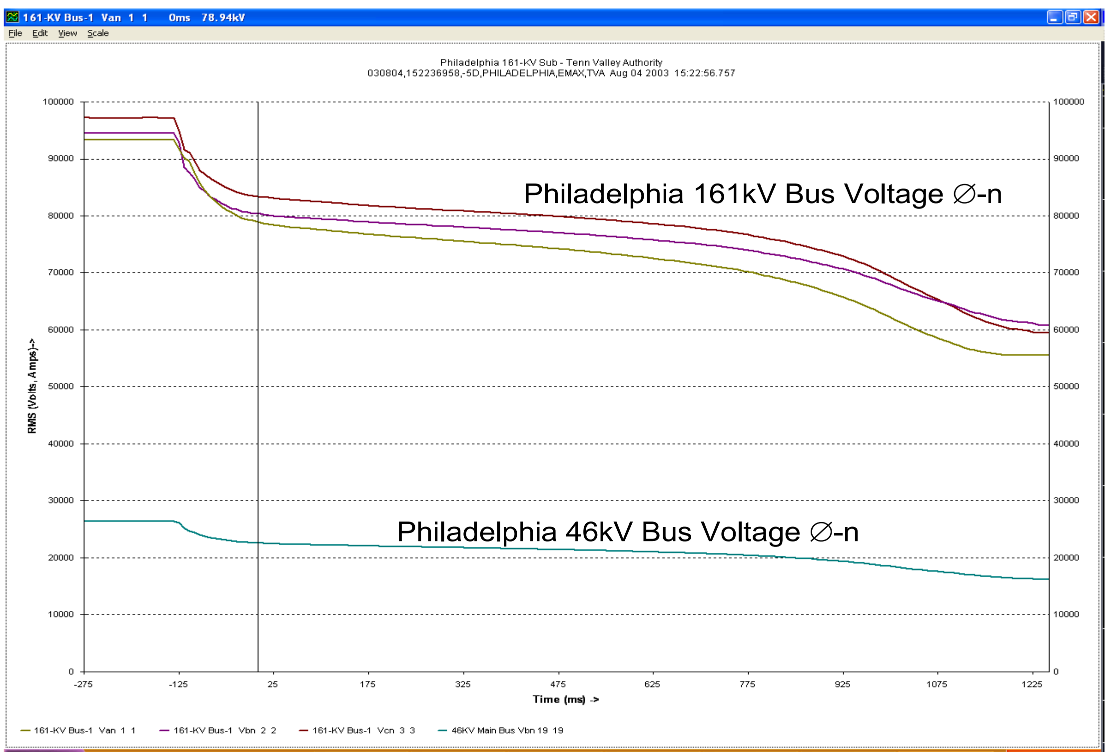


Figure 6 - Philadelphia Substation 161 kV and 46 kV Bus RMS Volts

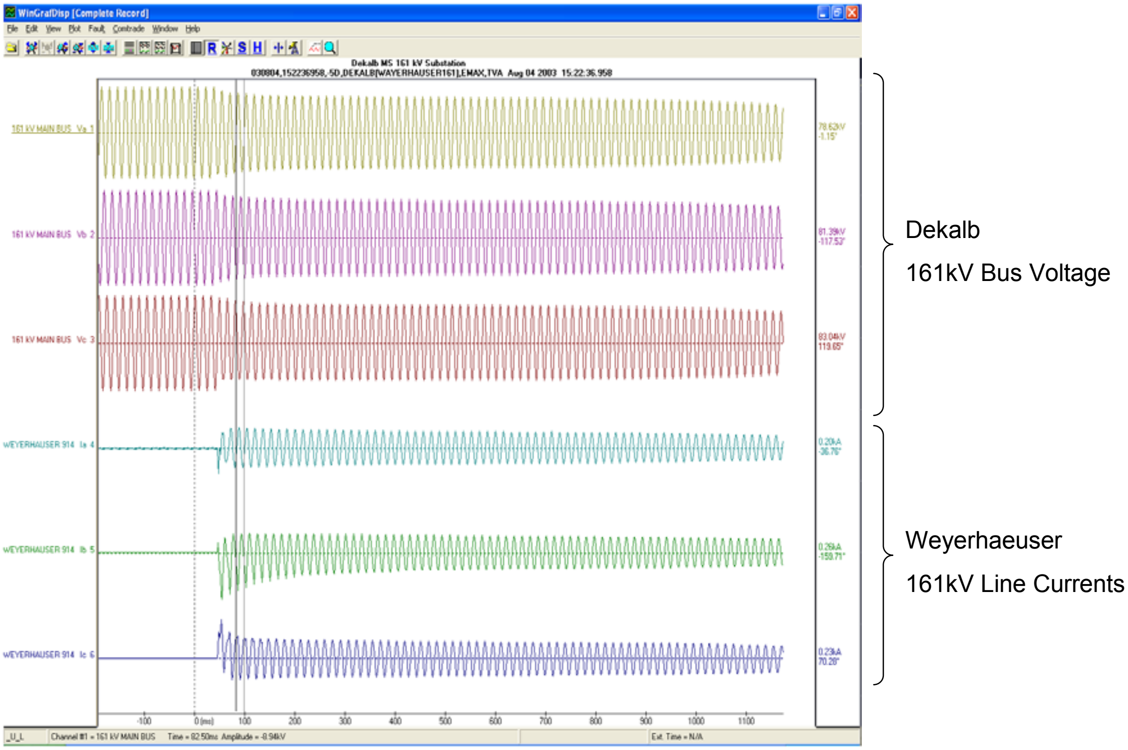


Figure 7 - Dekalb Substation 161 kV Bus Volts and Weyerhaeuser Line Current

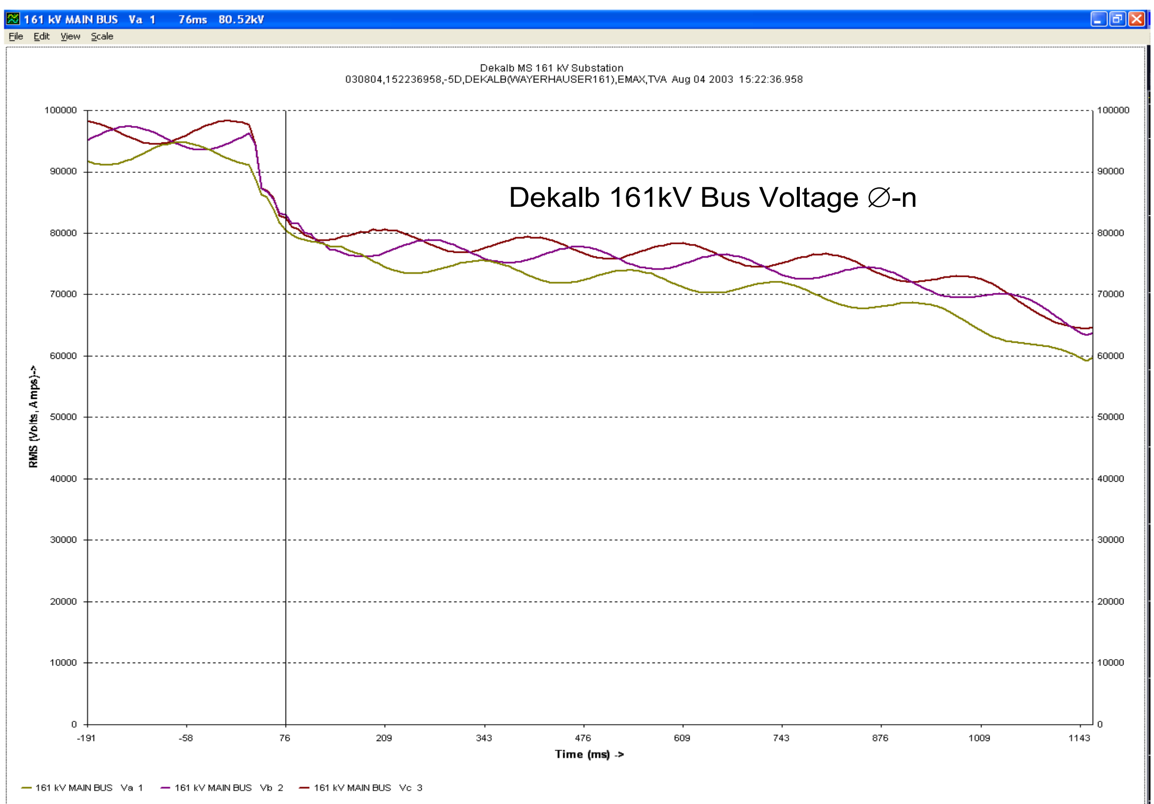


Figure 8 - Dekalb Substation 161 kV Bus RMS Volts

The closing of the breaker at Dekalb evidently caused this rapid voltage collapse at the Philadelphia and Dekalb substation. From the Dekalb DFR, the initial inrush measured to be about 42 MW and 36 MVAR. Loads typically consist of static loads, induction motors, thermostatic loads, discharge lighting, and other load components. Static loads are of normal lighting, solid state loads, appliances, etc. The real and reactive components of this type of loads are generally voltage dependent. Thermostatic loads are consisted of water heaters, space heaters, etc, and will still operate during low voltage condition. Discharge lighting loads will extinguish during low voltage conditions. Induction motor loads are the most dominant percentage of total loads, up to 85% of all loads. Examples are fans, pumps, compressors, etc. When the voltage sags below 0.9 pu, some induction motors will start to stall and draw very high amounts of reactive power.

It is suspected that when the breaker at Dekalb picked up the four tap loads on the Dekalb-Weyerhaeuser line, the excessive reactive demand from the induction motors caused this voltage collapse. Since this load center is far from any generation and only one transmission is feeding all the Philadelphia Mississippi loads, the transmission system was not able to meet this reactive demand.

From Table 1, there are 2 stages of under voltage load shedding at Philadelphia, one at 90 cycles, the second one at 105 cycles. At Dekalb, there is one stage, set to operate at 105 cycles. Figures 9 and 10 show the recovery of the bus voltage at Philadelphia and Dekalb. Even with staged shedding of load, the bus voltage at either substation was not able to recover fast enough to avoid the second stage. We also can see that the voltage at Philadelphia 161 kV bus dipped down to about 98 kV Ø-Ø, or about 0.61 pu, before the load shedding operated. With the reduced load, the 161 kV bus settled to 154 kV Ø-Ø, or about 0.96 pu. The Dekalb 161 kV bus dipped below 95 kV-Ø-Ø, 0.59 pu, before the load shedding relay operated. With the reduced load the Dekalb 161 kV bus settled to about 148 kV Ø-Ø, 0.92 pu. Again, even with reduced load, the bus voltages at Philadelphia and Dekalb were still depressed.

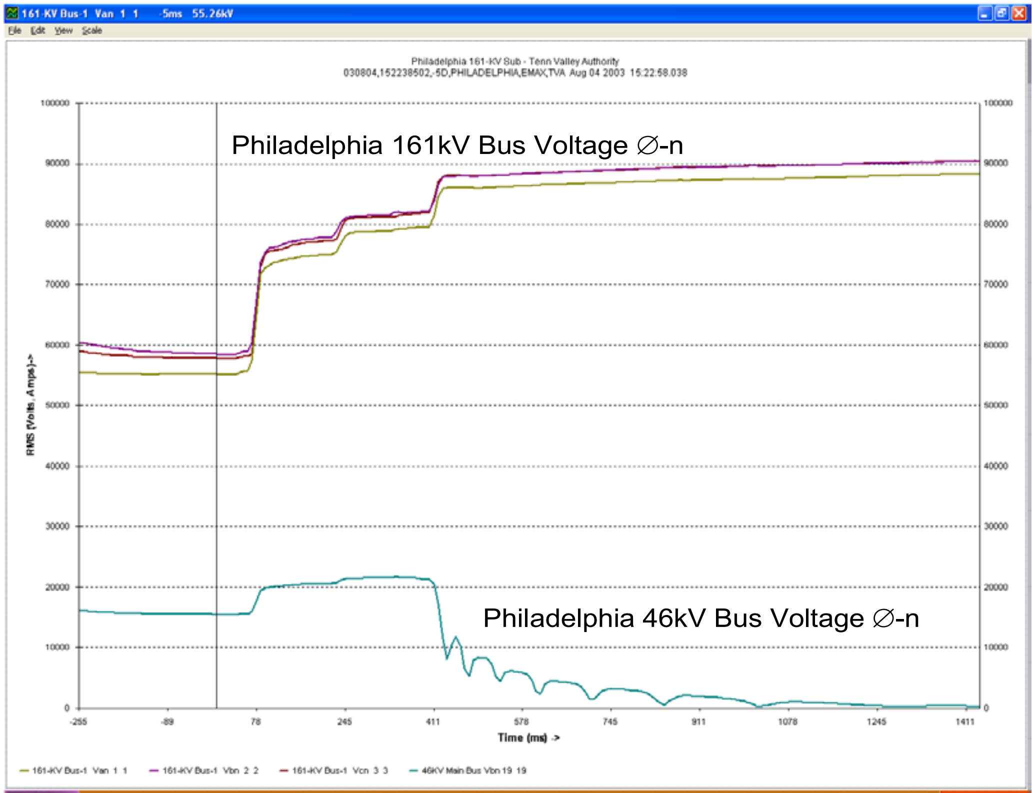


Figure 9 - Philadelphia Substation 161 and 46 kV Bus RMS Volts after Load Shed Operation

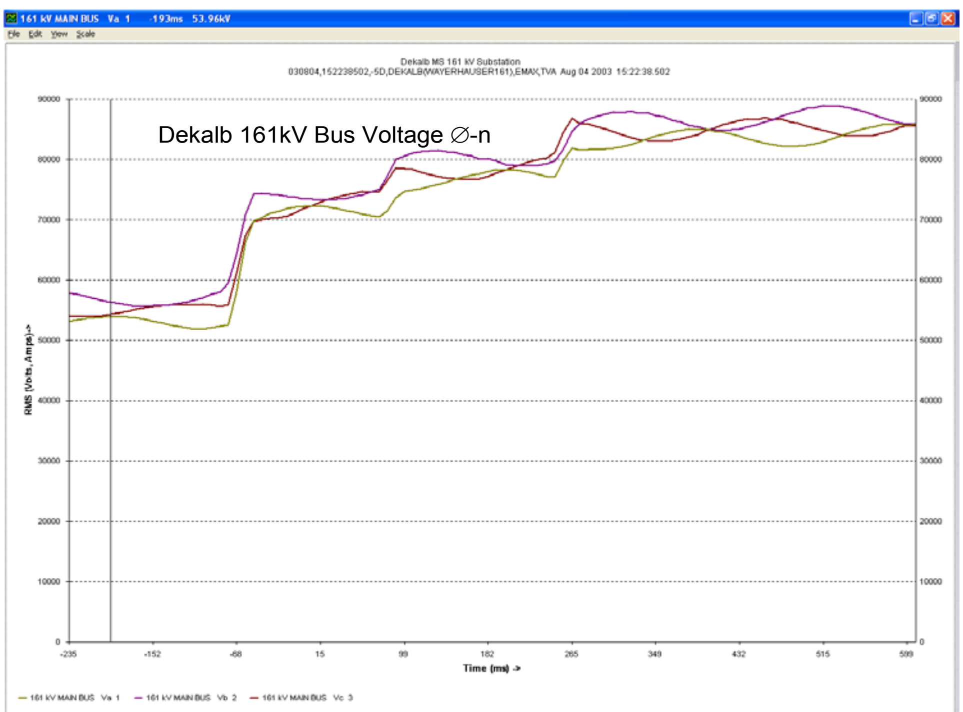


Figure 10 - Dekalb Substation 161 kV Bus RMS Volts after Load Shed Operation

It is instructive at this point to check the zone 3 relay element at Philadelphia on the Midway terminal. This terminal has redundant relaying, one microprocessor relay and one set of electromechanical relays. Both sets are in three-zone step distance schemes. Since each line terminal at Philadelphia has two sets of line protection, and each 161kV breaker has a breaker failure relay, the need for a zone 3 element is questionable. However, it has been TVA's practice to continue setting zone 3 as a reverse element in case of breaker failure. The zone 3 characteristics are shown in Figure 11:

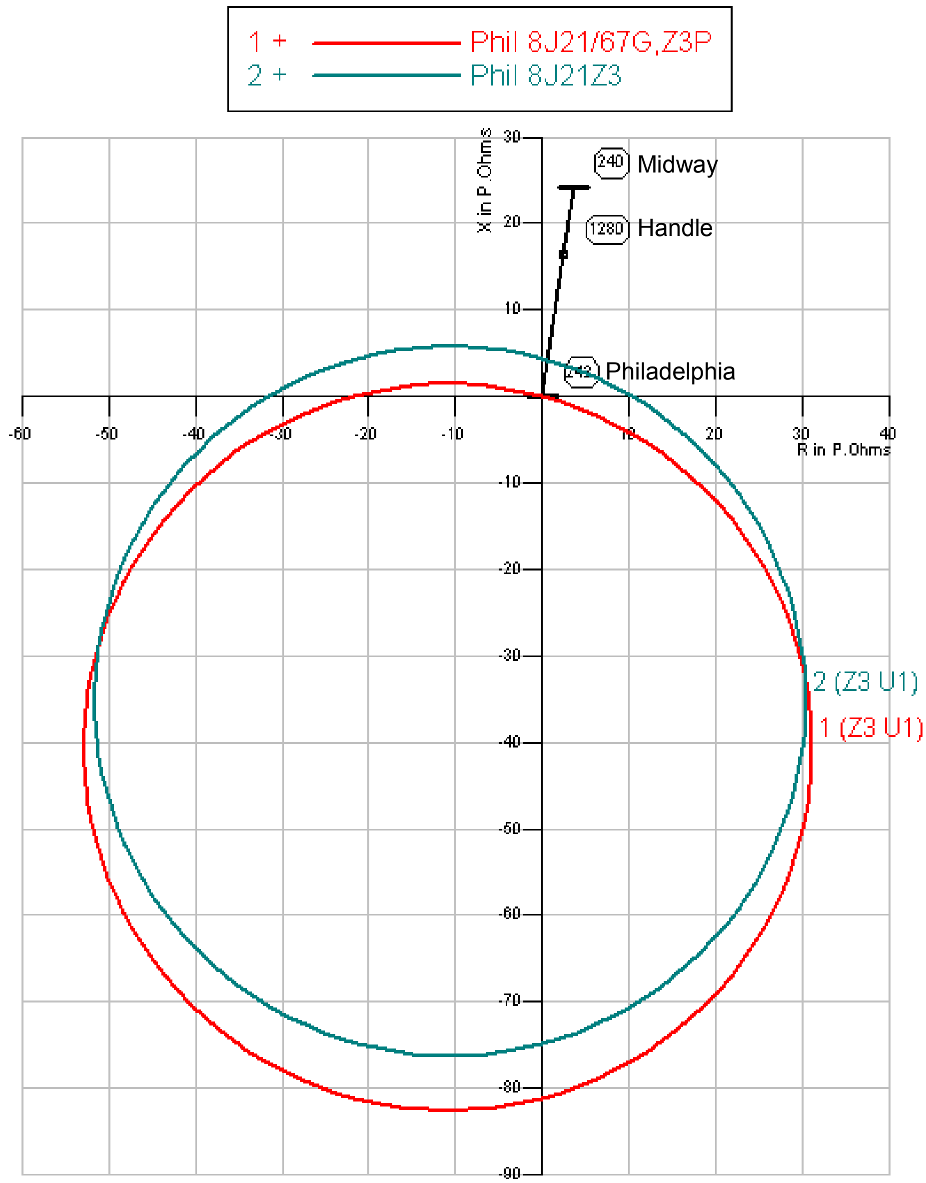


Figure 11. Midway terminal zone 3 elements at Philadelphia

After the fault was cleared, when the Midway line loading increased to -195MW+j95MVAR, neither zone 3 element was in danger of tripping, as shown in Figures 12 and 13.

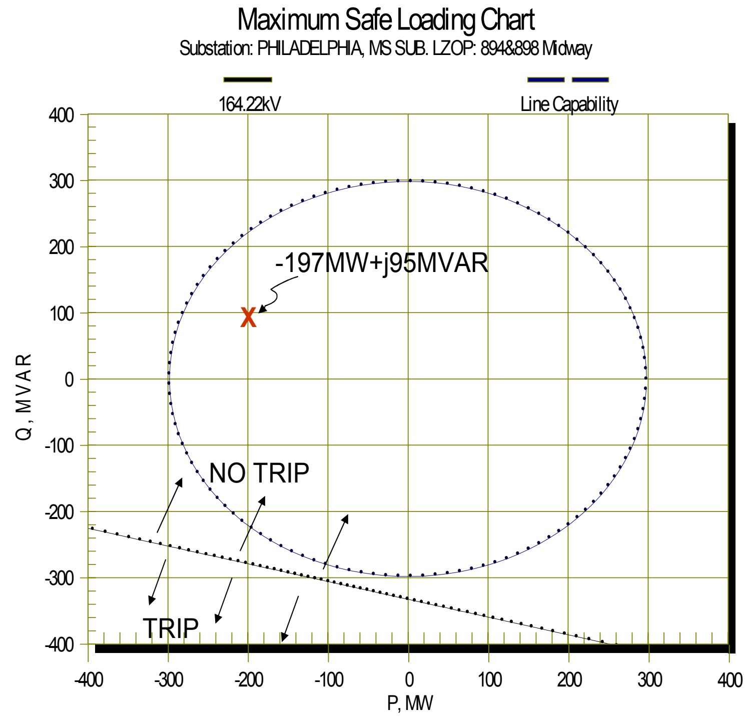


Figure 12. Maximum Safe Loading Chart for Midway Zone 3 (microprocessor) at Philadelphia, 1.02pu voltage (NOTE: Graph is in P-Q plane, circle is line capability)

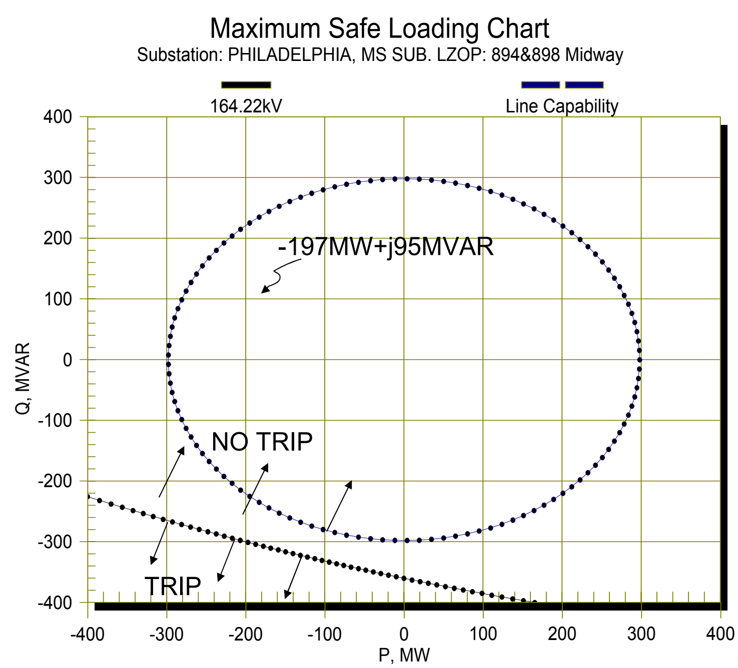


Figure 13. Maximum Safe Loading Chart for Midway Zone 3 (electromechanical) at Philadelphia, 1.02pu voltage (NOTE: Graph is in P-Q plane, circle is line capability)

Even after the Dekalb breaker closed to pickup the additional 42MW+j36MVAR of load, the elements still were not in danger of tripping, although at 0.6pu voltage the threshold cuts into the line capability (Figures 14 and 15).

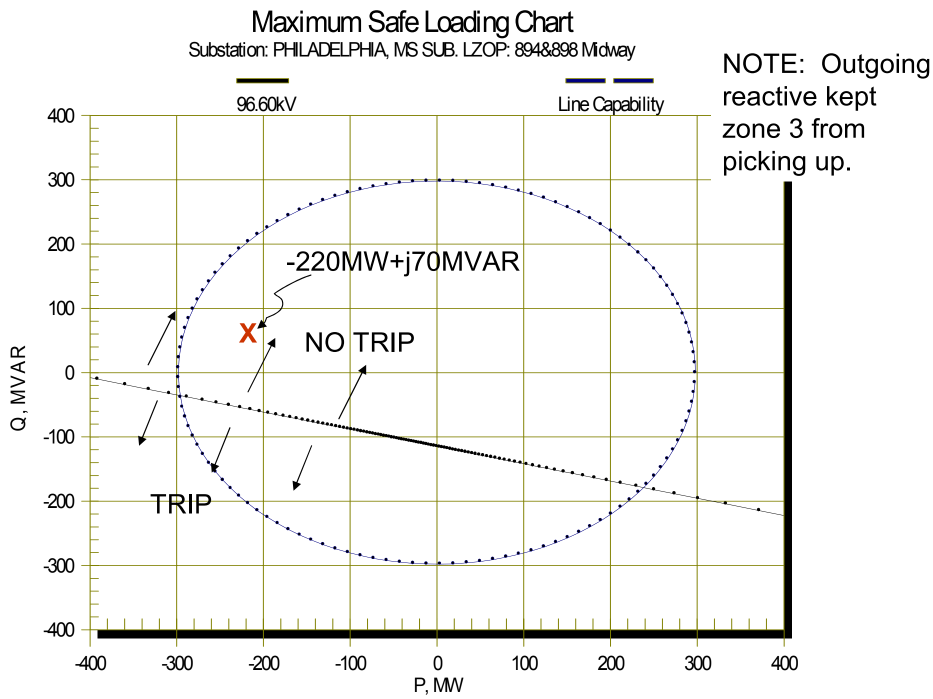


Figure 14. Maximum Safe Loading Chart for Midway Zone 3 (microprocessor) at Philadelphia, 0.6pu voltage (NOTE: Graph is in P-Q plane, circle is line capability)

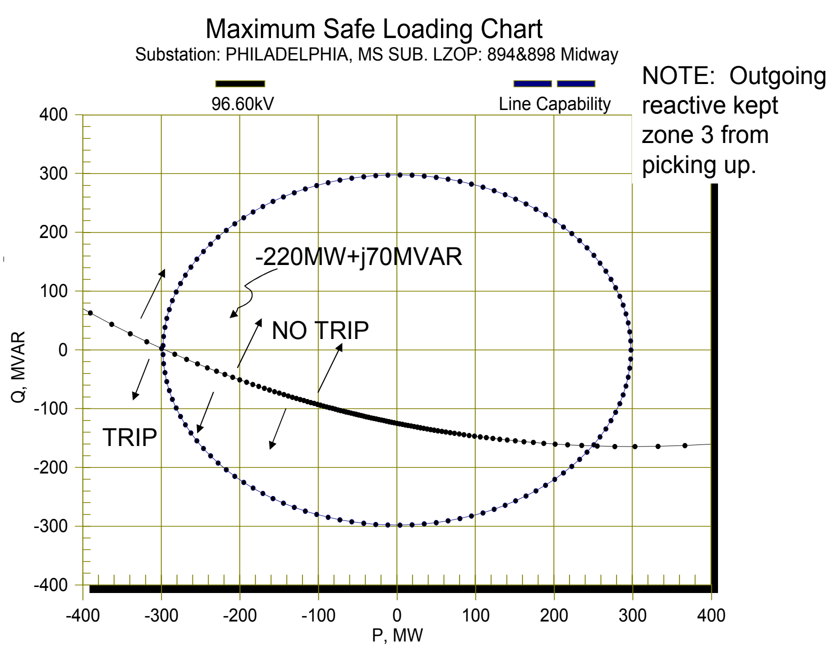


Figure 15. Maximum Safe Loading Chart for Midway Zone 3 (electromechanical) at Philadelphia, 0.6pu voltage (NOTE: Graph is in P-Q plane, circle is line capability)

If the 161kV capacitor banks had been switched off, it is likely that the zone 3 element would have picked up when the load increased to 220MW. However, the zone 3 timer was chosen to coordinate with the last step of the undervoltage load shedding scheme (zone 3 timer set on 120 cycles, last UVLS step on 105 cycles), so load shedding would have occurred prior to the zone 3 trip.

Another important point to highlight is the reactive output of the capacitor banks. It is well-known that the MVAR output of a capacitor is proportional to the square of the voltage applied. So when the voltage drops below 1.0pu, the MVAR output drops off rapidly. In this particular case, each Philadelphia cap bank is rated 18MVAR at 165.24kV.

$$MVAR = V_{L-L}^2 / X_c$$
$$Xc = 165.24 * 165.24 / 18 = 1517 \text{ ohms}$$

At 98kV, or 0.6pu voltage, the MVAR output of each bank drops to

$$MVAR = 98*98 / 1517 = 6.3MVAR$$
Total for four banks = 25MVAR

Obviously, during a voltage collapse, the capacitor banks can not be depended upon for full MVAR output.

After load shedding occurred, Weyerhaeuser 914 reclosed sync-check. With less load and two source lines, the Philadelphia 161kV bus voltage shot up to 180kV (112%). (Recall the capacitor bank regulating relays were in manual).

When the fault recurred, and was cleared by Weyerhaeuser and Dekalb, all tap loads (Shuqualak, South Macon, Macon, and Brooksville) were interrupted. The Philadelphia 161kV bus voltage increased to 192kV (119%). With only one source line, the percentage increase in bus voltage due to the capacitor bank is larger, and MVAR output increases (proportional to square of bus voltage: MVAR = 4 * 192*192 / 1517 = 97MVAR).

At this point, the Philadelphia capacitor banks (and all other equipment including transformer windings, bus support insulators, etc) were being overstressed by high voltage. With the capacitor bank controls in manual, all four banks remained switched in. The existing protection scheme, which was TVA standard in the mid 1990s, does not include phase overvoltage protection. TVA's present standard does include this protection, which is called for in IEEE C37.99 section 7.2.2.

Dekalb PCB 914 then reclosed successfully. Weyerhaeuser 914 did not reclose. Both reclosers have 90 second reset timers. The Dekalb 914 recloser had reset; the Weyerhaeuser 914 recloser had not. At this point the transmission operator is unaware that Weyerhaeuser 914 is open. The SCADA for this station is provided by an alarm-reporting telephone that does not update the SCADA display automatically.

The end result of this voltage collapse was a loss of 166MW of load. This sequence, from the initiation of the first fault occurrence on 8/4 to the last automatic relay operation, was 1 minute 34 seconds (see Figure 16).

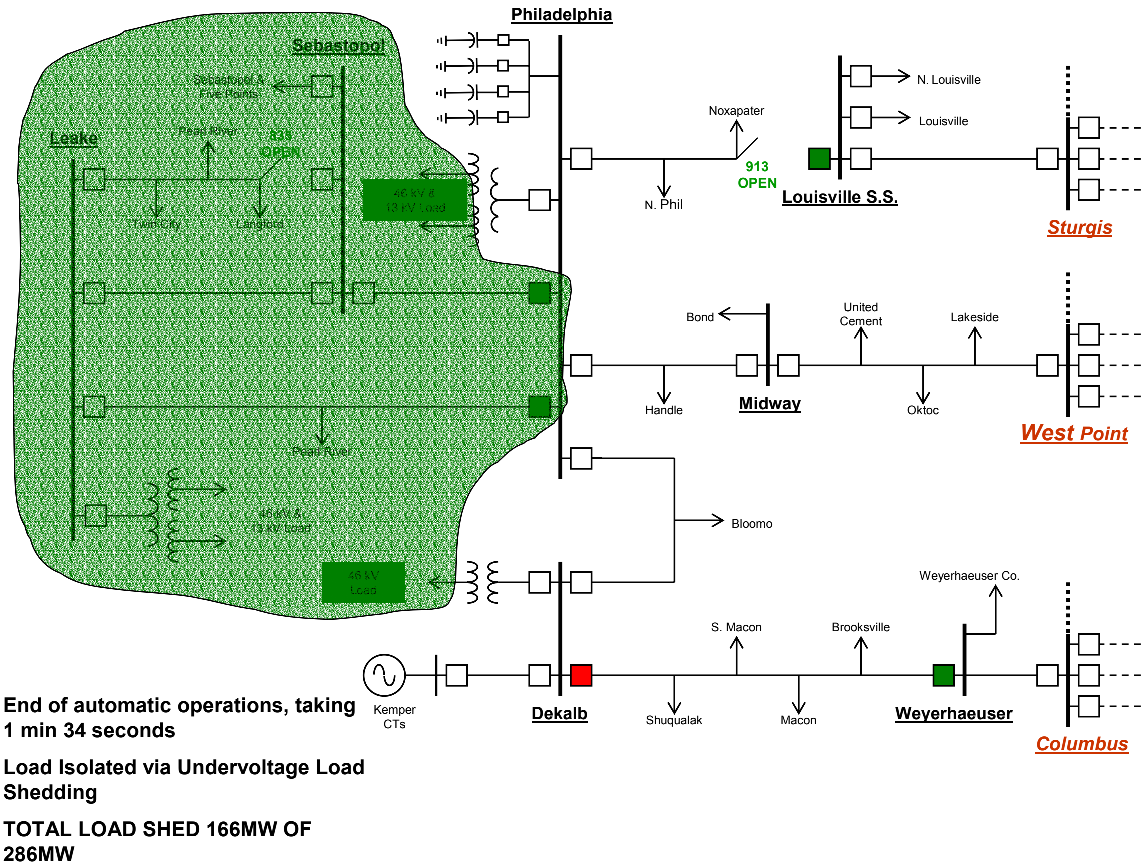


Figure 16. State of Philadelphia area after first voltage collapse

At this point, the operator catches his breath, surveys the situation, and decides on a plan of load restoration.

First Operator Intervention; Second Voltage Collapse

After resetting the load shed auxiliary relays, all four Philadelphia cap banks were tripped, which reduced the bus voltage to 165kV. Unaware that there was only one source line into Philadelphia, the operator attempted to close the Philadelphia breaker to Sebastopol, to energize Sebastopol, Sand Hill, Twin City, Leake, Five Points, and Pearl River (about 116MW). The addition of this load caused the voltage to collapse to 0.75pu, and UVLS tripped the Philadelphia breaker to Sebastopol.

Second Operator Action; Third Voltage Collapse

In an attempt to add smaller blocks of load, the operator opened the Leake breaker to Sebastopol. The Philadelphia breaker to Sebastopol was then closed, picking up about 28MW of load. The Philadelphia bus voltage sagged to 0.95pu, but recovered to 1.01pu.

Next, the operator opened the Leake breaker to Pearl River/Philadelphia, and closed at Philadelphia to pick up Pearl River (about 24MW). The Philadelphia bus voltage sagged to 0.95pu, but recovered to 1.03pu.

Next, the Leake breaker to Pearl River was closed, which energized Leake, Twin City, Pearl River, and Langford (about 62MW). The Philadelphia bus voltage sagged to 0.81pu, but recovered to 1.02pu before load shedding could occur.

Realizing the load was growing, and wanting to operate the Philadelphia bus at about 166kV or 1.03pu, the operator closed one cap bank, which raised the Philadelphia bus voltage to 1.04pu.

The Leake breaker to Sebastopol was then closed. (NOTE: In the initial voltage collapse sequence, an automatic sectionalizing scheme at Langford had run its course, leaving the MOD at Langford toward Sebastopol open. The operator was still unaware that this MOD was open. It would be a few days before this was realized).

At this point, the 46kV and 13kV load at Philadelphia and the Dekalb 46kV loads are still in the dark. Prior to reenergizing these loads, the operator switched in two more Philadelphia cap banks. The Philadelphia bus voltage was evidently in a slow decay, because switching in the second cap bank raised the bus voltage from 0.99pu to 1.02pu, and switching in the third cap bank raised the bus voltage from 1.0pu to 1.02pu.

The Dekalb load shedding auxiliary relay was reset, and the 46kV load restored (about 20MW). The Philadelphia bus voltage dropped to 1.0pu, so the fourth cap bank was switched in, raising the bus voltage to 1.03pu. After a few minutes, the bus voltage floated to 1.06pu, so one bank was switched off, lowering the bus voltage to 1.03pu.

Feeling confident, the operator restored the Philadelphia 46kV load (20MW). Unfortunately, the Philadelphia bus voltage collapsed to 0.6pu. Load shedding recurred at Philadelphia and Dekalb, and the Philadelphia bus voltage recovered, overshooting to 1.15pu.

Back to square one.

Third Operator Action; Fourth Voltage Collapse

This step was a repeat of the second voltage collapse.

After resetting the load shed auxiliary relays, the three remaining Philadelphia cap banks were tripped, which reduced the bus voltage to 1.06pu. The operator again attempts to close the Philadelphia breaker to Sebastopol, which effectively attempted to energize all taps (Sebastopol, Sand Hill, Twin City, Leake, Five Points, and Pearl River, about 116MW). The addition of this load caused the voltage to collapse to 0.84pu, and UVLS tripped the Philadelphia breaker to Sebastopol. The Philadelphia bus voltage recovered to 1.06pu.

Fourth Operator Action; Fifth Voltage Collapse

This step was a repeat of the second and fourth voltage collapses, but with a different breaker.

After resetting the load shed auxiliary relays, the three remaining Philadelphia cap banks were tripped, reducing the bus voltage to 1.06pu. The operator attempts to close the Philadelphia breaker to Leake/Pearl River, which effectively attempted to energize all taps (Sebastopol, Sand Hill, Twin City, Leake, Five Points, and Pearl River, about 116MW). The addition of this load caused the voltage to collapse to 0.84pu, and UVLS tripped the Philadelphia breaker to Leake/Pearl River. The Philadelphia bus voltage recovered to 1.06pu.

Load Restoration

Load was restored by opening the Leake breaker to Sebastopol and closing the Philadelphia breaker to Pearl River/Leake, energizing Pearl River, Leake, Twin City, Sand Hill, and Langford (about 86MW). The Philadelphia bus voltage sagged to 0.83pu, then recovered to 0.99pu, before the UVLS scheme could operate.

The Philadelphia breaker to Sebastopol was then closed to restore Sebastopol (28MW). The Philadelphia bus voltage sagged to 0.97pu, then rose to 1.03pu.

The Dekalb 46kV load (20MW) was restored, dropping the Philadelphia bus voltage to 0.99pu.

Three Philadelphia cap banks were switched in, raising the bus voltage to 1.05pu.

Philadelphia 46kV and 13kV load was then restored (41MW). The fourth Philadelphia cap bank was switched in, and the bus voltage was at 1.06pu.

It should be noted that these steps appear quite similar to the second operator action. The difference in results could be attributed to some load being tripped off, so less load was actually restored (than the numbers in parentheses shown).

Area Transmission System Restoration

By this time the transmission operator had ordered work halted on the Louisville-Noxapater line section, and it was returned to service. Shortly after, two Philadelphia cap banks switched off by automatic control, lowering the bus voltage to 1.04pu.

Also, the operator realized that Weyerhaeuser 914 was still open, so it was closed.

(NOTE: The work on Louisville-Noxapater was completed one week later on 8/11/2003, during an eight-hour outage -- a more realistic timeframe.)

Cause of Fault Located on Dekalb-Shuqualak 161kV line section

The cause of the intermittent fault was discovered to be a broken crossarm at structure 566, which confirmed the fault location provided.

Figure 17. Broken Pole/Crossarm of Structure 566 - Source of Intermittent Fault

The field system engineer pointed out that a previous aerial inspection of this structure had noted significant bowing of the pole (figure 18). This led him to recommend that line inspections of wood pole lines include not just butt rot and bird holes, but bowed poles as well.

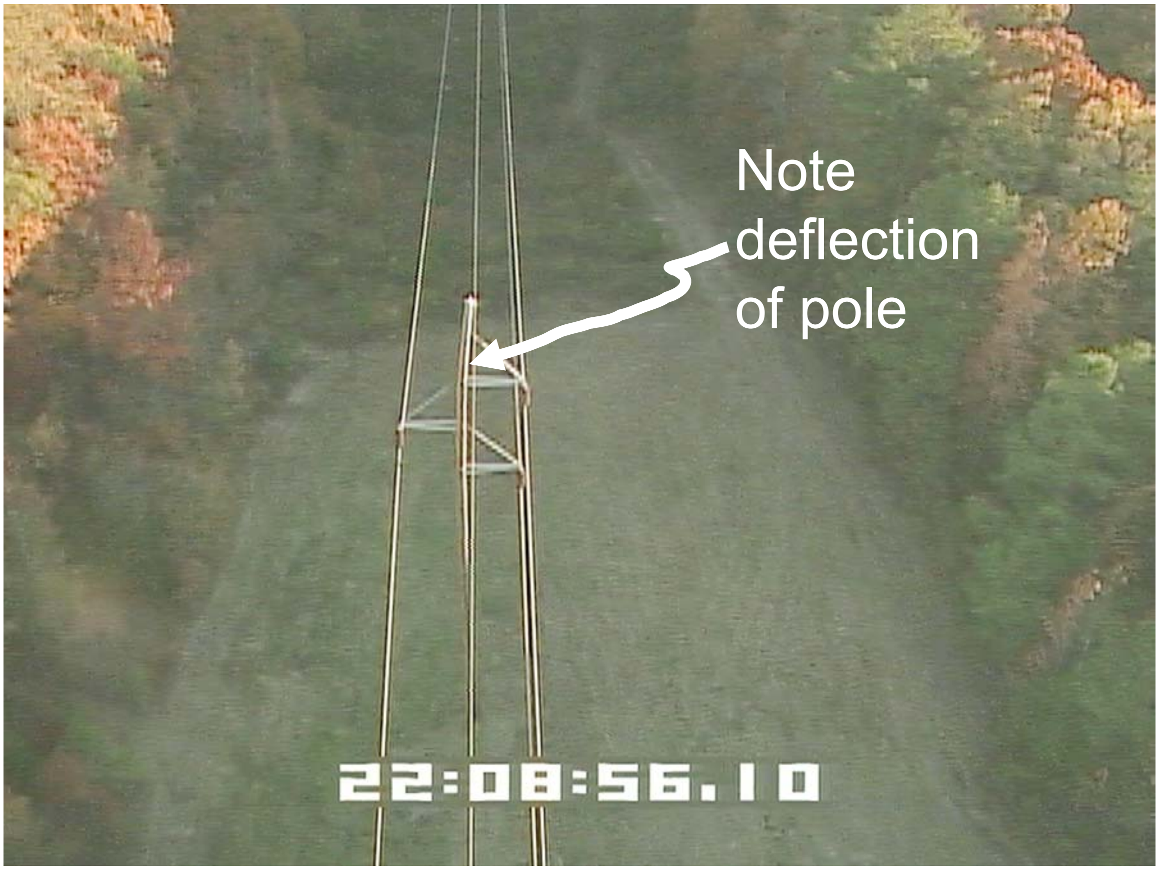


Figure 18. Bowed Structure 566 on Dekalb-Shuqualak line section

Recommendations

As a result of this disturbance, System Protection &Analysis made the following recommendations to transmission operators:

When one source line into Philadelphia is out of service:

- Investigate downsizing Philadelphia 161kV cap banks
- Turn off reclosing at load end of lines, including Philadelphia (toward Louisville, Midway, and/or Dekalb - depending on which line is out), Dekalb (toward Weyerhaeuser[1]), and Midway (toward West Point) (DONE)

[1] Weyerhaeuser has cogen and had requested sync-check reclosing only at Weyerhaeuser Switching Station.

- Turn on Kemper gas turbines for dynamic reactive support (DONE)

- Build additional transmission lines into Leake, Philadelphia, etc.

It should also be noted that the ART at Weyerhaeuser was replaced with a full-time SCADA RTU.

Conclusions

- All protective relaying schemes worked as designed (no misoperations).

- The capacitor bank controls at Philadelphia were left in manual by mistake. Had they been in automatic, they would have provided some overvoltage protection for the capacitor bank. In any event, the capacitor bank protection should include phase overvoltage protection to avoid damage to the capacitors.

- Check zone 3 timers to coordinate with load shedding timers. Load shedding should occur before zone 3 relays operate to open transmission lines.

- Load areas with zero or minimal generation and served by only a few transmission lines appear to be good candidates for UVLS schemes. With one line out for maintenance, the loss of a second line is a credible contingency that could result in voltage collapse. This is true even with the use of shunt capacitors on the bulk transmission system, which provide only artificial voltage support.

- Shunt capacitors on the bulk transmission system are no substitute for strengthening the system with additional lines/generation.

- During seasonally heavy loading periods, non-weather-related recurring faults should trigger a process that would stop schedule outages of nearby transmission lines, while generation in the area is off. The scheduled outage should be postponed until the cause of the recurring fault is located, analyzed, and corrected.

References

1. Gary C. Bullock, “Cascading Voltage Collapse in West Tennessee - August 22, 1987”, paper presented to 17th Annual Western Protective Relay Conference, Spokane, Washington, October 25, 1990

2. Hong-Ming Shuh, Jack R. Cowan, “Undervoltage Load Shedding - An Ultimate Application for Voltage Collapse”, paper presented to Georgia Tech Protective Relaying Conference, April 29-May 1, 1992

3. “Voltage Security Theory and Methods of Analysis”, Short Course Notes, Powertech Labs

4. Carson W. Taylor, Power System Voltage Stability, McGraw-Hill Inc, 1994

5. Prabha Kundur, Power System Stability and Control, McGraw-Hill Inc, 1994, pp 974-977

Biographical Sketches

Meyer M. Kao is a Transmission System Engineer in the System Protection & Analysis group for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. He is responsible for performing detailed technical analysis for unusual system events, including equipment failure and misoperations. He also has responsibility for protective relaying and control settings and field support. Prior to his position as Transmission System Engineer, Meyer was a field test engineer for the TVA’s Chattanooga Transmission Service Center. One of Meyer’s main responsibilities as a field test engineer was new installation and retrofit of substation control and protection circuits. Meyer earned the B.E.E. degree from the Georgia Institute of Technology in 1990. He is a registered professional engineer in the state of Tennessee.

Gary Kobet is a Project Specialist, System Protection & Analysis for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. His responsibilities include scoping relaying schemes for transmission and generation projects, as well as relay setpoint calculations. He has performed transient studies using EMTP for breaker TRV studies and switching surge overvoltages. Previously he worked as a field engineer and as power quality specialist. Mr. Kobet earned the B.S.E. (electrical) from the University of Alabama at Huntsville in 1989 and the M.S.E.E. from Mississippi State University in 1996. He is a member of the IEEE Power Engineering Society, CIGRE’, Eta Kappa Nu, Tau Beta Pi, and is a registered professional engineer in the state of Alabama.

APPENDIX - SEQUENCE OF EVENTS

Time	Event
	PRELIMINARY EVENTS
08/02/2003 18:23:38.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line - Fault cleared, reclosing successful
08/02/2003 18:26:42.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line - Fault cleared, reclosing successful
08/03/2003 15:58:36.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line - Fault cleared, line locked out (South Macon MOD on Weyerhaeuser side left open after autosectionalizing scheme sequence)
	At Shuqualak, line crew opens disconnect on Weyerhaeuser side of tap
08/03/2003 16:52:00.000	Operator remotely closed Dekalb 914 (efforts to locate fault unsuccessful), picking up Shuqualak
	South Macon-Shuqualak line section isolated, operator/line crew erroneously assume fault is on this section
	At South Macon, line crew opens MOD on Dekalb side of tap, closes MOD on Weyerhaeuser side of tap
08/03/2004 17:04:00.000	Operator remotely closed Weyerhaeuser 914, picking up Brooksville, Macon, South Macon
	NOTE: Line crew inspects South Macon-Shuqualak line section and finds nothing (correctly, since fault is intermittent on Dekalb-Shuqualak)
08/03/2004 21:26:00.000	Operator remotely tripped Dekalb 914
	At Shuqualak, line crew closes disconnect on Weyerhaeuser side of tap
	At South Macon, line crew closes MOD on Dekalb side of tap
	Operator remotely closes Dekalb 914
	System back to "normal"
08/04/2003 7:00:00.000	Louisville-Noxapater 161kV line outage for maintenance
	Two 161kV source lines left into Philadelphia, one with a hidden problem about to recur
	Initial load in area 286MW
	INITIAL VOLTAGE COLLAPSE; RECURRING FAULT ON DEKALB-WEYERHAEUSER 161KV LINE
08/04/2003 15:22:00.000	Philadelphia 161kV bus voltage at 1.04pu
	Philadelphia 161kV capacitor banks providing 75MVAR (Four banks, 18MVAR each)
	Incoming load at Philadelphia on Midway 161kV line loading at -120MW+j35MVAR (Note outgoing reactive)
08/04/2003 15:22:49.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line (between Dekalb and Shuqualak) - Fault cleared in 4 cycles
	Philadelphia 161kV bus voltage steady at 1.02pu
	Philadelphia 161kV capacitor bank output drops to 71MVAR
	Incoming load at Philadelphia on Midway 161kV line loading increases to -197MW+j95MVAR (Note outgoing reactive)

APPENDIX - SEQUENCE OF EVENTS

Time	Event
08/04/2003 15:22:50.500	Dekalb 914 recloses successfully, adds 42MW+j36MVAR of load Philadelphia 161kV bus voltage drops to 0.6pu Philadelphia 161kV capacitor bank output drops to 25MVAR Incoming load at Philadelphia on Midway 161kV line loading increases to -220MW+j70MVAR (Note outgoing reactive)
08/04/2003 15:22:52.000	Philadelphia 888 and 944 trip by UVLS, shedding 116MW of load Philadelphia 161kV bus voltage recovers to 0.8pu Philadelphia 161kV capacitor bank output raises to 44MVAR
08/04/2003 15:22:52.250	Philadelphia 464 and 304 trip by UVLS, shedding 30MW of load Dekalb 424 and 444 trip by UVLS, shedding 20MW of load Philadelphia 161kV bus voltage recovers to 0.96pu Total load shed 166MW, dropping total load to 120MW (approximate 60% reduction) Philadelphia 161kV capacitor banks still connected, output raises to 63MVAR
08/04/2003 15:22:53.500	Weyerhaeuser 914 recloses sync-check Philadelphia 161kV bus voltage raised to 1.12pu (due to load decrease and two source lines back in) Philadelphia 161kV capacitor bank output raises to 86MVAR
08/04/2003 15:23:31.500	Langford 835 opens after autosectionalizing scheme sequence
08/04/2003 15:24:07.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line (between Dekalb and Shuqualak) recurs - Fault cleared in 4 cycles Philadelphia 161kV bus voltage rises to 1.2pu Philadelphia 161kV capacitor bank output raises to 100MVAR
08/04/2003 15:24:08.500	Dekalb 914 recloses successfully, adds 42MW+j36MVAR of load Weyerhaeuser 914 recloser goes to lockout (one shot exhausted on previous reclose, reset timer set on 90 seconds) NOTE: Operator does NOT know Weyerhaeuser 914 is open Philadelphia 161kV bus voltage decreases to 1.09pu Philadelphia 161kV capacitor bank output decreases to 81MVAR

FIRST OPERATOR INTERVENTION; SECOND VOLTAGE COLLAPSE

08/04/2003 15:25:30.000	Operator remotely trips all four Philadelphia 161kV cap banks by SCADA Philadelphia 161kV bus voltage decreases to 1.02pu
08/04/2003 15:27:26.000	Operator remotely closes Philadelphia 888 in attempt to pickup Sebastopol-Leake loop/loads (116MW) (Operator does NOT know Langford 835 is open) Philadelphia 161kV bus voltage collapses to 0.75pu

APPENDIX - SEQUENCE OF EVENTS

Time	Event
08/04/2003 15:27:27.500	Philadelphia 888 tripped by UVLS Philadelphia 161kV bus voltage recovers to 1.02pu
	SECOND OPERATOR INTERVENTION; THIRD VOLTAGE COLLAPSE
08/04/2003 15:28:55.000	Operator remotely trips Leake 954
08/04/2003 15:29:53.000	Operator remotely closes Philadelphia 888, picking up Sebastopol (28MW) Philadelphia 161kV bus voltage drops to 0.95pu, recovers to 1.01pu
08/04/2003 15:30:11.000	Operator remotely trips Leake 944
08/04/2003 15:30:18.000	Operator remotely closes Philadelphia 944, picking up Pearl River (24MW) Philadelphia 161kV bus voltage drops to 0.99pu, recovers to 1.03pu
08/04/2003 15:30:33.000	Operator remotely closes Leake 944, picking up Leake, Twin City, Sand Hill, Langford (62MW) Philadelphia 161kV bus voltage drops to 0.81pu, recovers to 1.02pu
08/04/2003 15:30:50.000	Operator remotely closes one Philadelphia 161kV cap bank Philadelphia 161kV bus voltage rises to 1.04pu
08/04/2003 15:31:23.000	Operator remotely closes Leake 954 Philadelphia 161kV bus voltage steady at 1.03pu, slowly decreases to 0.99pu
08/04/2003 15:37:40.000	Operator remotely closes second Philadelphia 161kV cap bank Philadelphia 161kV bus voltage rises to 1.02pu, slowly decreases to 1.0pu
08/04/2003 15:44:44.000	Operator remotely closes third Philadelphia 161kV cap bank Philadelphia 161kV bus voltage rises to 1.02pu
08/04/2003 15:44:48.000	Operator closes Dekalb 424 and 444 (20MW) Philadelphia 161kV bus voltage decreases to 1.0pu
08/04/2003 15:49:36.000	Operator remotely closes fourth Philadelphia 161kV cap bank Philadelphia 161kV bus voltage rises to 1.03pu
08/04/2003 15:58:14.000	Philadelphia 161kV bus voltage rises to 1.06pu

APPENDIX - SEQUENCE OF EVENTS

Time	Event
	Operator remotely trips one Philadelphia 161kV cap bank Philadelphia 161kV bus voltage decreases to 1.03pu
08/04/2003 16:02:40.000	Operator remotely closes Philadelphia 464 (20MW) Philadelphia 161kV bus voltage collapses to 0.6pu
08/04/2003 16:02:42.000	Philadelphia 888 and 944 trip by UVLS, shedding 116MW of load Philadelphia 464 and 304 trip by UVLS, shedding 30MW of load Dekalb 424 and 444 trip by UVLS, shedding 20MW of load Philadelphia 161kV bus voltage recovers to 1.15pu Three Philadelphia 161kV capacitor banks still connected
	THIRD OPERATOR ACTION; FOURTH VOLTAGE COLLAPSE
08/04/2003 16:03:37.000	Operator remotely trips three remaining Philadelphia 161kV cap banks Philadelphia 161kV bus voltage decreases to 1.06pu
08/04/2003 16:03:47.000	Operator remotely closes Philadelphia 888 in attempt to pickup Sebastopol-Leake loop/loads (116MW) Philadelphia 161kV bus voltage collapses to 0.84pu
08/04/2003 16:03:50.000	Philadelphia 888 tripped by UVLS Philadelphia 161kV bus voltage recovers to 1.06pu
	FOURTH OPERATOR ACTION; FIFTH VOLTAGE COLLAPSE
08/04/2003 16:04:20.000	Operator remotely closes Philadelphia 944 in attempt to pickup Sebastopol-Leake loop/loads (116MW) Philadelphia 161kV bus voltage collapses to 0.84pu
08/04/2003 16:04:22.000	Philadelphia 944 tripped by UVLS Philadelphia 161kV bus voltage recovers to 1.06pu
	LOAD RESTORATION
08/04/2003 16:04:56.000	Operator remotely trips Leake 954
08/04/2003 16:05:09.000	Operator remotely closes Philadelphia 944, picking up Pearl River, Leake, Twin City, Sand Hill, Langford (86MW)

APPENDIX - SEQUENCE OF EVENTS

Time	Event
	Philadelphia 161kV bus voltage collapses to 0.83pu, then increases slowly to 0.99pu before UVLS occurs
08/04/2003 16:05:11.000	Dekalb UVLS relay trips, but Dekalb 424 and 444 had not yet been closed after previous reset Philadelphia 161kV bus voltage at 1.03pu
08/04/2003 16:05:30.000	Operator remotely closes Philadelphia 888, picking up Sebastopol (28MW) Philadelphia 161kV bus voltage sags to 0.97pu, then recovers to 1.03pu
08/04/2003 16:10:14.000	Operator remotely closes Dekalb 424 and 444 (20MW) Philadelphia 161kV bus voltage sags to 0.99pu
08/04/2003 16:10:38.000	Operator remotely closes one Philadelphia 161kV cap bank
08/04/2003 16:10:53.000	Operator remotely closes second Philadelphia 161kV cap bank
08/04/2003 16:14:44.000	Operator remotely closes third Philadelphia 161kV cap bank Philadelphia 161kV bus voltage at 1.05pu
08/04/2003 16:19:00.000	Operator remotely closes Philadelphia 464 (20MW) and 304 (21MW)
08/04/2003 16:24:37.000	Operator remotely closes fourth Philadelphia 161kV cap bank Philadelphia 161kV bus voltage at 1.06pu

AREA TRANSMISSION SYSTEM RESTORATION

08/04/2003 16:26:39.000	Louisville-Noxapater 161kV line returned to service
08/04/2003 16:26:42.000	One Philadelphia 161kV cap bank trips by automatic voltage control
08/04/2003 16:26:57.000	Second Philadelphia 161kV cap bank trips by automatic voltage control Philadelphia 161kV bus voltage at 1.04pu
08/04/2003 16:30:00.000	Operator remotely closes Weyerhaeuser 914 (after realizing it was open)

CAUSE OF FAULT LOCATED ON DEKALB-SHUQUALAK

08/04/2003 17:17:48.000	Operator remotely trips Dekalb 914 (line crew searching for cause of fault)
08/04/2003 17:20:37.000	A-ground fault on Dekalb-Weyerhaeuser 161kV line (between Dekalb and Shuqualak) recurs - Fault cleared in 4 cycles

APPENDIX - SEQUENCE OF EVENTS

Time	Event
08/04/2003 17:21:18.000	Dekalb-Shuqualak line section isolated
08/04/2003 17:26:00.000	Operator remotely closes Weyerhaeuser 914 to restore Brooksville, Macon, South Macon, Shuqualak
	SUBSEQUENT EVENTS
08/04/2003 18:15:39.000	Operator remotely closes Leake 954
A few days later	Operator closes Langford 835 (after realizing it had opened)

APPENDIX - AREA LOAD

Substation	Customer Load	KW	KVAR OUT	KVAR IN	KVA
Philadelphia	Philadelphia CEPA 46 kV	20,252	4,182	-	20,679
	Philadelphia CEPA 13 kV	9,526	3,208	-	10,052
	Philadelphia City PU	11,547	2,009	-	11,720
Leake	Leake 13 kV CEPA	9,428	2,349	-	9,716
	Singleton	11,249	1,572	-	11,358
	Kosciusko	6,576	-	1,805	6,819
Sebastopol	Sebastopol Bank 1	10,575	1,089	-	10,631
	Sebastopol Bank 2	9,029	1,961	-	9,240
	Five Points Bank 2	9,141	-	536	9,157
Dekalb	Cleveland 424	2,031	324	-	2,057
	Dekalb Dist 444	17,703	-	6,752	18,947
	Scooba 434	4,847	-	97	4,848
Midway	Bond	5,002	689	-	5,049
Total		126,906	17,383	9,190	128,420

APPENDIX - AREA LOAD

Lines		KW	KVAR OUT	KVAR IN	KVA
Philadelphia-Leake	Pearl River Bank 1	13,211	1,875	-	13,343
	Pearl River Bank 2	11,310	3,741	-	11,913
Sebastopol-Leake #2	Twin City	8,947	1,136	-	9,019
	Sand Hill Bank 1	2,864	-	84	2,865
	Sand Hill Bank 2	4,879	1,354	-	5,063
	Langford	18,497	5,309	-	19,244
Dekalb-Philadelphia	Bloomo Bank 1	3,780	916	-	3,889
	Bloomo Bank 2	4,229	795	-	4,303
Dekalb-Weyerhaeuser	Brooksville	13,984	1,957	-	14,120
	Macon	7,128	1,089	-	7,211
	S Macon	11,275	1,918	-	11,437
	Shuqualak	5,916	1,277	-	6,052
Philadelphia-Louisville SS	N. Philadelphia	14,915	2,128	-	15,066
	Noxapater	6,367	969	-	6,440
Philadelphia-Midway	Handle	5,112	480	-	5,134
West Point-Midway	Lakeside	10,912	1,568	-	11,024
	Oktoc	9,467	1,743	-	9,626
	United Cement Bank 1	3,020	760	-	3,114
	United Cement Bank 2	3,010	763	-	3,105
Total		158,823	29,778	84	161,590