POLAR VORTEX AND GENERATION FUEL DIVERSITY

by

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A REPORT

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Approved by:

Major Professor
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Abstract

The unusual weather events during the polar vortex of 2014 illuminated the needs for fuel diversity for power generation in order to allow reliable operation of the electricity grid. A system wide reliability assessment for winter months should be undertaken in addition to the summer months to ensure reliable operation of the electricity grid throughout the year. Severe weather conditions that lead to equipment malfunction during the polar vortex should be thoroughly investigated and remediations to ensure satisfactory future performance of the grid must be undertaken. Environmentally unfriendly emissions from power plants must be minimized but diversity of generation fuel must be maintained. Future energy policies must be formulated with consideration that approximately 14 GW of coal generation in Pennsylvania Jersey Maryland Regional Transmission Organization's control area available during the polar vortex will be retired by 2015 and replaced with plants that utilize fuel types other than coal.

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Acknowledgements

I am grateful to my major professor, Dr. Anil Pahwa, for his guidance. I would also like to thank other members on the supervisory committee, Dr. Ruth Miller and Dr. Shelli Starrett, for their constant support.

Dedication

I dedicate this work to my parents and wife for their continued support.

Chapter 1 - Introduction

Significance of Work

The 2014 polar vortex was a significant event that will have far-reaching consequences for the environment and the electric grid. This report investigates the impacts of polar vortex on the electric grid of PJM control area. As demonstrated during the polar vortex, adequate performance of the electric grid depends on the preservation of generation fuel diversity and heavy reliance on a particular generation fuel type must be avoided. Current reliability assessment of the PJM system, however, is not conducted for winter months and as demonstrated during the polar vortex in 2014 unique challenges may be presented to grid operators during winter months. Therefore, reliability assessment only for summer months may not ensure year-round reliable operation of the PJM grid. A discussion of FERC order 111d may cause the retirement of additional coal generation due to high environmental compliance costs. FERC order 111d may potentially disturb generation fuel diversity. Future energy policies such as the order 111d should be put into practice only after mitigating potential risks, such as generation fuel shift.

Polar Vortex Phenomenon

A polar vortex is a persistent large-scale cyclone that circles Earth's North and South Poles. The base of polar vortices is located in the middle and upper troposphere, extending into the stratosphere. The vortices surround the polar highs and lie in the wake of the polar front. These cold-core low pressure areas strengthen in the winter and weaken in the summer due to their dependence upon the temperature differential between the Equator and the Poles [1]. They typically span less than 1000 km in diameter within which air circulates counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. During the 2014 polar vortex, the North Pole was theoretically shifted down towards the South Pole, causing an atypically higher cold wave across the north eastern United States.

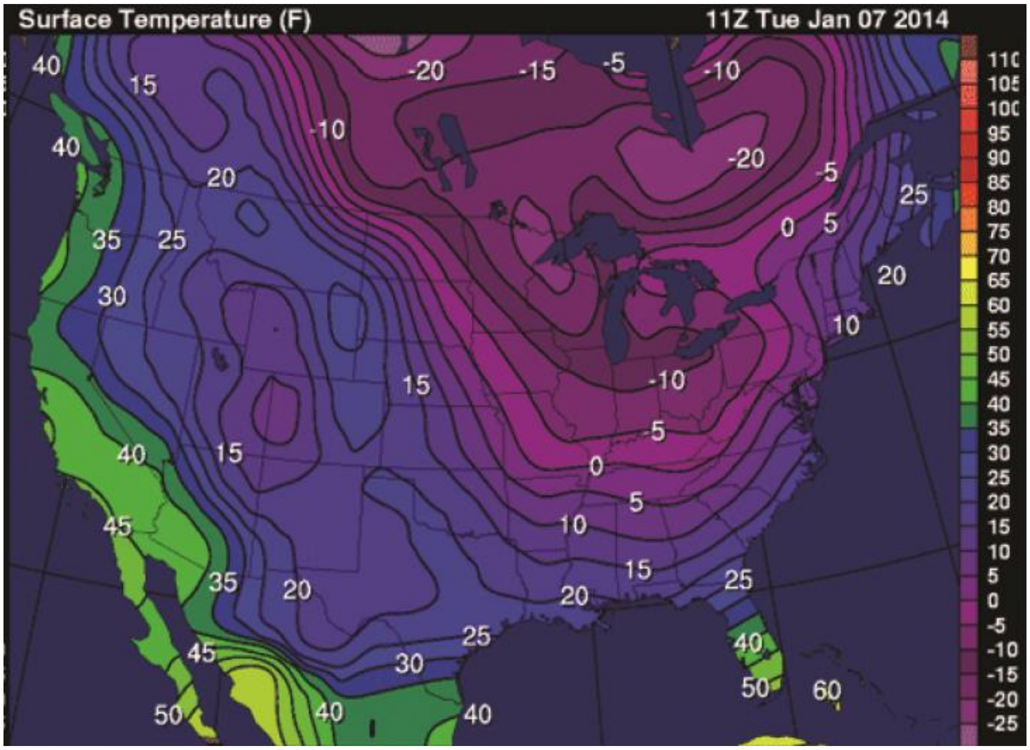


Figure 1.1 Temperature Contour Map of North America during the 2014 Polar Vortex [2]

Figure 1.1 shows temperature contour throughout the North America during the morning of January 7, 2014. As shown, temperatures north of the Great Lakes dropped as low as -20°F, and temperatures south of the Great Lakes fell as low as -10°F.

Pennsylvania Jersey Maryland Regional Transmission Organization

PJM interconnection is a RTO that coordinates movement of wholesale electricity in all or parts of the states of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. As a neutral, independent party, PJM operates a competitive wholesale electricity market and manages the high-voltage electricity grid to ensure reliability for more than 61 million people.

PJM’s long-term regional planning process provides a broad, interstate perspective that identifies the most effective, cost-efficient grid improvements to ensure reliability and economic benefits throughout the system. An independent board oversees PJM’s activities. Effective governance and a collaborative stakeholder process allow PJM to achieve its vision “To be the electric industry leader – today and tomorrow – in reliable operations, efficient wholesale markets, and infrastructure development [3].”

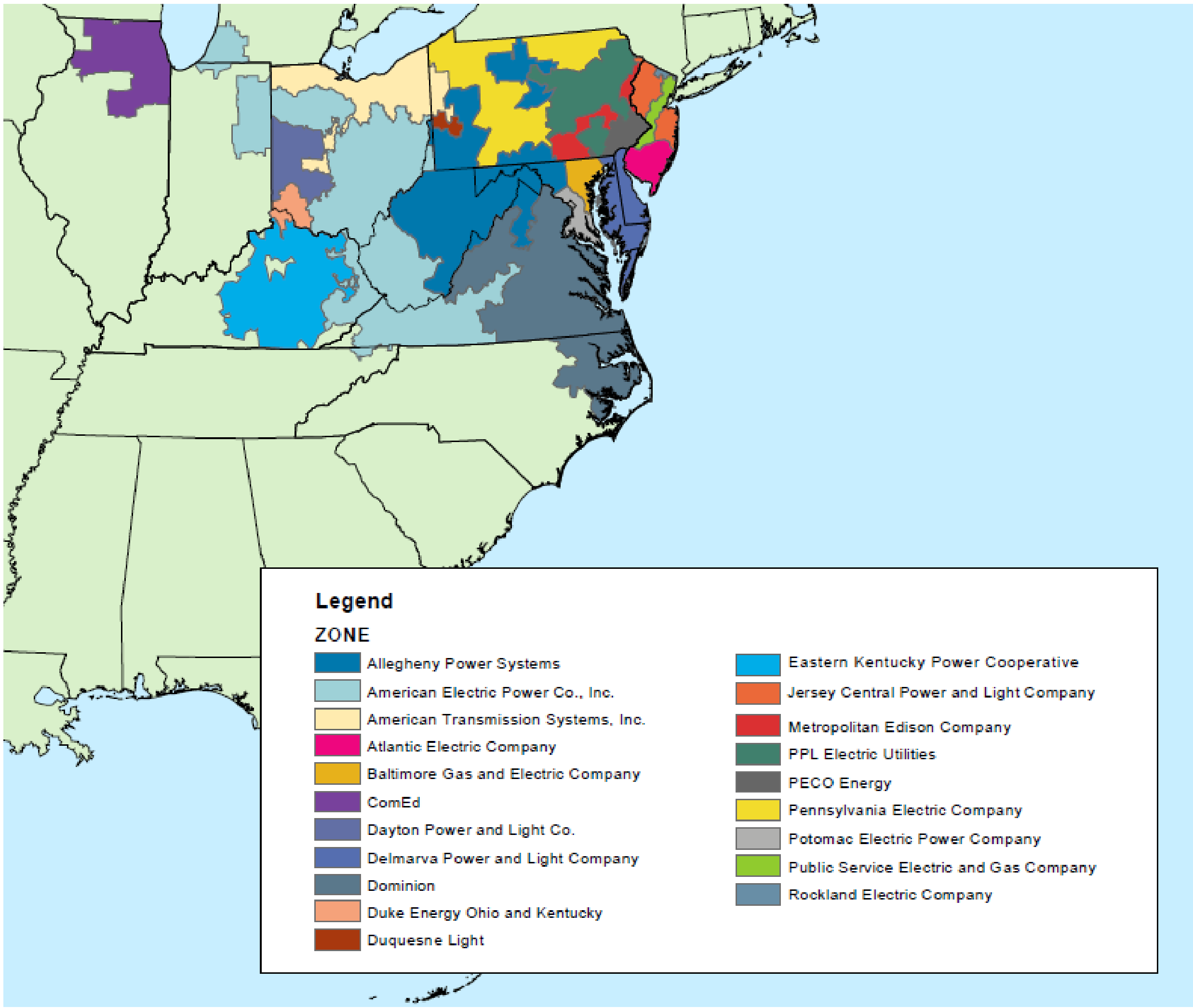


Figure 1.2 PJM Control Area [4]

Figure 1.2 displays PJM’s territory. A “zone” is comprised of various companies or electric utilities affiliated with PJM. Common Wealth Edison, American Electric Power, Dominion, American Transmission Systems, and Eastern Kentucky Power Cooperative are examples of large PJM utilities.

Summary of Work

In this report, PJM’s electric grid performance during the polar vortex of 2014 is analyzed by identifying capacity limitations on the transmission system. The report also contains brief discussion of transmission facility outages and generation plant outages in addition to PJM generation operating reserve margin and net energy interchange during the polar vortex. Natural gas prices and the impact on locational marginal pricing (LMP) are also discussed. Finally, reliability assessment of the PJM control area is performed by applying polar vortex conditions on a load flow case, taking into account 2015 generation retirements and associated transmission upgrades.

Chapter 2 - Electric System Performance

This section analyzes electric grid operational performance in the PJM control area during the polar vortex of 2014.

Real-time Transmission Constraints

Due to abnormally low temperatures during the polar vortex of 2014, several major transmission facilities throughout the PJM operated beyond their normal / emergency ratings. As a result, the facilities were either taken out of service or load was shed to return loadings below normal / emergency ratings. Constrained major transmission facilities during the polar vortex are listed in Table 2.1. Breed-Wheatland 345 kV line overloaded in real-time PJM analysis for the outage of Rockport-Jefferson 765 kV line. Alleghany South, Bedington-Black Oak, and PJM West interfaces were constrained in real-time PJM analysis under system normal conditions (no outage). Similarly, Red Lion, Susquehanna, and Miami Fort transformers were constrained under real-time PJM analysis under contingency conditions.

Table 2.1 Constrained Major Transmission Facilities [5]

Overloaded Facility	System Condition
AEP Breed – Cinergy Wheatland 345 kV	Outage of AEP Jefferson-Rockport 765 kV
Alleghany South Interface	No Outage
Bedington-Black Oak Interface	No Outage
PJM West Reactive Interface	No Outage
Red Lion 500/230 kV Transformer #50	Outage of Red Lion 500/230 kV Transformer #51
Susquehanna 500/230 kV Transformer	Susquehanna Unit 1
Miami Fort 345/138 kV Transformer	Tanners Creek-Dearborn 345 kV

Major Transmission Outages

During the polar vortex of 2014 several major transmission facilities were offline due to planned maintenance outage or were forced out due to severe weather conditions at various times. These facilities were offline at some point during the Polar vortex and were not necessarily out of service at the same. Major transmission facilities out of service during the polar vortex are listed below [6]:

AEP Baker Phase 3 765kV Reactor, AEP Broadford 765kV Reactors, AEP Cook 345kV L & L2 CBs, AEP Desoto 345kV C2 CB, AEP Dumont 765kV Reactors, AEP Elkhart 138kV G CB, AEP Hanging Rock 765kV D2 CB, AEP Hayden 345kV C2 CB, AEP Hyatt CS 345kV 302N CB, AEP Kammer 765kV Reactors, AEP Kammer-Vassell-Maliszewski 765kV Line, AEP Kanawha River 345kV 1 & 2 Series Capacitors, AEP Maliszewski 1 765/138kV Transformer, AEP Twin Branch 345/138kV #6 Transformer, AEP Vassell 765kV Bus 2, BGE Conastone 500/230kV 500-3 Transformer, ComEd 108 Lockport-120 Lombard 345kV Line 10808, ComEd 115 Bedford Park 345/138kV TR82 Transformer, ComEd 177 Burnham-153 Taylor 345kV Line 17724, Dayton Shelby 345kV HH CB, DEOK Terminal 345kV 1305 CB, Dom Loudoun-Pleasant View 500kV Line, Dom Mt Storm 500kV Capacitors, DOM Mt Storm 500kV G2T554 CB, Dom/FE-Fairmont Doubs-Mt Storm 500kV line, DPL Red Lion 500kV 502 CB, Duquesne Collier 345/138kV T3 Transformer, FE-Reading Smithburg 500/230kV T1 Transformer, FE-Wadsworth Beaver Valley-Mansfield 1 345kv Line, FE-Wadsworth Harding 345/138kV #2 Transformer, FE-Wadsworth Highland 345kV B95 CB, FE-Wadsworth Inland 345kV S578 Tie CB, FE-Wadsworth Juniper 345/138kv #3 Transformer, FE-Wadsworth Juniper 345kV Capacitor, PE Limerick 500kV Capacitor, PEP Brighton 500kV #6 CB, PPL Alburtis 500kV Capacitor 1, PPL Alburtis 500kV Capacitor 2, PPL Juniata 500kv Capacitor 500-2, PPL Juniata Keystone-Alburtis Tie 500kV CB, and PS Branchburg 500kV 2-15 Tie Bus.

Generation Outages

This section discusses generation unavailability during the polar vortex. As shown in Table 2.2, 21% of PJM’s installed generation capacity (ICAP), or approximately 39,500 MW, was unavailable during the morning of January 8, 2014. Historical generation outage percentages between 2009 and 2013 were at 5-9% of the ICAP, whereas generation outages during the polar vortex of 2014 were 20% of the ICAP. Generation outages experienced during the Polar vortex of 2014 were approximately two to three times higher than the usual.

Table 2.2 Generation Outages during the Polar vortex [7]

	1/6/2014 8 PM	1/7/2014 8 AM	1/7/2014 7 PM	1/8/2014 8 AM	1/8/2014 8 PM
Installed Capacity (MW)	189,658	189,658	189,658	189,658	189,658
Generation Outages (MW)	31,312	36,087	39,136	40,713	28,151
% Capacity	17%	19%	21%	21%	15%
Maintenance (MW)	1,073	1,018	1,103	1,193	1,107
Forced (MW)	30,239	35,069	38,033	39,520	27,044
Outages due to Gas Curtailments (MW)	2,160	7,489	6,368	9,046	9,046

Figure 2.1 describes causes of generation outages during the polar vortex. As demonstrated, natural gas interruptions contributed most significantly to outages. Extreme cold temperatures during the polar vortex resulted in increased residential natural gas demand. Natural gas power plants operate primarily with interruptible gas contracts, thereby allowing natural gas power plants to be supplied with natural gas at lower rates with an understanding that natural gas supply to the plant could be curtailed if the supplier is unable to meet plant demand.

During the polar vortex, many natural gas suppliers exercised their right and interrupted gas supply to the power plants in order to meet increased residential gas demand. As a result, many natural gas power plants were unable to operate due to interruption in natural gas supply. Natural gas interruptions attributed for 24% of the total amount of unavailable generation during the polar vortex.

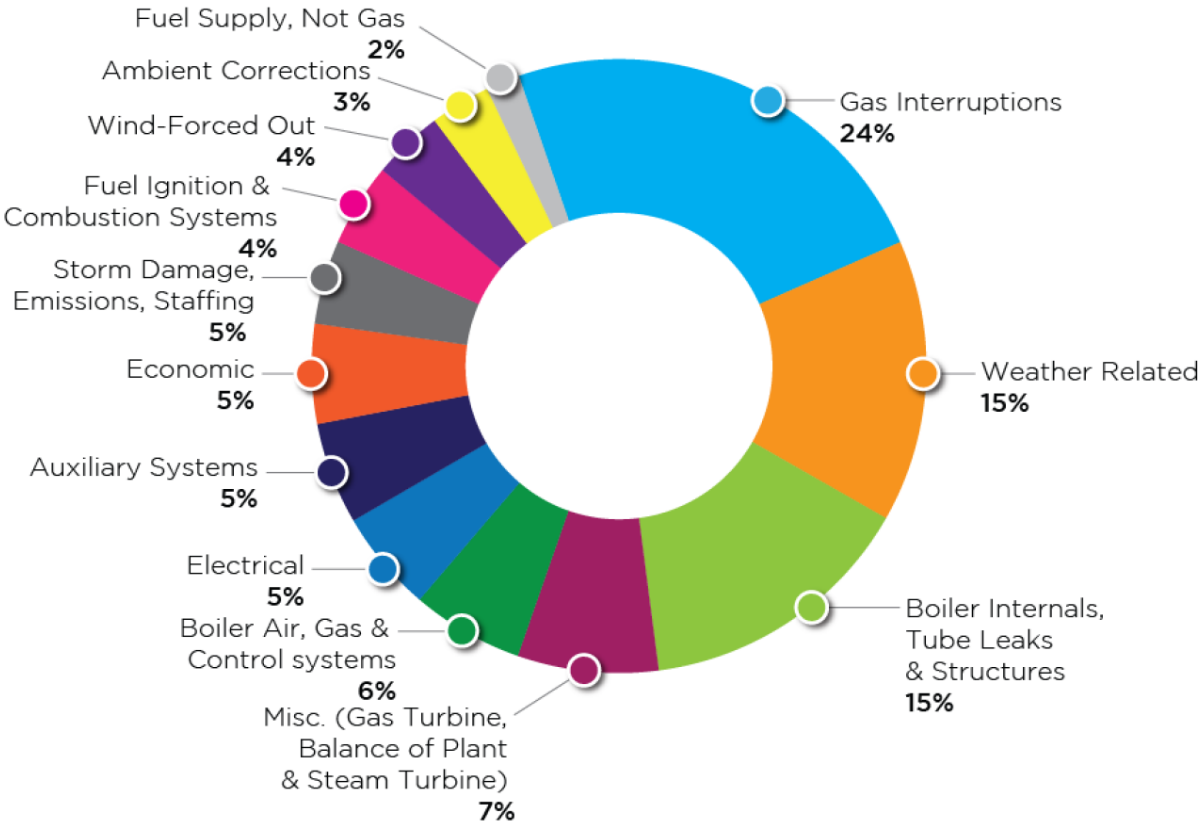


Figure 2.1 Generation Outage Causes during the Polar vortex [8]

Pennsylvania Jersey Maryland Regional Transmission Organization Operating Reserves

PJM was under energy emergency for at least two days during the Polar vortex as its operating reserve margin was insufficient. On January 6 and January 7, 2014, PJM initiated actions to correct the emergency conditions including purchase of energy from outside PJM, load management, and voltage reductions. PJM generation reserve margin during the polar vortex is shown in table 2.3.

Table 2.3 PJM Generation Reserve Margin during Polar Vortex [9]

Synchronized Reserves	01/06/2014 Evening Peak	01/07/2014 Morning Peak	01/07/2014 Evening Peak
Available	919 MW	496 MW	2285 MW
Required	1372 MW	1385 MW	1373 MW
Surplus	-453 MW	-889 MW	912 MW

Primary reserves in PJM are defined as plants that are dispatched but not at full output and can therefore increase energy production to full output fairly quickly if required. Synchronous reserves are plants that are not dispatched but are synchronized with the grid and can produce energy quickly if required. In addition, non-spinning reserves, or offline generators can begin to produce energy if required under emergency conditions.

Figure 2.2 describes PJM operating reserve performance during the evening peak of January 6, 2014, from 4:00-8:30 PM. Figure 2.2 is a graphical view of data provided in the second column of Table 2.3. PJM was operating below both the primary and synchronous reserve margin for approximately 2 hours during the evening peak of January 6, 2014. Emergency procedures, such as voltage reduction, were initiated around 8:00 PM on January 6, 2014 to restore system operating reserve margins to acceptable levels.

Figure 2.3 describes PJM operating reserve performance during the morning peak of January 7, 2014. Figure 2.3 is also a graphical view of the data provided in third column of Table 2.3. PJM was operating below the primary and synchronous reserve margins for approximately 4 hours during the morning peak of January 7, 2014. PJM initiated emergency procedures, such as purchase of emergency energy, during the morning peak of January 7, 2014.

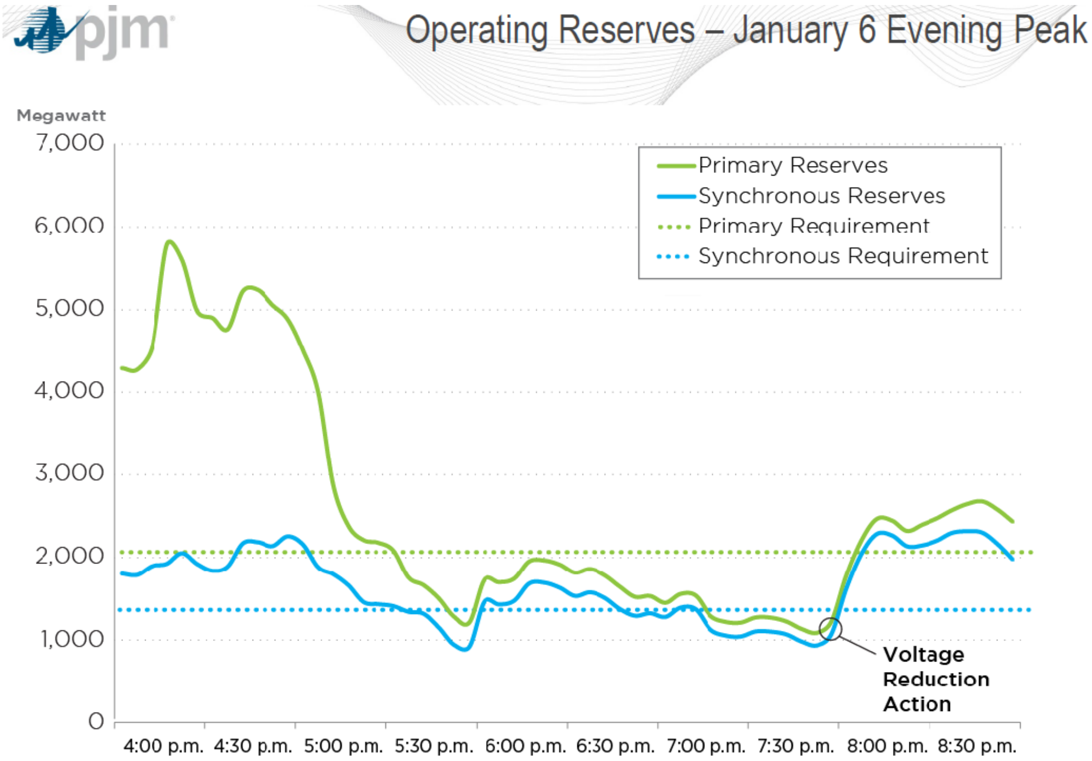


Figure 2.2 PJM Operating Reserves January 6, 2014, Evening Peak [10]

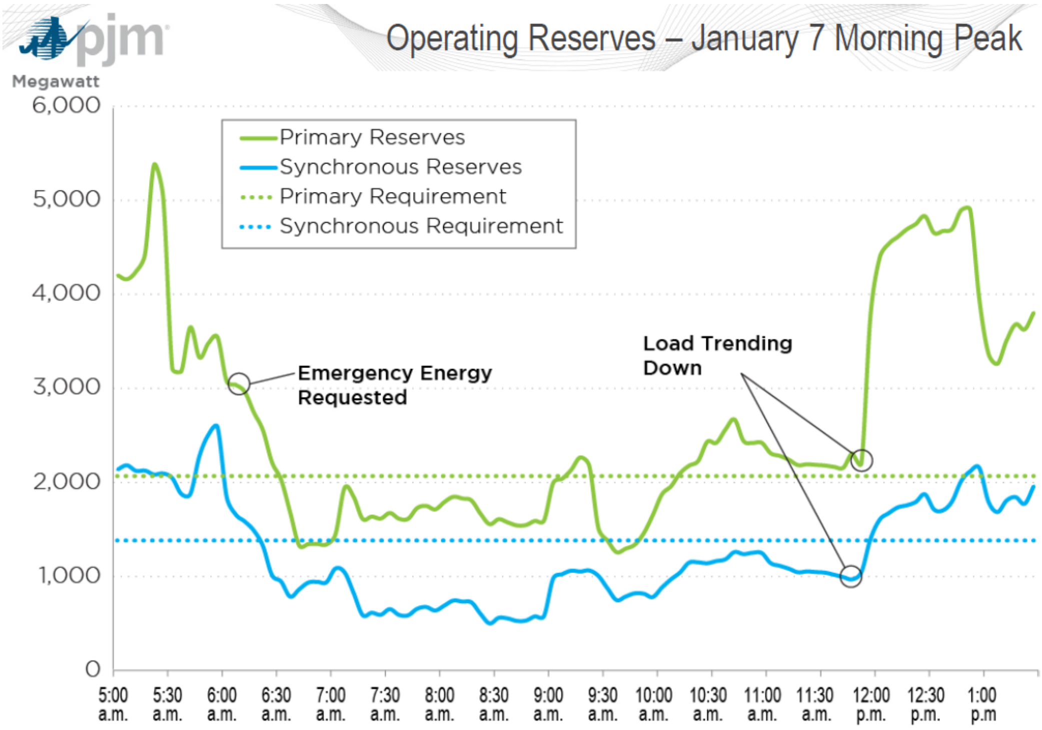


Figure 2.3 PJM Operating Reserves January 7, 2014, Morning Peak [11]

Pennsylvania Jersey Maryland Regional Transmission Organization Net Energy Interchange

As discussed, PJM initiated maximum emergency generation actions during the evening of January 6, 2014, and again during the morning of January 7, 2014. During these events, PJM analyzed current and expected system conditions and explored the possibility of curtailing export interchange schedules with neighboring balancing authorities. Because export curtailment would have negatively impacted PJM's neighbors to the point of additional load curtailments, PJM decided not to limit export schedules. PJM net energy interchange with neighbors on January 7, 2014, is shown in Figure 2.4. As shown in Figure 2.4, PJM net schedule and net actual interchange overlapped for the most part (with the exception of 2 hours) on January 7, 2014.

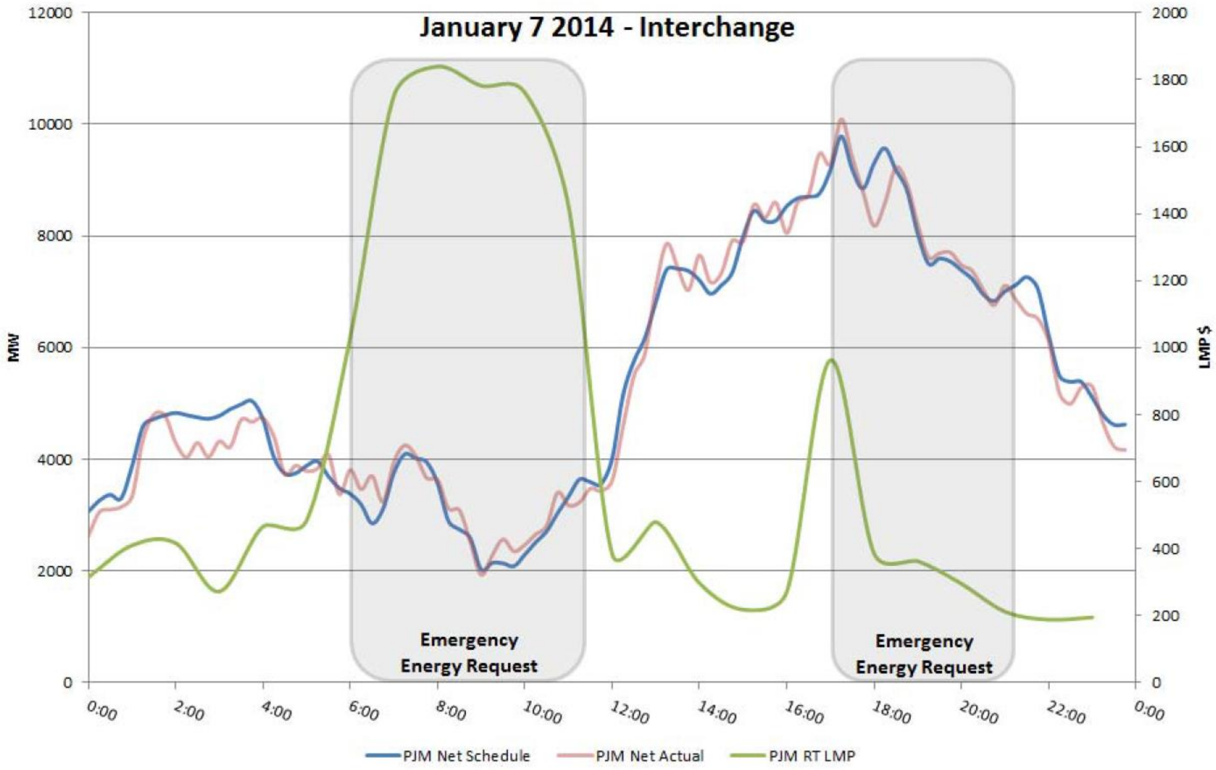


Figure 2.4 PJM Net Energy Interchange with Neighbors during the Polar Vortex [12]

The following sections investigate natural gas prices during the polar vortex and the impact on end users. PJM is responsible for planning, managing and operating the bulk electric system (BES), 100 kV and above in its control area. Therefore, an outage on the BES may not result in an end user (customer) outage. However, increasing or decreasing gas prices result in change in production cost, thereby causing a change in energy cost that becomes consumer's responsibility. Therefore, in addition to analyzing the operational performance of the PJM grid during the polar vortex, trends of natural gas prices during the polar vortex must also be analyzed.

Natural Gas Prices and Load Weighted Locational Marginal Pricing

As shown in Figure 2.5, natural gas prices were as high as $60/MMbtu during the peak load demand of January 7, 2014 resulting in an average load weighted Locational Marginal Pricing (LMP) of approximately $680/MWh during the peak of January 7, 2014.

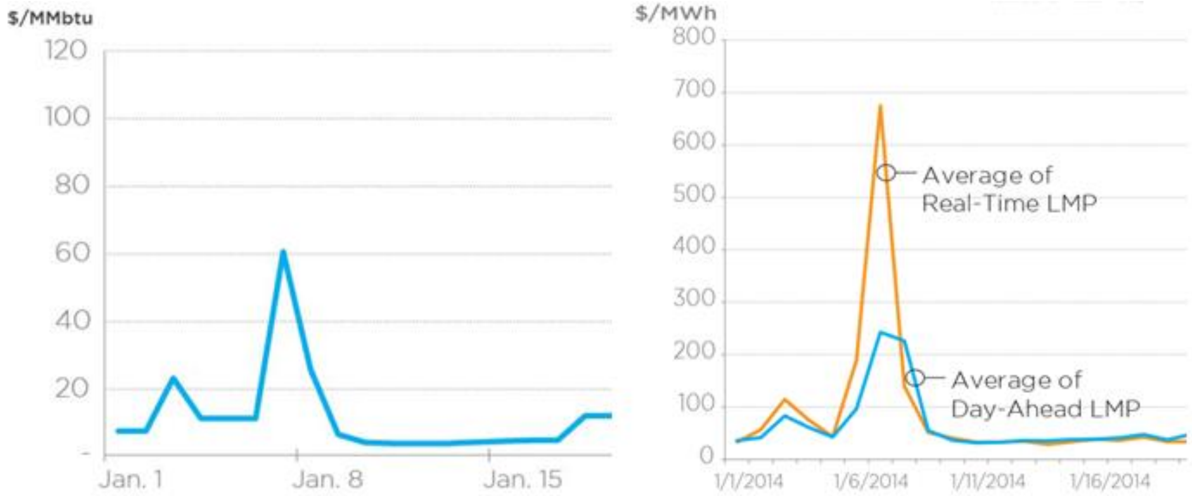


Figure 2.5 Gas Prices of East Market during the Polar Vortex [13]

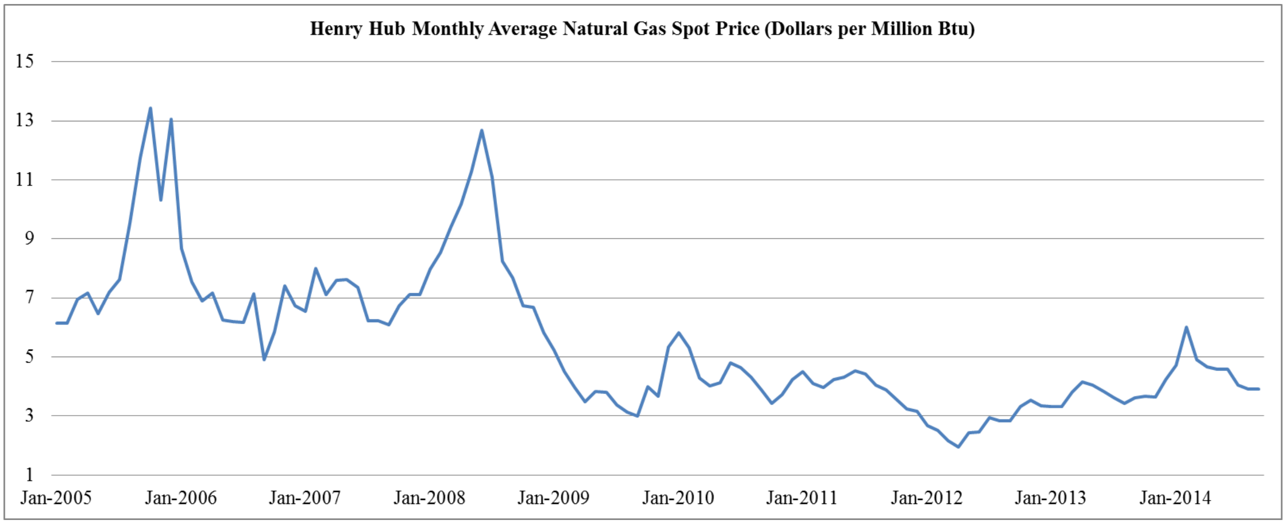


Figure 2.6 Henry Hub Monthly Average Natural Gas Spot Price [14]

Figure 2.6 shows the trend of natural gas prices over the past 10 years. A downward trend of natural gas prices began towards the end of 2009. Although, current monthly average gas prices are still lower than prices between 2005 and 2009, the polar vortex caused a spike in natural gas prices; monthly average gas prices reached an all-time high since the prices dropped in 2009.Since the polar vortex in 2014, average monthly gas prices have been consistently higher compared to prior years (after 2009). Although natural gas is currently inexpensive but it may not remain so as more power plants convert to natural gas. The natural gas market is very fragile: As soon as the demand for natural gas increases, gas prices quickly increase.

Chapter 1 of this report briefly introduced the polar vortex phenomenon and Chapter 2 explained PJM RTO. Operational performance of the electric grid during the polar vortex was also discussed in relation to real-time transmission constraints, major outages on the transmission and generation systems, and PJM operational reserve margin. In addition, natural gas prices and the impact on LMP were discussed, and a comparison between natural gas prices during the polar vortex and prior years was made. Chapter 3 investigates future load flow reliability assessment of the PJM grid.

Chapter 3 - Load Flow Reliability Assessment

This section includes load flow analysis performed by preparing a custom load flow case. The intent is to access system reliability and readiness if polar vortex conditions reoccur in the future; taking into account announced 2015 coal generation retirements and associated approved transmission upgrades.

Step 1: Load Flow Base Case

A 2018 summer peak PJM Regional Transmission Expansion Plan (RTEP) model was used as a starting point for the study. The case had built-in 2018 approved system topology, including 2015 generation retirement and associated approved transmission upgrades to address transmission system limitations as a result of retirements. A list of all PJM generators to be retired and a list of PJM-approved transmission upgrades to mitigate system issues as a result of generation retirement are provided in Appendix A.

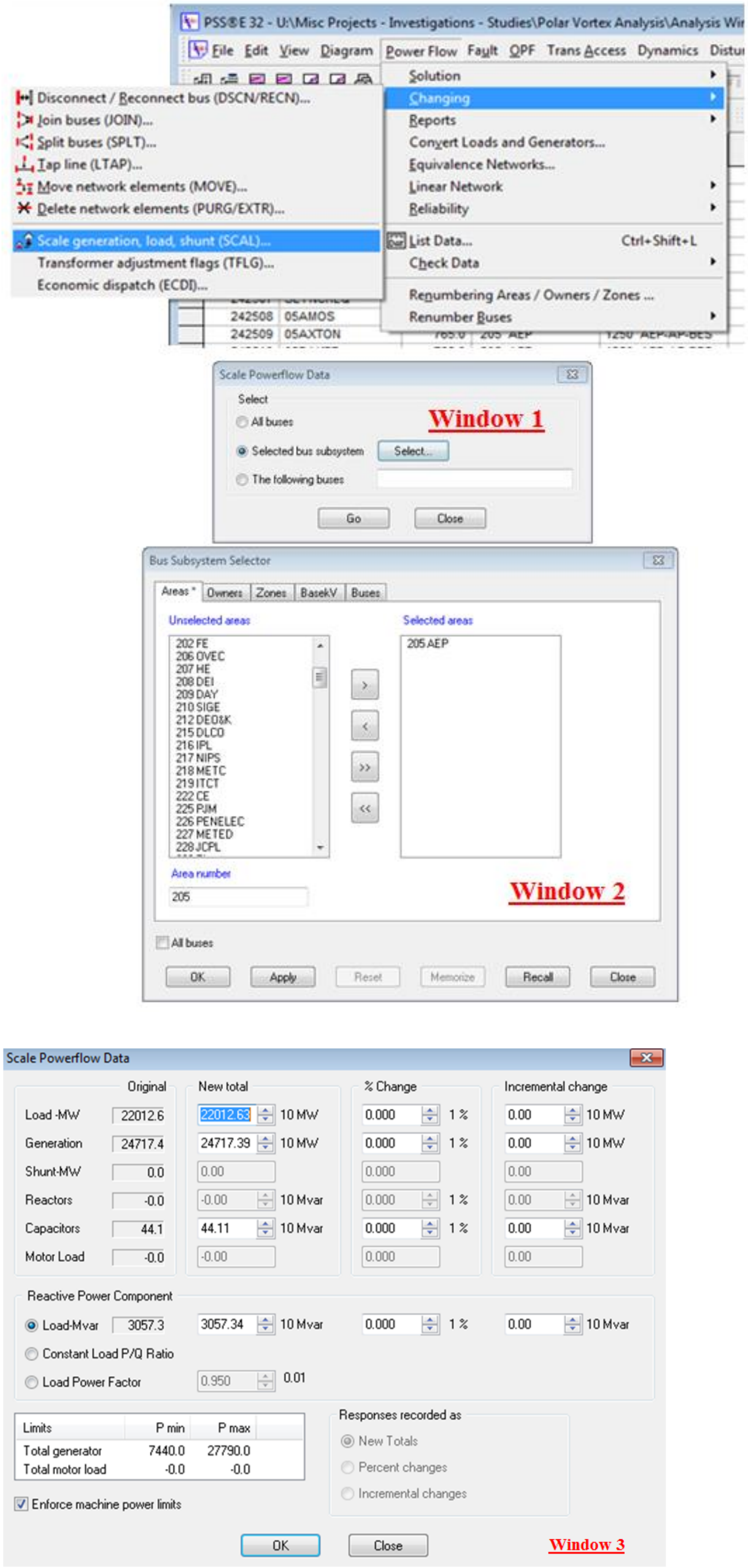
Step 2: Base Case Modifications to Match Polar Vortex Conditions

Polar vortex conditions for the PJM control area, including load demand, generation dispatch, and energy interchange were applied to load flow case under Step 1. Load demand and generation dispatch information for the PJM control area during the polar vortex is provided in Appendix B. This was an intense process because the load and respective generation amounts had to be changed in very small increments in order for the load flow case to solve. Although the study area was PJM, generation outside PJM had to be scaled up or down depending on the location in order to match flows between areas during the polar vortex.

Generation and load dispatch was readjusted to match polar vortex conditions using PTI Siemens PSS/E software. Steps are shown in Figure 3.1. In the upper tab clicking on the "Power

Flow” button, then “Changing button “ button and, then “Scale Generation button, Load, Shunt (SCAL)” button opens window 1. Clicking “select” under window 1 opens window 2. Because the study area was PJM, all PJM area companies were entered in order to change their generation and load demand dispatch. In Figure 3.1, American Electric Power Company (AEP) is selected under Window 2 and, “Ok” was selected consequently opening Window 3, as shown in Figure 3.1. As mentioned load and generation was changed in small increments to ensure good case solution. PSS/E case solution options are shown in Figure 3.2.

As demonstrated in Figure 3.2, “Solve” button on the Graphical User Interface (GUI) is shown in a red box in the top left corner and case solution status is shown in the bottom right corner in a red box. If the case successfully solves, the status bar reads as “Met Convergence Tolerance”; if the case does not successfully solve, the status bar shows “Iterations Limits Exceeded” or “Blown Up”, thereby initiating troubleshooting steps that are beyond the scope of this report. Case solution settings are shown in Figure 3.2. A “Fixed sloped decoupled Newton-Raphson” method was used for this study. Tap adjustments were selected to “Stepping,” switched shunt adjustments were selected to “Enable all,” area interchange control was selected to “Disabled,” and VAR limits were selected to “Apply immediately.” Area interchange was enforced manually afterwards. These solution settings are standard settings recommended by PJM. Because swing machine picks up system slack, status of the swing machine in the case is a vital item of study while solving case, as shown in figure 3.2. P and Q values for the slack machine must be within predefined maximum and minimum limits. As shown in Figure 3.2, 1BR FERRY, or the case swing machine (selected by PJM) in this particular screenshot generated P and Q values within defined maximum and minimum limits.



Window 1 – Scale Powerflow Data

Select

○ All buses

● Selected bus subsystem [Select...]

○ The following buses

Window 2 – Bus Subsystem Selector

Unselected areas: 202 FE, 206 OVEC, 207 HE, 208 DEI, 209 DAY, 210 SIGE, 212 DEO&K, 215 DLCO, 216 IPL, 217 NIPS, 218 METC, 219 ITCT, 222 CE, 225 PJM, 226 PENELEC, 227 METED, 228 JCPL

Selected areas: 205 AEP

Area number: 205

☐ All buses

Window 3 – Scale Powerflow Data

	Original	New total		% Change		Incremental change	
Load -MW	22012.6	22012.63	10 MW	0.000	1 %	0.00	10 MW
Generation	24717.4	24717.39	10 MW	0.000	1 %	0.00	10 MW
Shunt-MW	0.0	0.00		0.000		0.00	
Reactors	-0.0	-0.00	10 Mvar	0.000	1 %	0.00	10 Mvar
Capacitors	44.1	44.11	10 Mvar	0.000	1 %	0.00	10 Mvar
Motor Load	-0.0	-0.00		0.000		0.00	

Reactive Power Component

● Load-Mvar	3057.3	3057.34	10 Mvar	0.000	1 %	0.00	10 Mvar
○ Constant Load P/Q Ratio							
○ Load Power Factor		0.950	0.01				

Limits	P min	P max
Total generator	7440.0	27790.0
Total motor load	-0.0	-0.0

☑ Enforce machine power limits

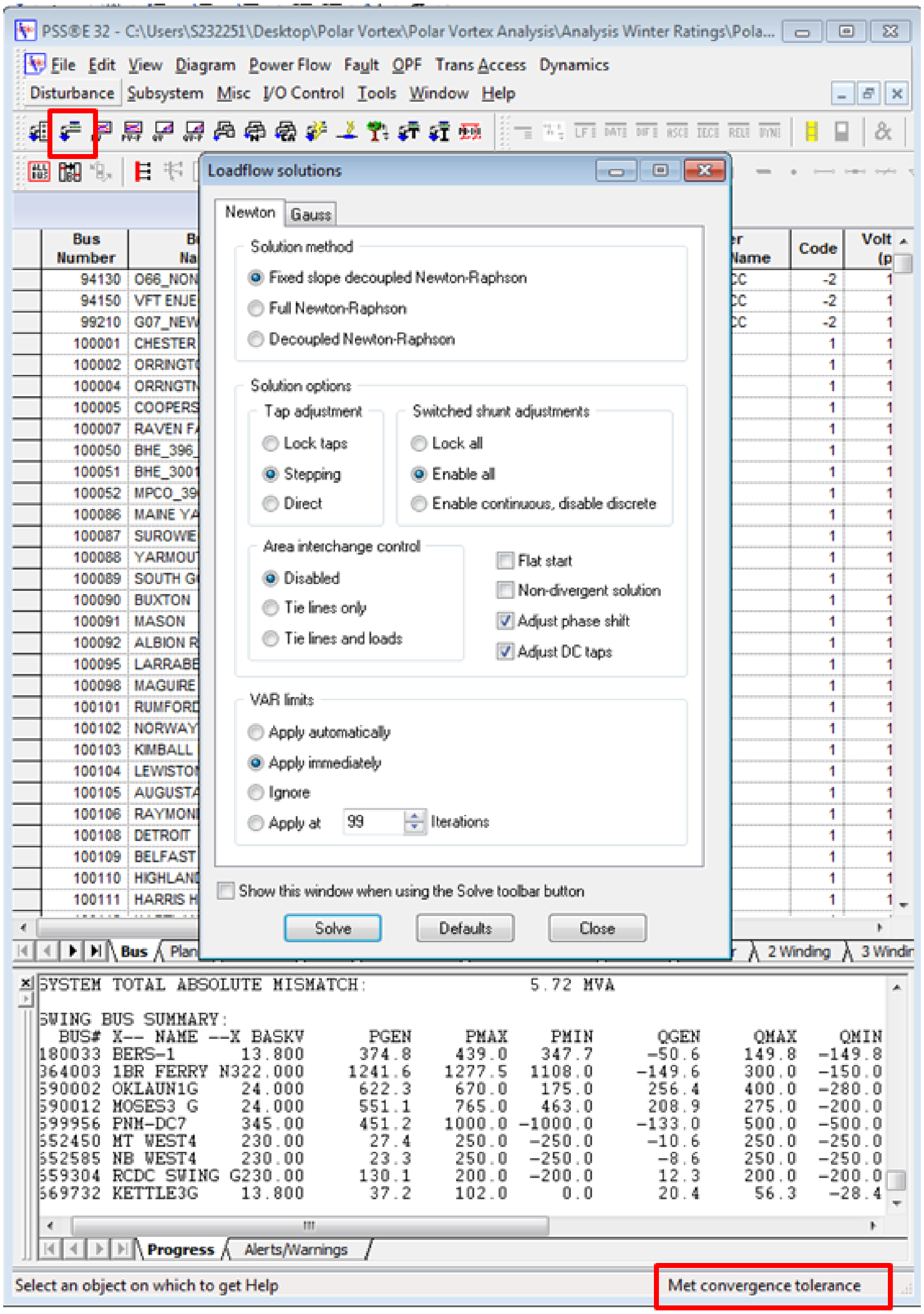
Responses recorded as

● New Totals

○ Percent changes

○ Incremental changes

Figure 3.1 PSS/E Steps to Adjust Generation and Load Dispatch



Bus Number	Bı Na	ır Name	Code	Volt (p
94130	O66_NON	CC	-2	1
94150	VFT ENJE	CC	-2	1
99210	G07_NEW	CC	-2	1
100001	CHESTER		1	1
100002	ORRINGT		1	1
100004	ORRNGTI		1	1
100005	COOPERS		1	1
100007	RAVEN F		1	1
100050	BHE_396_		1	1
100051	BHE_3001		1	1
100052	MPCO_39		1	1
100086	MAINE YA		1	1
100087	SUROWIE		1	1
100088	YARMOUT		1	1
100089	SOUTH G		1	1
100090	BUXTON		1	1
100091	MASON		1	1
100092	ALBION R		1	1
100095	LARRABE		1	1
100098	MAGUIRE		1	1
100101	RUMFORD		1	1
100102	NORWAY		1	1
100103	KIMBALL		1	1
100104	LEWISTO		1	1
100105	AUGUSTA		1	1
100106	RAYMONI		1	1
100108	DETROIT		1	1
100109	BELFAST		1	1
100110	HIGHLANI		1	1
100111	HARRIS H		1	1

Solution method
- ● Fixed slope decoupled Newton-Raphson
- ○ Full Newton-Raphson
- ○ Decoupled Newton-Raphson

Solution options

Tap adjustment
- ○ Lock taps
- ● Stepping
- ○ Direct

Switched shunt adjustments
- ○ Lock all
- ● Enable all
- ○ Enable continuous, disable discrete

Area interchange control
- ● Disabled
- ○ Tie lines only
- ○ Tie lines and loads

- ☐ Flat start
- ☐ Non-divergent solution
- ☑ Adjust phase shift
- ☑ Adjust DC taps

VAR limits
- ○ Apply automatically
- ● Apply immediately
- ○ Ignore
- ○ Apply at 99 Iterations

☐ Show this window when using the Solve toolbar button

```
SYSTEM TOTAL ABSOLUTE MISMATCH:                5.72 MVA

SWING BUS SUMMARY:
  BUS# X-- NAME --X BASKV      PGEN     PMAX    PMIN      QGEN     QMAX    QMIN
180033 BERS-1       13.800    374.8    439.0   347.7     -50.6    149.8  -149.8
364003 1BR FERRY N322.000    1241.6   1277.5  1108.0    -149.6    300.0  -150.0
590002 OKLAUN1G     24.000    622.3    670.0   175.0     256.4    400.0  -280.0
590012 MOSES3 G     24.000    551.1    765.0   463.0     208.9    275.0  -200.0
599956 PNM-DC7      345.00    451.2   1000.0 -1000.0    -133.0    500.0  -500.0
652450 MT WEST4     230.00     27.4    250.0  -250.0     -10.6    250.0  -250.0
652585 NB WEST4     230.00     23.3    250.0  -250.0      -8.6    250.0  -250.0
659304 RCDC SWING G230.00    130.1    200.0  -200.0      12.3    200.0  -200.0
669732 KETTLE3G     13.800     37.2    102.0     0.0      20.4     56.3   -28.4
```

Select an object on which to get Help

Met convergence tolerance

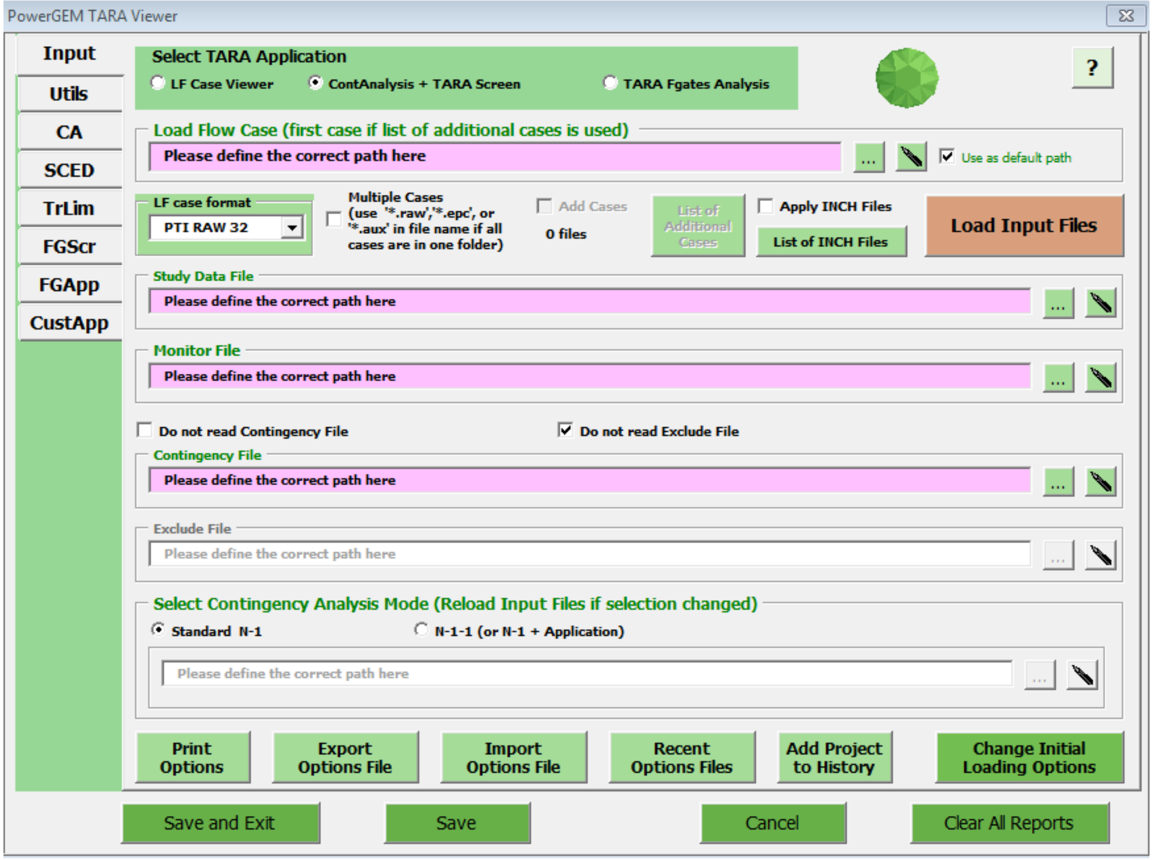
Figure 3.2 PSS/E Case Solution

Step 3: Load Flow Analysis

PowerGEM's TARA tool was used to perform the load flow analysis using the case in Step 2. Case was built using PTI Siemen's PSS/E software.

TARA Tool Graphical User Interface

This section explains the graphical user interface (GUI) of the TARA tool and the steps to initiate a contingency analysis in TARA. Load flow study case, study data file, monitor file, and contingency files were individually loaded and then the "Load Input Files" button was selected to load all input files correctly. The PSS/E tool directly produces the load flow case file, as explained in the previous section. Details regarding the "Contingency File" will be explained later. "Study Data File" and "Monitor File" are shown in Figure 3.4 and Figure 3.5 respectively.


PowerGEM TARA Viewer

Select TARA Application
○ LF Case Viewer ● ContAnalysis + TARA Screen ○ TARA Fgates Analysis

Load Flow Case (first case if list of additional cases is used)
Please define the correct path here
☑ Use as default path

LF case format: PTI RAW 32
☐ Multiple Cases (use '*.raw','*.epc', or '*.aux' in file name if all cases are in one folder)
☐ Add Cases
0 files
☐ Apply INCH Files

Study Data File
Please define the correct path here

Monitor File
Please define the correct path here

☐ Do not read Contingency File
☑ Do not read Exclude File

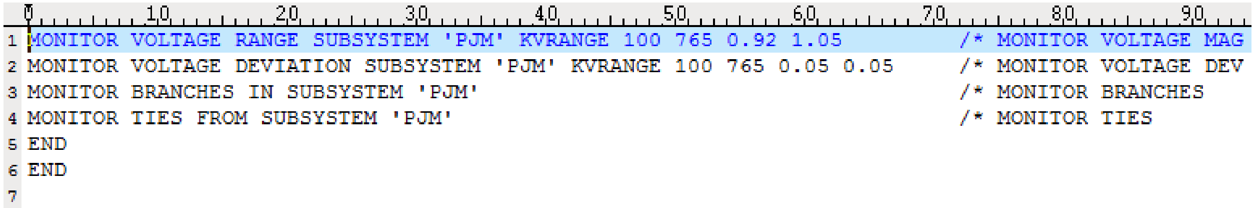
Contingency File
Please define the correct path here

Exclude File
Please define the correct path here

Select Contingency Analysis Mode (Reload Input Files if selection changed)
● Standard N-1 ○ N-1-1 (or N-1 + Application)
Please define the correct path here

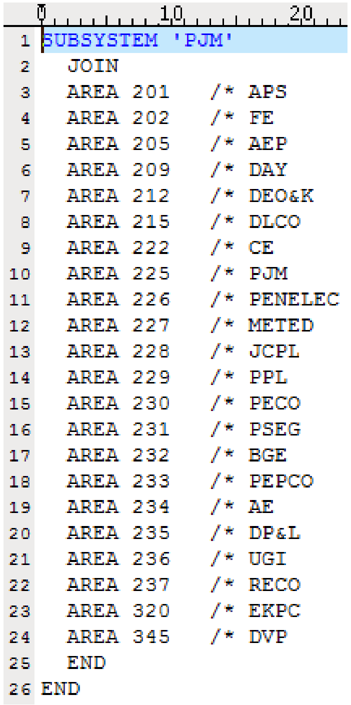
Figure 3.3 PowerGEM TARA Tool GUI

Generic monitor file code is shown in Figure 3.4. For example, the PJM Bulk Electric System (BES), or facilities between 100 kV and 765 kV, must maintain voltage between 0.92 PU (per unit) and 1.05 PU, and the magnitude of voltage deviation for a particular PJM BES facility must not exceed 5%, as shown in Figure 3.4. As shown on line 4, Figure 3.4, monitor file calls subsystem “PJM”. Details on subsystem PJM are shown in Figure 3.4. All PJM companies were listed by area number in the subsystem file.



```
1 MONITOR VOLTAGE RANGE SUBSYSTEM 'PJM' KVRANGE 100 765 0.92 1.05         /* MONITOR VOLTAGE MAG
2 MONITOR VOLTAGE DEVIATION SUBSYSTEM 'PJM' KVRANGE 100 765 0.05 0.05     /* MONITOR VOLTAGE DEV
3 MONITOR BRANCHES IN SUBSYSTEM 'PJM'                                     /* MONITOR BRANCHES
4 MONITOR TIES FROM SUBSYSTEM 'PJM'                                       /* MONITOR TIES
5 END
6 END
7
```

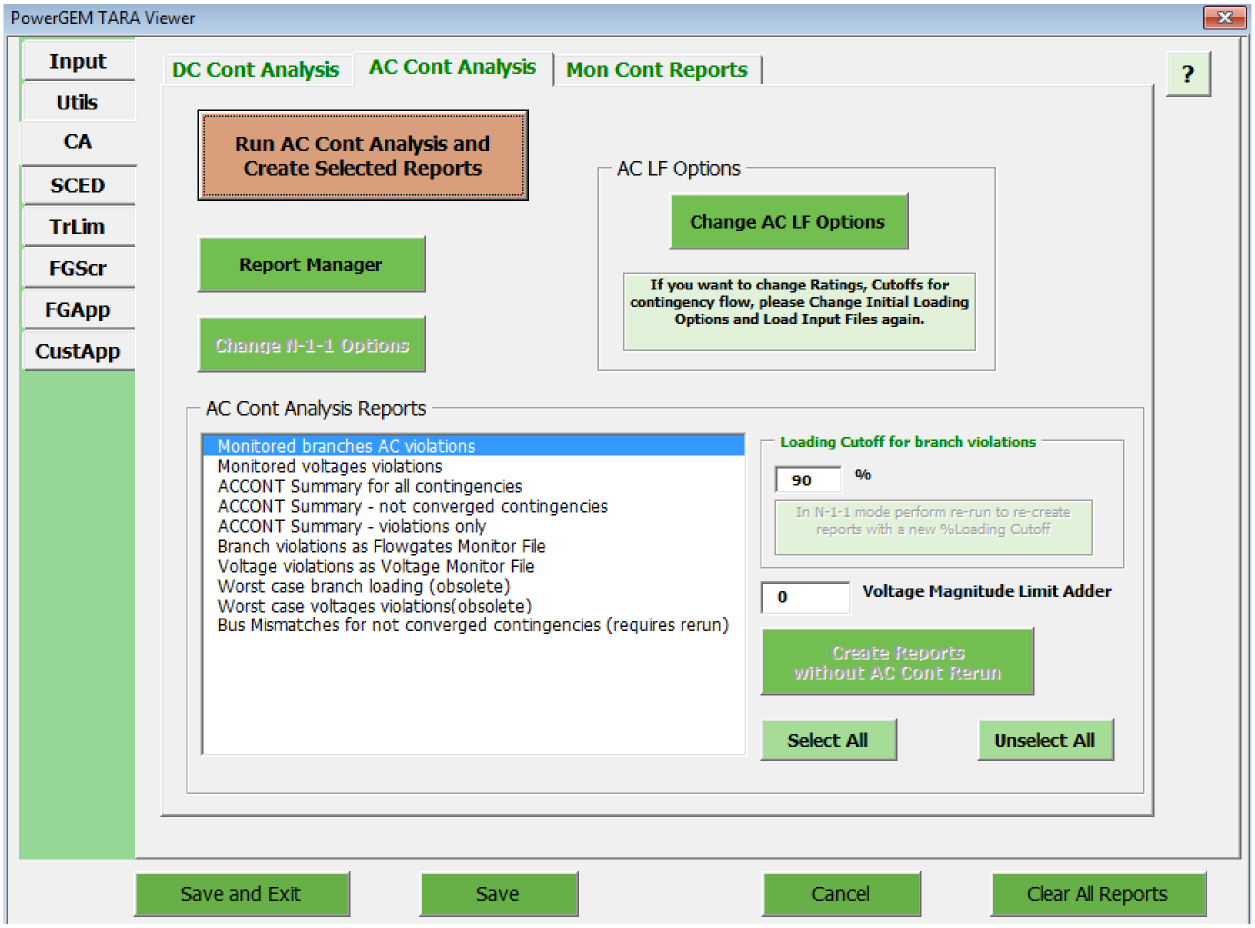
Figure 3.4 Monitor File Code



```
SUBSYSTEM 'PJM'
  JOIN
  AREA 201   /* APS
  AREA 202   /* FE
  AREA 205   /* AEP
  AREA 209   /* DAY
  AREA 212   /* DEO&K
  AREA 215   /* DLCO
  AREA 222   /* CE
  AREA 225   /* PJM
  AREA 226   /* PENELEC
  AREA 227   /* METED
  AREA 228   /* JCPL
  AREA 229   /* PPL
  AREA 230   /* PECO
  AREA 231   /* PSEG
  AREA 232   /* BGE
  AREA 233   /* PEPCO
  AREA 234   /* AE
  AREA 235   /* DP&L
  AREA 236   /* UGI
  AREA 237   /* RECO
  AREA 320   /* EKPC
  AREA 345   /* DVP
  END
END
```

Figure 3.5 Subsystem File Code

When all specified files specified were successfully loaded, the “CA” button was selected to open the window shown in Figure 3.6. AC contingency analysis was used for this analysis. Desired AC contingency analysis reports were selected and “Run AC Contingency Analysis and Create Selected Reports” button was selected to initiate the run. AC contingency reports selected for this study included “Monitored branches AC violations,” “Monitored voltage violation,” and “ACCONT Summary for all contingencies.”



If you want to change Ratings, Cutoffs for contingency flow, please Change Initial Loading Options and Load Input Files again.

AC Cont Analysis Reports:

- Monitored branches AC violations
- Monitored voltages violations
- ACCONT Summary for all contingencies
- ACCONT Summary - not converged contingencies
- ACCONT Summary - violations only
- Branch violations as Flowgates Monitor File
- Voltage violations as Voltage Monitor File
- Worst case branch loading (obsolete)
- Worst case voltages violations(obsolete)
- Bus Mismatches for not converged contingencies (requires rerun)

Loading Cutoff for branch violations: 90 %

In N-1-1 mode perform re-run to re-create reports with a new %Loading Cutoff

0 Voltage Magnitude Limit Adder

Figure 3.6 PowerGEM TARA Tool Contingency Analysis GUI

NERC TPL Standards

Normal system, single contingency, and multiple contingency analyses were performed specified in North American Electric Reliability Corporation (NERC) Transmission Planning

(TPL) TPL-001, TPL-002 and TPL-003 standards. Details of NERC TPL standards are provided in Table 3.1.

Table 3.1 NERC TPL Standards

Standard	Category	Contingencies
TPL-001 (Normal System)	A	All Facilities in Service
TPL-0002 (Single Contingency)	B1	Fault Involving Generator Unit
	B2	Fault Involving Line
	B3	Fault Involving Transformer
TPL-0003 (Multiple Contingencies)	C1	Fault Involving Station Bus
	C2	Fault Involving Breaker Failure
	C5	Fault Involving Tower Lines

Contingency definitions are explained by the station oneline diagram shown in Figure 3.7. Normal system conditions imply that everything is in-service with no system outages. A fault involving a generator means outage of a single generator, and fault involving a line means outage of a single line. For example, in Figure 3.7, a Category B2 contingency would be outage of line C, B1, B2, E, F, G, or H. No other facility would be out of service under the given station configuration. A fault involving a transformer means outage of a single transformer. For example, in Figure 3.7, a Category B3 contingency would be outage of a transformer between the circuit breaker (CB) A2 and CB E. No other facility would be out of service under the given station configuration.

Category C1 contingency under the station configuration shown in Figure 3.7 would be fault on 345 kV bus1, 345 kV bus2, or the 138 kV bus. A fault involving 345 kV bus1 would open CB C1 and B1, and no line would trip under this fault. A fault involving 345 kV bus2 would open CB A2, B2, and C1. Line C would also trip under a fault involving 345 kV bus2. A fault involving 138 kV bus would open circuit breaker E, F, G, and H, implying that, line F, line

G, and line H would also open under a fault involving 138 kV bus with the given station configuration. Category C2 contingency under the station configuration shown in Figure 3.7 could be a failure of CB C1, B1, B, B2, A2, E, F, G, or H. If a fault occurred on line C, in order to isolate this fault, CB C1, A2, and B2 would open under the given station configuration in Figure 3.7. If CB C1 failed to open, CB B1 would open to isolate the fault on line C. This scenario describes a Category C2 contingency involving CB C1. If a fault occurred on line F, in order to isolate this fault, CB F would open under the given station configuration in Figure 3.7. If CB F fails to open, in order to isolate the fault on line F, CB E, G, and H would also open. The scenario describes a Category C2 contingency involving CB F. Category C5 contingency under the station configuration shown in Figure 3.7 would be a fault involving tower line carrying line B1 and B2. In order to isolate this fault, CB B1 and B2 would open to clear the fault on the tower line.

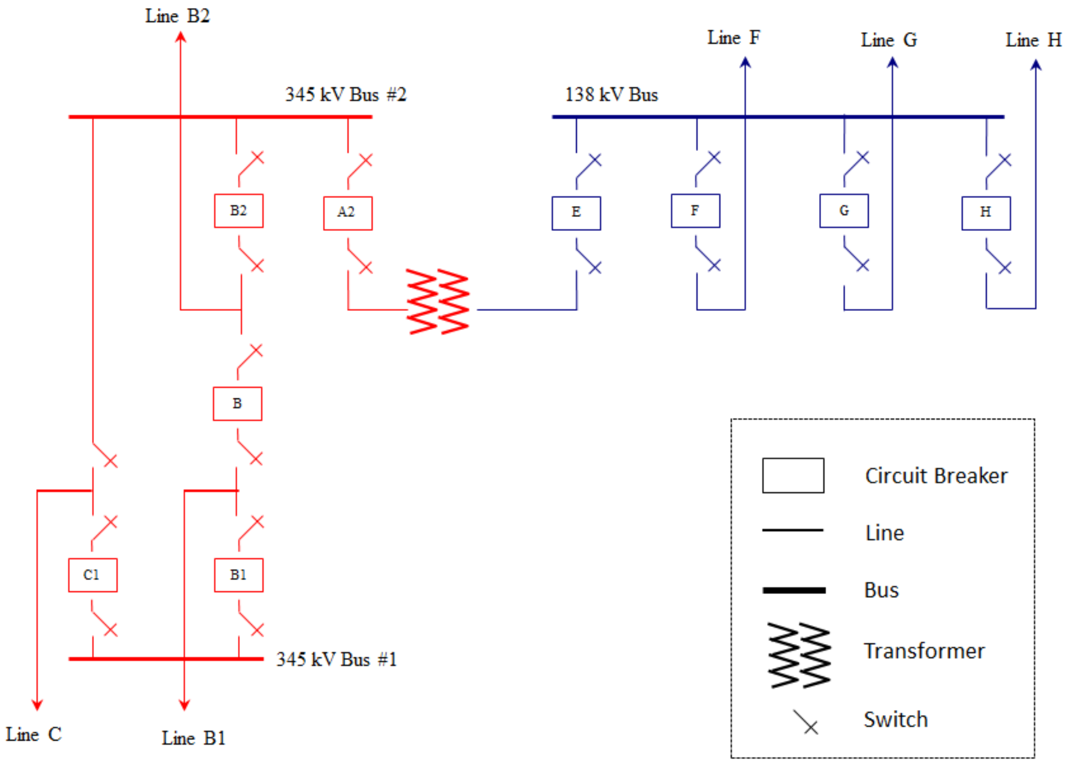
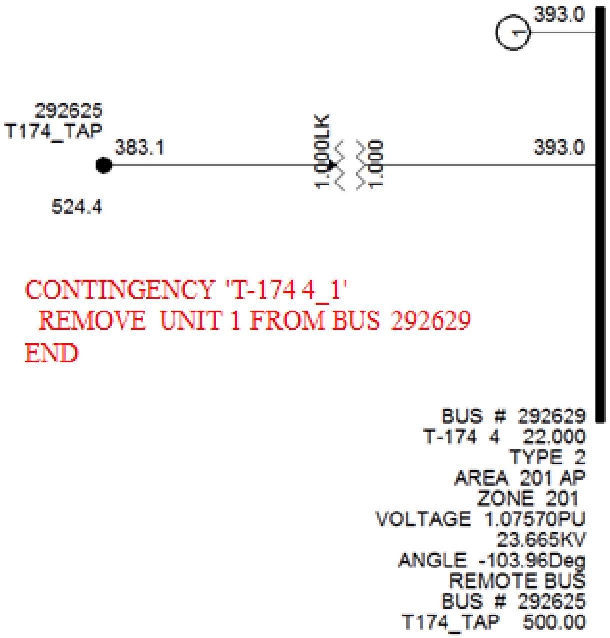


Figure 3.7 Sample Station Simplified Oneline Diagram

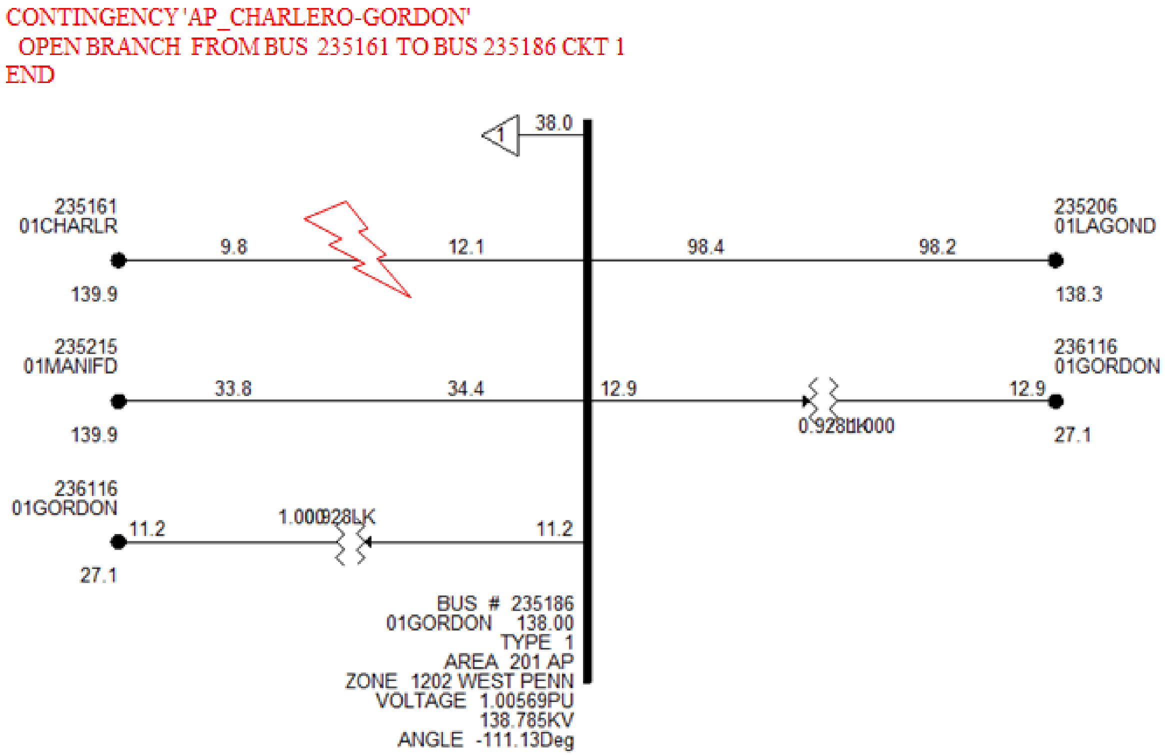
North America Electric Reliability Corporation Transmission Planning Contingencies and PSS/E Software Illustration

Category B1, B2, B3, C5, C2, and C1 contingency definitions and PSS/E model illustrations are shown in Figures 3.8 to 3.13, respectively. Red text in these figures denotes contingency definition directly from the contingency file (.con extension). As shown in Figure 3.8, unit 1 from T-174 4 bus was removed to represent a Category B1 contingency (single generator outage) involving the T-174 4 Generator 1. Similarly, as shown in Figure 3.9, the branch between 01GORDON and 01CHARLR buses was removed to represent a Category B2 (single line outage) contingency involving the GORDON-CHARLR 138 kV line. As shown in Figure 3.10, the transformer branch between 08TERMNL 345 kV bus and 08TERMNL 138 kV bus was removed to represent a Category B3 contingency (single transformer outage) involving the TERMNL 345/138 kV transformer. As shown in Figure 3.11, branches between 01BEDNGT 138 kV and 01MARLOW 138 kV buses and 01BEDNGT 138 kV and 01SHEPRD 138 kV buses was removed to represent a Category C5 contingency (tower outage) involving the double circuit 138 kV tower line between 01BEDNGT and 01MARLOW/01SHEPRD buses. Figure 3.12 shows that the branch between 05FOSTOR 345 kV bus and 05ELIMA 345 kV bus and also the transformer branch between 05FOSTOR 345 kV bus and 05FOSTOR 138 kV bus was removed to represent a Category C2 contingency (circuit breaker failure) involving a circuit at 05FOSTOR 345 kV station. Finally as shown in Figure 3.13, the branch between 05E.LPSC 138 kV bus and 02RICHJ 138 kV bus, the transformer branch between 05E.LPSC 138 kV bus and 05ELEIPL 13.2 kV bus, and the transformer branch between 05E.LPSC 138 kV bus and E.LEIPSC 71.0 kV bus was removed to represent a Category C1 contingency (bus outage) at E.LIPSC 138 kV station.



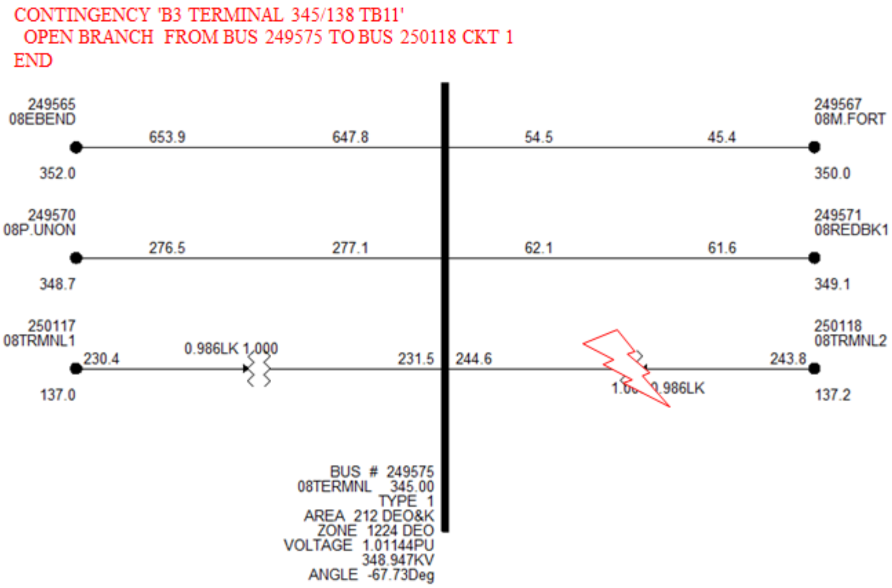
```
CONTINGENCY 'T-174 4_1'
 REMOVE  UNIT 1 FROM BUS  292629
END
```

Figure 3.8 Sample Category B1 Contingency Definition and PSS/E Model Illustration



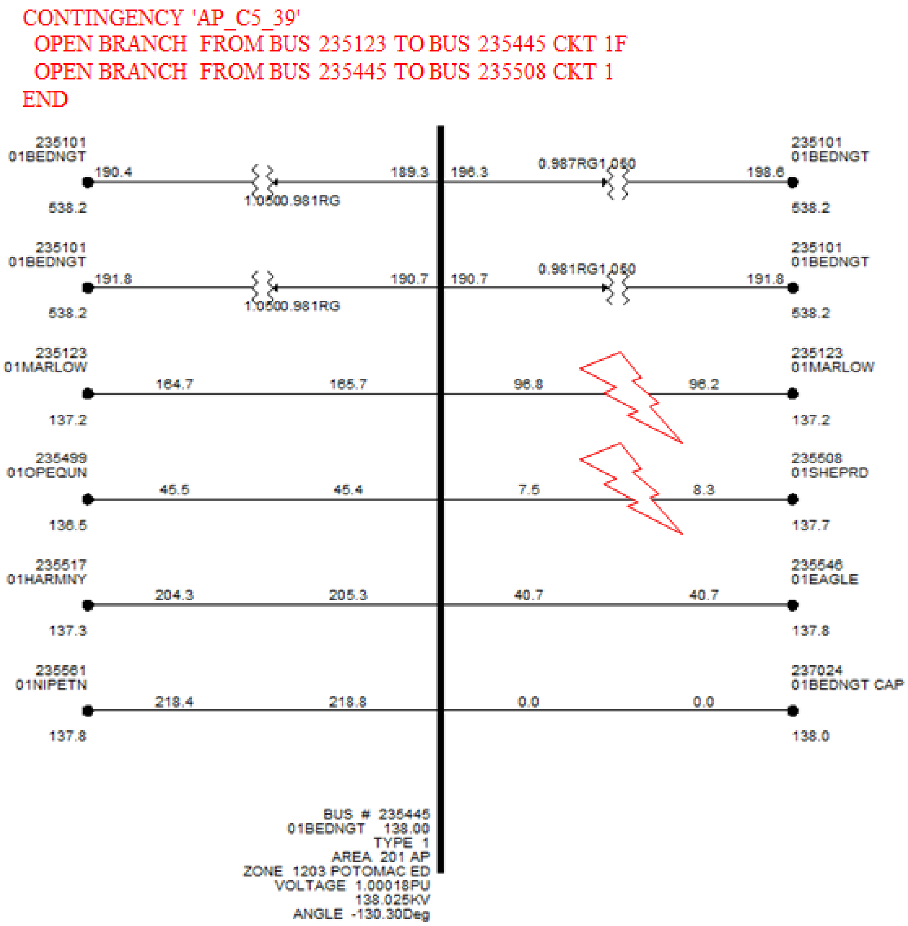
```
CONTINGENCY 'AP_CHARLERO-GORDON'
 OPEN BRANCH  FROM BUS  235161 TO BUS 235186 CKT 1
END
```

Figure 3.9 Sample Category B2 Contingency Definition and PSS/E Model Illustration



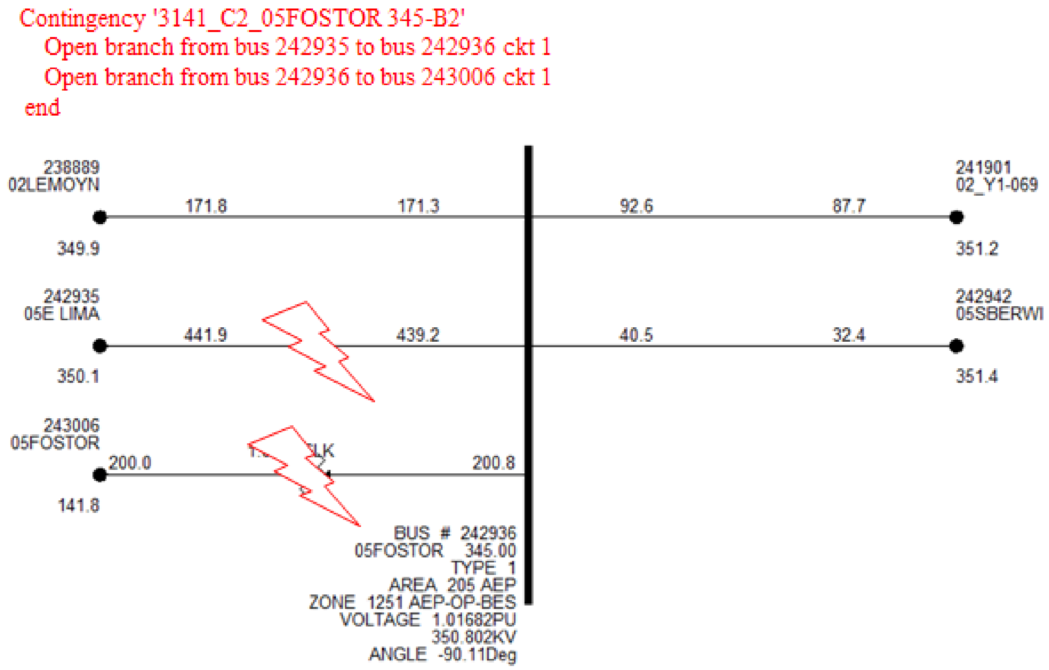
```
CONTINGENCY 'B3 TERMINAL 345/138 TB11'
  OPEN BRANCH  FROM BUS 249575 TO BUS 250118 CKT 1
END
```

Figure 3.10 Sample Category B3 Contingency Definition and PSS/E Model Illustration



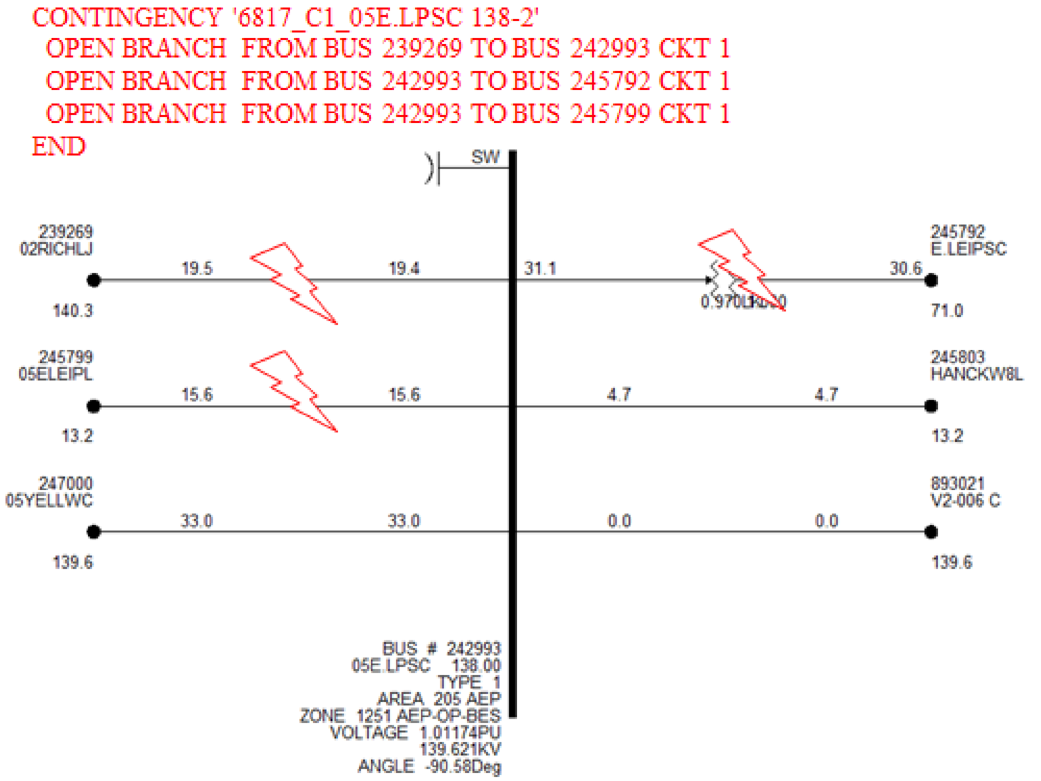
```
CONTINGENCY 'AP_C5_39'
  OPEN BRANCH  FROM BUS 235123 TO BUS 235445 CKT 1F
  OPEN BRANCH  FROM BUS 235445 TO BUS 235508 CKT 1
END
```

Figure 3.11 Sample Category C5 Contingency Definition and PSS/E Model Illustration



```
Contingency '3141_C2_05FOSTOR 345-B2'
   Open branch from bus 242935 to bus 242936 ckt 1
   Open branch from bus 242936 to bus 243006 ckt 1
 end
```

Figure 3.12 Sample Category C2 Contingency Definition and PSS/E Model Illustration



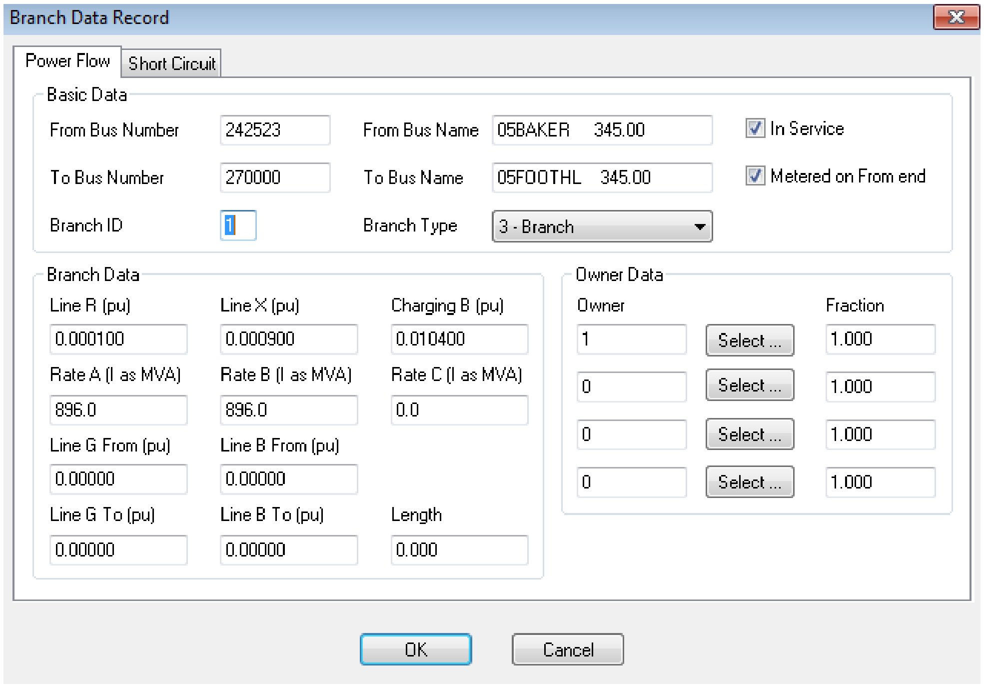
```
CONTINGENCY '6817_C1_05E.LPSC 138-2'
 OPEN BRANCH  FROM BUS 239269 TO BUS 242993 CKT 1
 OPEN BRANCH  FROM BUS 242993 TO BUS 245792 CKT 1
 OPEN BRANCH  FROM BUS 242993 TO BUS 245799 CKT 1
END
```

Figure 3.13 Sample Category C1 Contingency Definition and PSS/E Model Illustration

Step 4: Application of Winter Facility Ratings

As demonstrated in Step 1, a 2018 summer load flow model was used as the initial case, meaning that all the facilities were operating under the summer normal and summer emergency ratings. Because the polar vortex occurred during the winter months and winter ratings are typically higher than summer ratings due to changes in ambient temperatures, summer ratings had to be substituted with winter ratings in the load flow case. Winter load flow models were not available at the time of this study. Instead of manually entering winter ratings of each PJM facility, load flow analysis was performed on the case with summer ratings and a list of overloaded facilities was prepared. Winter ratings were then applied to overloaded facilities to determine whether or not the facilities were still overloaded with winter ratings. If the facilities were overloaded, a refined list of overloaded facilities was prepared. Overloaded transmission facilities (lines and transformers) in the PJM control area at winter ratings under contingency Categories A, B, and C and associated details are provided in Appendix C.

PSS/E branch data record GUI is shown in Figure 3.14. As presented in the figure, the data record contains bus name, number information, and branch/circuit ID. It also contains a check box to indicate whether or not a branch is normally in-service. Branch parameters such as resistance, reactance, and charging can also be entered using this record. Rate A and Rate B are the normal and emergency ratings of the branch. If load flow case is a summer case, Rate A and Rate B would represent summer normal and summer emergency ratings, respectively. Similarly, if the case is a winter case, Rate A and Rate B would represent winter normal and winter emergency ratings, respectively.



Branch Data Record

Power Flow | Short Circuit

Basic Data

From Bus Number: 242523
From Bus Name: 05BAKER 345.00
☑ In Service
To Bus Number: 270000
To Bus Name: 05FOOTHL 345.00
☑ Metered on From end
Branch ID: 1
Branch Type: 3 - Branch

Branch Data

Line R (pu): 0.000100
Line X (pu): 0.000900
Charging B (pu): 0.010400
Rate A (I as MVA): 896.0
Rate B (I as MVA): 896.0
Rate C (I as MVA): 0.0
Line G From (pu): 0.00000
Line B From (pu): 0.00000
Line G To (pu): 0.00000
Line B To (pu): 0.00000
Length: 0.000

Owner Data

Owner		Fraction
1	Select ...	1.000
0	Select ...	1.000
0	Select ...	1.000
0	Select ...	1.000

Figure 3.14 PSS/E Branch Data Record

Step 5: Explanation of the Results

In generally no PJM facility must be overloaded beyond its normal ratings under normal system conditions implying that no facility in the system is out of service. In addition, no PJM facility must be overloaded beyond its emergency ratings under single and multiple contingency conditions. Contingency categories were described in Table 3.1.

Load Shed Value

Load shed value was calculated in order to translate data in Appendix C into easily understood information. For example, approximately 6,300 MW of load would have to be dropped under contingency Category C and approximately 6,000 MW of load would have to be dropped under contingency Category B to ensure that no transmission facility operates beyond its emergency ratings under contingency conditions. Load dump values were calculated by manually removing loads in small increments in proximity of the overloaded facility until facility loadings were restored to acceptable operating conditions. Approximately 6,000 MW of load would be equivalent to the total winter peak load of Public Service Electric and Gas Company (PSEG). PSEG is one of New Jersey's largest utility, serving approximately three fourths of New Jersey's population. A load amount of 6,000 MW would mean dumping approximately 5% of PJM winter peak load of 136,000 MW. The PSEG control area and the state of New Jersey are shown in Figure 3.15. The PSEG control area may appear to be relatively small but PSEG's service territory includes large parts of urban New Jersey.

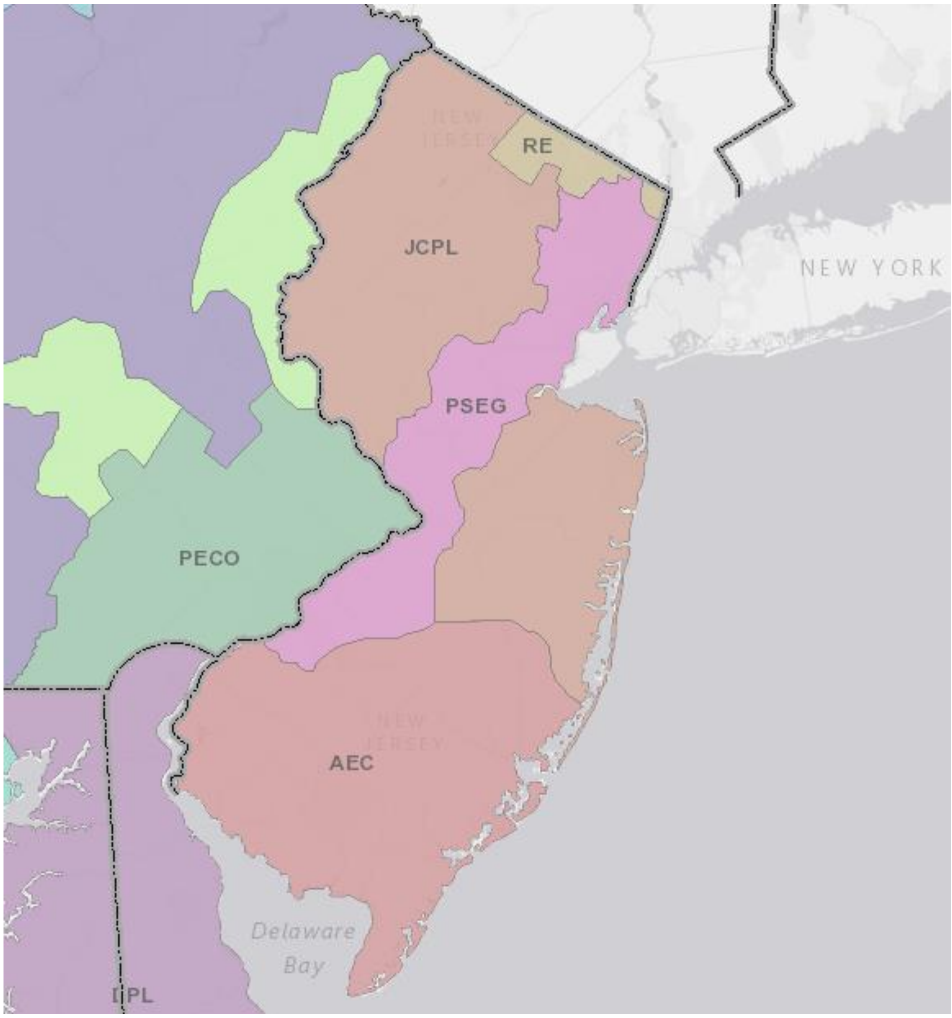


Figure 3.15 PSEG Control Area and the State of New Jersey [15]

Significance of Results

Table 3.2 below lists overloaded transmission facilities by voltage and contingency categories.

Table 3.2 Overloaded Facilities by Voltage Class and Type

Facility Voltage	Type	Count
Contingency Category B		
765/345 kV	Transformer	1
500 kV	Line	1
345 kV	Line	5
230 kV	Line	2
138 kV	Line	54
Sub-Transmission (< 100 kV)	Line/Transformer	85
Contingency Category C		
345 kV	Line	2
500/230 kV	Transformer	1
230 kV	Line	14
345/138 kV	Transformer	2
161/138 kV	Transformer	1
138 kV	Line	36

As shown in Table 3.2, one 765/345 kV transformer, one 500 kV line, five 345 kV lines, two 230 kV lines, fifty-four 138 kV lines and, eighty-five sub transmission facilities were overloaded under contingency Category B. Sub transmission facilities contain lines less than 100 kV and transformers with low side voltage less than 100 kV. For example, a 69 kV line and a 138/69 kV transformer are both classified as sub transmission facilities. In addition, as shown in Table 3.2, two 345 kV lines, one 500/230 kV transformer, fourteen 230 kV lines, two 345/138 kV transformers, one 161/138 kV transformer, and thirty-six 138 kV lines were overloaded under contingency Category C. Note that sub transmission facilities are not planned for Category

C contingencies and, therefore, overloads on the sub transmission facilities under Category C contingencies were ignored for this study.

Shedding load is a last resort, not a standard practice for an electric utility. As a first step, a utility will attempt to improve the system reliability by implementing necessary upgrades. Load shed results in decreased revenue for the company and tarnishes public relations. On the other hand, transmission system upgrades, although entirely possible majority of the times, require time and money to implement. Therefore, in order to address system overloads, approximate cost estimates to undertake upgrades are provided. The objective of the upgrade is to ensure that the system is reliable for single and multiple contingencies. In this study, the state of IN was used as an example to calculate the lower limit of upgrade costs. In general, overhead rural upgrades are less expensive to undertake than underground urban upgrades.

Replacement of an existing 765/345 kV transformer would conceptually cost approximately $20 million. Cost of a new 500 kV line is approximately $3.5 million per mile and cost of a new double circuit 345 kV line is approximately $3 million per mile. Cost of a new 230 kV line, 138 kV line, and 69 kV line is approximately $2 million, $1.5 million and $1 million per mile respectively. Using Table 3.2 an assumption can be made that a 765/345 kV transformer must be replaced, 1 mile of one 500 kV, 1 mile each of five 345 kV lines, 1 mile each of two 230 kV lines, 1 mile each of fifty-four 138 kV lines, and 1 mile each of eighty-five 69 kV lines must be upgraded in order to make the system reliable for a single contingency. Therefore, $210 million must be spent in order for the system to be reliable for single contingency. Another $115 million must be spent in order for the system to be reliable for multiple contingencies. Therefore, a total of $325 million must be spent in order for the system to be reliable for both single and double contingencies under these fictitious assumptions.

All mentioned costs are for overhead rural upgrades; costs increase for underground urban construction. To establish minimum line upgrade cost, an assumption was made that each overloaded transmission line was 1 mile in length. While there could be many other solutions to address a line overload, the solution considered was rebuilding the existing line utilizing a larger conductor so that line power carrying capability could be increased. For example, if fifteen 345 kV lines overloaded under the assumption that each line was 1 mile in length, upgrade cost would be $45 million (cost to upgrade 1 mile of a 345 kV line is $3 million). When line lengths for overloaded lines were calculated from a map, the line lengths appeared to be greater than 1 mile. Therefore, 1 mile minimum line length assumption is realistic to establish minimum upgrade cost.

Graphical Illustration of Selected Results

This section provides graphical illustration of selected overloads. Base maps were taken from PJM’s website and have been modified to reflect various contingency scenarios. Figure 3.16 shows overload on the Ronco-Hatfield 500 kV line (shown in bold green) for the loss of Mount Storm-Doubs 500 kV line (shown in bold blue, contingency Category B2). Two 500 kV lines serve the Mount Storm area (right side of Figure 3.16); therefore, when one 500 kV line is out, a section of the other 500 kV line overloads in an attempt to balance west to east flows into the Mount Storm area. The Ronco-Hatfield 500 kV line is located in southwest Pennsylvania, and the Mount Storm-Doubs 500 kV line is located in northeastern West Virginia and north Virginia. The lower half of Figure 3.16 illustrates the outage and corresponding overload. Out-of-service elements are represented by dotted lines, whereas, the overloaded element is represented by a full red box. The entire bus number 292556 is taken out of service to accurately reflect the outage involving the Mount Storm-Doubs 500 kV line.

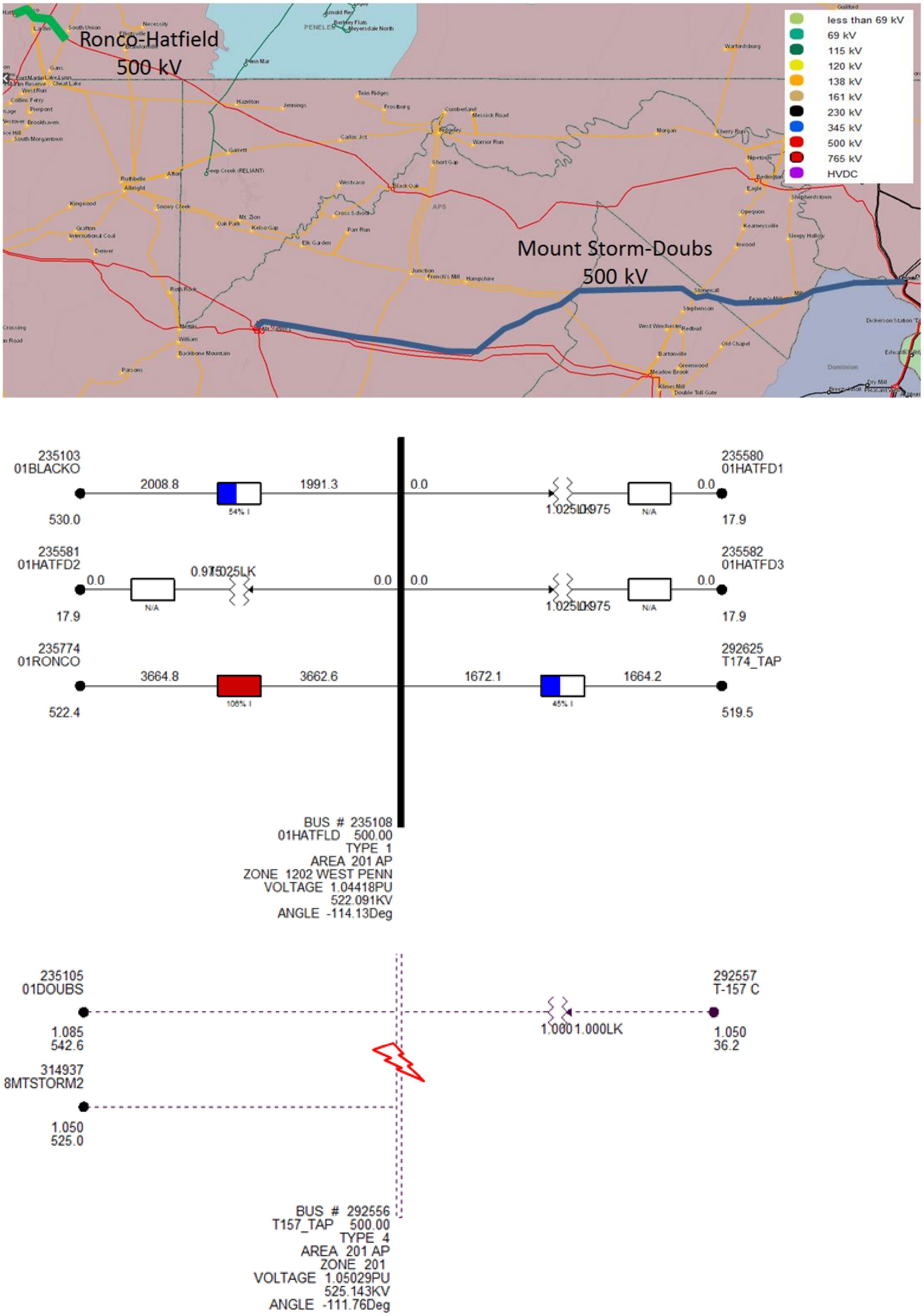


Figure 3.16 Ronco-Hatfield 500 kV Line Overload

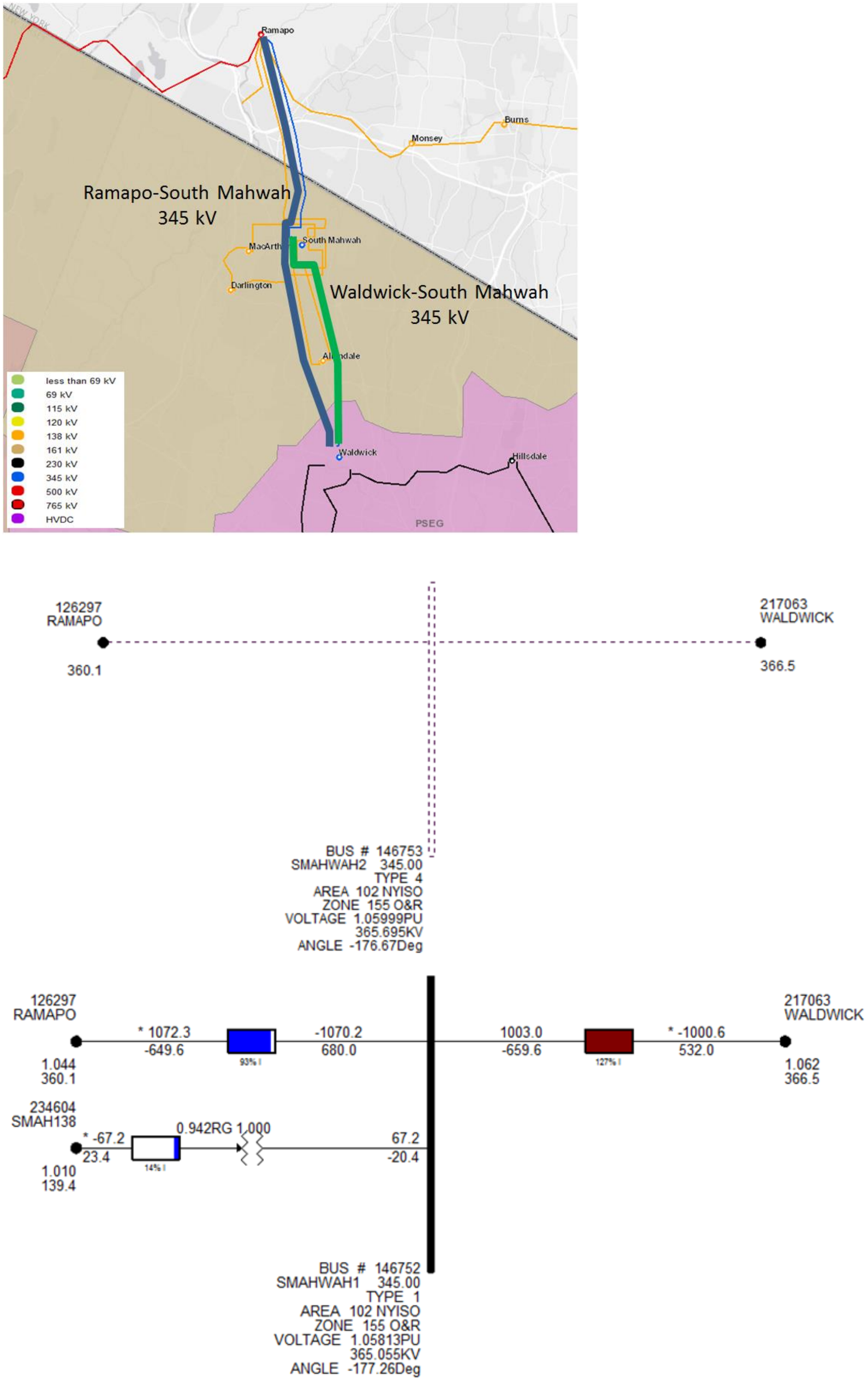


Figure 3.17 Waldwick-South Mahwah 345 kV Line Overload

Figure 3.17 shows overload on the Waldwick-South Mahwah 345 kV line (shown in bold green) for the loss of Ramapo-South Mahwah 345 kV line (shown in bold blue, contingency Category B2). Two 345 kV lines serve the Waldwick (lower half of the Figure 3.17), so when one 345 kV line is out, the other 345 kV line overloads in an attempt to balance flows. These facilities are located in northeastern New Jersey. The lower half of the Figure 3.17 illustrates the outage and corresponding overload. Out-of-service elements are represented by dotted lines, whereas overloaded element is represented by a full red box. The entire bus number 146753 is taken out of service to accurately reflect the outage involving the Ramapo-South Mahwah 345 kV line.

Figure 3.18 shows overload on the Arsenal-Brunot Island 345 kV line (shown in bold green) for the loss of the second Arsenal-Brunot Island 345 kV line (shown in bold blue, contingency Category B2). Two 345 kV lines connect the Arsenal and Brunot Island area through a low impedance path. When one 345 kV line is out, the other 345 kV line overloads in an attempt to balance through flows. These facilities are located in western Pennsylvania. The lower half of the Figure 3.18 illustrates the outage and corresponding overload. Out-of-service elements are represented by dotted lines, whereas overloaded element is represented by a full red box. The out-of-service facility and overloaded facility are shown on the same PSS/E window. The dotted branch on the left is out of service, whereas the branch with the full red box is the overloaded facility.

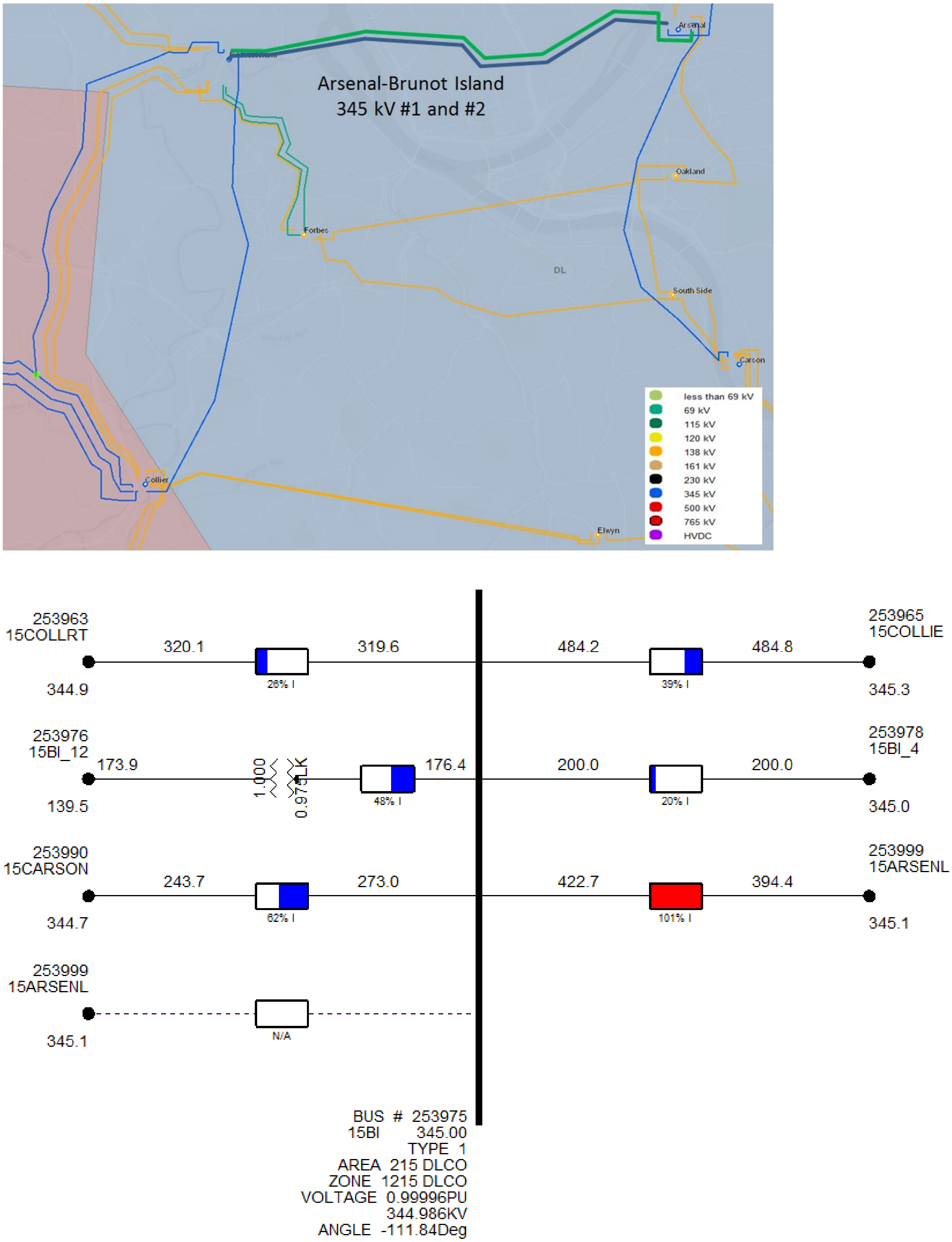
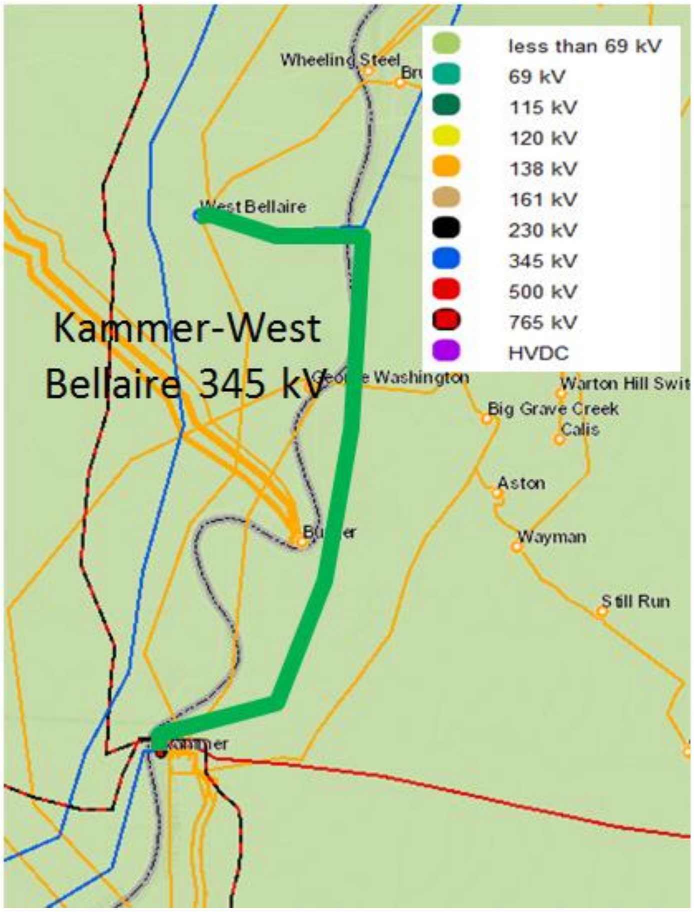


Figure 3.18 Arsenal-Brunot Island 345 kV Line Overload

Figure 3.19 shows overload on the Kammer-West Bellaire 345 kV line (shown in bold green) for circuit breaker NN failure at Kammer station. Kammer station oneline diagram is provided in Figure 3.19. As shown in Figure 3.19, failure involving CB NN took out the Kammer-South Canton 765 kV line and the Kammer 765/500 kV transformer, resulting in transfer of power on the underlying 345 kV system. As a result, the Kammer-West Bellaire 345 kV line overloads. This is an example of contingency Category C2 (circuit breaker failure). These facilities are located in southeastern Ohio. The outage and corresponding overload is also shown in Figure 3.19. Out-of-service elements are represented by dotted lines, whereas the overloaded element is represented by a full red box.



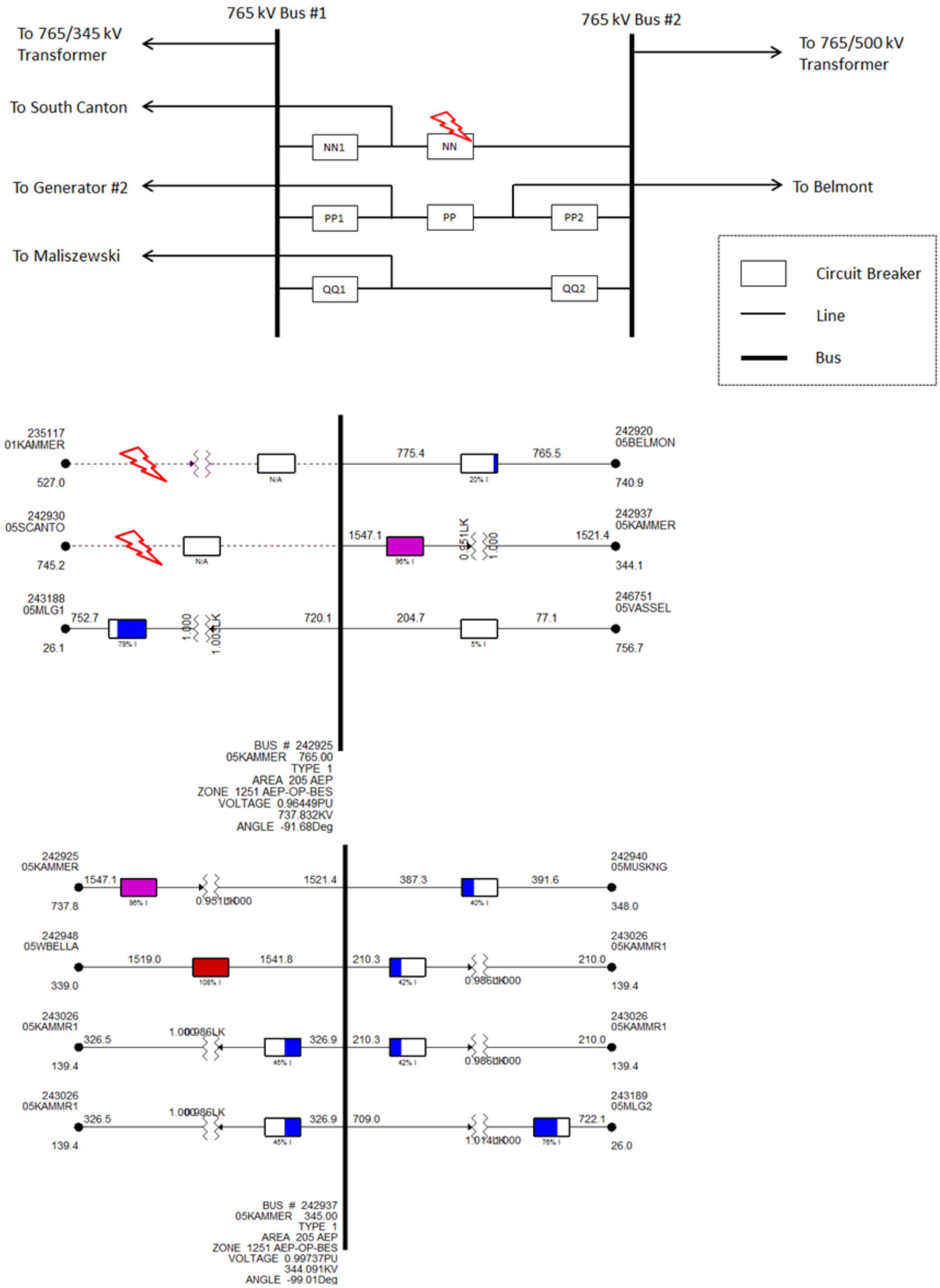


Figure 3.19 Kammer-West Bellaire 345 kV Line Overload

Chapter 4 - Conclusion and Future Work

Polar Vortex Facts

The polar vortex of 2014 was an unusual weather event. Generation forced outage rate was two to three times higher than the normal peak winter outage rate of approximately 7-10%. Equipment issues associated with coal and natural gas units caused the greatest portions of forced outages; natural gas interruptions comprised of approximately 25% of total outages. During peak hour demand, 22% of total generation capacity was unavailable. PJM peak energy demand during the month of January was 25% higher than typical, an amount approximately equivalent to the electricity demand of Chicago, Washington, D.C, and Baltimore combined. PJM set a new winter peak record of 141,846 MW on the evening of January 7, 2014. Twice during the polar vortex, PJM synchronized generation reserves were below minimum requirements and emergency procedures were initiated.

Generation Fuel Diversity

The electric grid of PJM's control area performed satisfactory overall during the winter months of 2014. However, approximately 14,000 of coal generation that was available during the polar vortex will be retired by the end of 2015 and be replaced by plants utilizing natural gas or other renewable fuels. Coal generation retirement will severely impact the fuel diversity of PJM. As the polar vortex demonstrated, natural gas prices increase with increased demand. As power plants convert to natural gas, natural gas prices continue to show an upward trend. Natural gas power plants have interruptible service contracts; their gas supply is interrupted when domestic gas demand increases and the gas pipelines are unable to meet the power plant's demand. The polar vortex of 2014 revealed that many gas plants were unable to run when asked by PJM due to natural gas supply interruptions. Generation fuel diversity must be preserved so the grid can perform reliably by not relying heavily on a particular generation fuel type. Environmentally unfriendly emissions from power plants must be minimized but not at the expense of disturbing the generation fuel diversity.

Electric Grid Reliability Assessment

Reliability assessment demonstrated that approximately 12,000 MW, or 9%, of PJM winter peak load is at risk of being dropped under Category B and C contingencies combined if the polar vortex conditions reoccur in the future. 12,000 MW is approximately double the total winter peak load of PSEG. In order for the system to be reliable for single and multiple contingencies, expensive transmission upgrades that will take many years to implement will be required. Currently, reliability assessment of the PJM system does not occur for winter months because PJM is a summer peaking area overall. A recommendation is made that winter assessment of the PJM system should be performed to ensure that the grid performs reliably throughout the year.

Future Work

Severe weather conditions that caused plant equipment malfunction during the polar vortex should be thoroughly investigated and remediations to ensure satisfactory future performance must be undertaken. Future energy policies must be formulated with consideration of the fact that approximately 14 GW of coal generation in the PJM control area that was available during the polar vortex will be retired by 2015 and substituted by power plants that utilize other fuel types. Stakeholders must scrutinize energy policies so that associated risks and mitigation plans can be preemptively identified.

References

[1] Wikipedia, “Polar Vortex”, http://en.wikipedia.org/wiki/Polar_vortex as retrieved on Aug 2014

[2] PJM Interconnection, “Analysis of Operational Events and Market Impacts During the January 2014 Cold Weather Events,” May 2014, pp. 10, http://www.pjm.com/~/media/documents/reports/20140509-analysis-of-operational-events-and-market-impacts-during-the-jan-2014-cold-weather-events.ashx as retrieved on July 2014

[3] PJM Interconnection, “About PJM”, http://www.pjm.com/about-pjm/who-we-are.aspx as retrieved on November 2014

[4] PJM Interconnection, “PJM Zone Map”, http://www.pjm.com/documents/maps.aspx as retrieved on November 2014

[5] PJM Interconnection, “Data request for January 2014 Weather Events”, January 2010, pp. 12, http://www.pjm.com/~/media/documents/reports/20140113-pjm-response-to-data-request-for-january%202014-weather-events.ashx as retrieved on July 2014

[6] PJM Interconnection, “Data request for January 2014 Weather Events”, January 2010, pp. 13-14, http://www.pjm.com/~/media/documents/reports/20140113-pjm-response-to-data-request-for-january%202014-weather-events.ashx as retrieved on July 2014

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Appendix A - PJM Generation Retirements and Transmission Upgrades

Appendix A lists coal generation plants that are announced to be retired in 2015 and approved PJM transmission remediation projects that are required to ensure grid reliability during 2015 and beyond.

Retired PJM Generation

Table A.1 lists all generators that are to be retired by 2015.

Table A.1 Retired 2015 PJM Generation

Transmission Zone	Capacity	Unit Name
Atlantic City Electric Comp	496 MW	Cedar, Deep Water, Missouri Avenue, BL England Diesel and Middle Energy.
American Electric Power	5408 MW	Clinch River, Glen Lyn, Kammer, Kanawha River, Muskingum River, Picway, Sporn, Tanners Creek and Big Sandy.
American Trans. System Inc.	885 MW	Ashtabula, East Lake and Lake Shore.
Baltimore Gas and Electric Comp	194 MW	Riverside
The Dayton Power and Light Comp	277 MW	Hutchings
Duke Energy Ohio and Kentucky	652 MW	Walter C Beckjord
Virginia Electric and Power Comp	900 MW	Chesapeake and Yorktown
Delmarva Power and Light Comp	34 MW	McKee
Duquesne Light Comp	125 MW	AES Beaver Valley
East Kentucky Power Coop	193 MW	Dale

Jersey Central Power and Light Comp	472 MW	Glen Gardner, Werner CT and Gilbert CT
Metropolitan Edison Comp	401 MW	Portland
Pennsylvania Power Comp	597 MW	Shawville
Potomac Power Comp	1224 MW	Dickerson and Chalk Point
Pennsylvania Power and Light Comp	382 MW	Sunbury
Public Service Electric and Gas Comp	2171 MW	Kearny, Bergen, Burlington, National Park, Mercer, Sewaren, Essex and Edison

Approved PJM Generation Retirement Transmission Remediation Projects

Table A.2 lists all the transmission remediation projects that are required to ensure all generators that are to be retired by 2015.

Table A.2 PJM Approved Transmission Remediation Projects

Upgrade ID	Description	Transmission Owner	Estimated Cost (Million)
b2017	Reconductor or rebuild Sporn - Waterford - Muskingum River 345 kV line	AEP	$200.00
b2020	Rebuild Amos - Kanawha River 138 kV corridor	AEP	$150.00
b1908	Rebuild Lexington â€“ Dooms 500 kV	Dominion	$112.37
b1254	Build a new 500/230 kV substation (Hanover Pike)	BGE	$87.00
b2282	Rebuild the Siegfried-Frackville 230 kV line	PPL	$84.50
b1948	Establish a new 765/345 interconnection at Sporn. Install a 765/345 kV transformer at Mountaineer and build a ¾ of a mile of 345 kV to Sporn	AEP	$65.00
b2161	Rebuild approximately 20 miles of the Allen - S073 double circuit 138 kV line (with one circuit from Allen - Tillman - Timber Switch - S073 and the other circuit from Allen - T-131 - S073)	AEP	$60.00

b1912	Install a 500 MVAR SVC at Lands town 230 kV	Dominion	$60.00
b1905.1	Surry to Skiffs Creek 500 kV Line (7 miles overhead)	Dominion	$58.30
b1696	Install a breaker and a half scheme with a minimum of eight 230 kV breakers for five existing lines at Idyllwild 230 kV	Dominion	$55.00
b1900	Add a 3rd 230 kV transmission line between Chi Chester and Linwood substations and remove the Linwood SPS	PECO	$51.40
b2146	Reconfigure the Brunswick 230 kV and 69 kV substations	PSEG	$47.00
b1994	Convert Lewis Run-Farmers Valley to 230 kV using 1033.5 ACSR conductor. Project to be completed in conjunction with new Farmers Valley 345/230 kV transformation	PENELEC	$46.80
b1905.4	New Skiffs Creek - Wheaton 230 kV line	Dominion	$46.40
b1937	Build a new Leroy Center 345/138 kV substation by looping in the Perry â€“ Harding 345 kV line	ATSI	$46.00
b2218	Rebuild 4 miles of overhead line from Edison - Meadow Rd - Metuchen (Q-1317)	PSEG	$46.00
b1959	Build a new West Fremont-Groton-Hayes 138kV line	ATSI	$45.00
b1905.3	Skiffs Creek 500-230 kV TX and Switching Station	Dominion	$42.40
b1977	Build new Toronto 345/138 kV substation by looping in the Sami's- Wylie Ridge 345 kV line and tie in four 138 kV lines	ATSI	$41.80
b1694	Rebuild Loudoun - Brambleton 500 kV	Dominion	$40.00
b2003	Construct a Whippany to Montville 230 kV line (6.4 miles)	JCPL	$37.50
b1663	Install a new 765/138 transformer, 6 new 138 kV breakers at Jackson's Ferry, breaker disconnect switches and associated bus work, 2 new 138 kV breakers at Wythe, breaker disconnect switches and associated equipment	AEP	$37.00
b2019	Establish Burger 345/138 kV station	AEP	$35.00
b2459	Install SVC at Lake Shore	ATSI	$34.70

b1490.1	Acquire station site for a future 345/138kV station near Wilmington Tap Switch. Establish a new 69/12kV distribution station near Cedar. Construct 7 miles of 69kV Double Circuit Tower Line to Butler C	AEP	$32.00
b2053	Rebuild AltaVista - Skimmer 28 mile 115 kV line	Dominion	$31.80
b1983	Add 150 MVAR SVC and a 100 MVAR capacitor at New Castle	ATSI	$31.70
b2021	Add 345/138 transformer at Sporn, Kanawha River & Muskingum River stations	AEP	$30.00
b1991	Construct Farmers Valley 345/230 kV and 230/115 kV substation. Loop the Homer City-Stole Road 345 kV line into Farmers Valley	PENELEC	$29.50
b2139	Reconductor the Mickleton - Gloucester 230 kV parallel circuits with double bundle conductor	PSEG	$28.35
b1254.1	Rebuild the Hanover Pike - North West 230 kV circuits to separate pole-lines with bundled conductor	BGE	$26.00
b2448	Install a 2nd Sunbury 900MVA 500-230kV transformer and associated equipment.	PPL	$25.00
b2006.1	Install Lauschtown 500/230 kV substation (500 kV portion)	PPL	$20.00
b1910	Rebuild line #262 from Yadkin - Chesapeake 230 kV for 1204 MVA load dump rating and re-conductor line #2110 from Suffolk - Thrasher 230 kV for 1593 MVA load dump rating	Dominion	$19.00
b1911	Add a second Valley 500/230 kV TX	Dominion	$18.70
b2137	Reconductor the Morgantown - Talbert 230 kV '23085' circuit and replace terminal equipment at Morgantown	PEPCO	$18.40
b1608	Construct a new 345/115 kV substation (Mainesburg) and loop the Mansfield - Evert’s 115 kV	PENELEC	$18.20
b1667	Establish Melmore as a switching station with both 138 kV circuits terminating at Melmore. Extend the double circuit 138 kV line from Melmore to Fremont Center	AEP	$18.00
b1907	Install a 3rd 500/230 kV TX at Clover	Dominion	$17.00
b2288	Build a new 138kV line from Piney Grove - Watts Ville	DPL	$16.30
b1906.5	Install a third 500/230 kV TX at Yadkin	Dominion	$16.00

b2008	Reconductor feeder 23032 and 23034 (Dickerson Station "H" - Quince Orchard 230 kV) to high temp. conductor (10 miles)	PEPCO	$16.00
b2018	Loop Conesville - Bixby 345 kV circuit into Ohio Central	AEP	$15.00
b2160	Add a fourth circuit breaker to the station being built for the U4-038 project (Connelly), rebuild U4-038 - Grant Tap line as double circuit tower line	AEP	$15.00
b2449	Rebuild the 7-mile 345 kV line between Meadow Lake and Reynolds 345 kV stations	AEP	$15.00
b2176	Change the tap setting on the Stuart 345/138 kV transformer from 1.00 pu to 1.025 pu	Dayton	$15.00
b2174.1	Convert the Wilson 69kV substation to 138kV	DL	$14.20
b1466.1	Create an in and out loop at Adams Station by removing the hard tap that currently exists	AEP	$13.50
b1666	Build new nine (9) breaker 138 kV station near Ohio Power Company's Morrical Switch Station tapping both circuits of the Fostoria Central - East Lima 138 kV line	AEP	$13.50
b1662	Rebuild 4 miles of 46 kV line to 138 kV from Pemberton to Cherry Creek	AEP	$13.00
b1698	Install a 2nd 500/230 kV transformer at Brambleton	Dominion	$13.00
b1993	Relocate the Erie South 345 kV line terminal	PENELEC	$13.00
b2136	Reconductor the Morgantown - V3-017 230 kV '23086' circuit and replace terminal equipment at Morgantown	PEPCO	$11.40
b1588	Reconductor the Eagle Point - Gloucester 230 kV circuit #1 and #2 with higher conductor rating	PSEG	$10.95
b2147	At Deep Run, install 115 kV line breakers on the B2 and C3 115 kV lines	JCPL	$10.70
b2022	Terminate Tristate - Kyger Creek 345 kV line at Sporn	AEP	$10.00
b1909	Uprate Bremo â€“ Midlothian 230 kV to its maximum operating temperature	Dominion	$10.00
b2226	Upgrade the Tuckahoe to Mill 69 kV circuit	AEC	$9.90
b1906.1	At Yadkin 500 kV, install six 500 kV breakers	Dominion	$9.00
b1470.1	Build a new 138 kV double circuit off the Kanawha â€“ Baileysville #2 138 kV circuit to Skin Fork	AEP	$8.50

	Station		
b1468.1	Expand Selma Parker Station and install a 138/69/34.5 kV transformer	AEP	$8.00
b2140	Install a 3rd Emilie 230/138 kV transformer	PECO	$8.00
b2122.1	Reconductor the ATSI portion of the Howard - Brookside 138 kV line	ATSI	$7.75
b1906.3	Install a 2nd 230/115 kV TX at Chesapeake	Dominion	$7.30
b2372	Upgrade the Chalk Point - T133TAP 230 kV Ck. 1 (23063) and Ckt. 2 (23065) to 1200 MVA ACCR	PEPCO	$6.79
b1671	Install four 138 kV breakers in Danville area	AEP	$5.00
b2030	Install 345 kV circuit breakers at West Bellaire	AEP	$5.00
b1699	Reconfigure Line #203 to feed Edwards Ferry sub radial from Pleasant View 230 kV and install new breaker bay at Pleasant View Sub	Dominion	$4.97
b2023	Rebuild the North Temple - Riverview - Cartech 69 kV line (4.7 miles) with 795 ACSR	ME	$4.82
b1901	Rebuild the Ohio Central - West Trinway (4.84 miles) section of the Academia - Ohio Central 138 kV circuit. Upgrade the Ohio Central riser, Ohio Central switch and the West Trinway riser	AEP	$4.80
b1982	Reconductor the Hoytdale â€“ Newcastle 138 kV lines #1 and #2 with 795 ACSS	ATSI	$4.80
b1992	Reconductor Cambria Slope-Summit 115kV with 795 ACSS Conductor	PENELEC	$4.80
b1985	Reconductor a portion of the Mitchell-Wilson 138kV line	DL	$4.50
b1700	Install a 230/115 kV transformer at the new Liberty substation to relieve Gainesville Transformer #3	Dominion	$4.50
b1945	Install second 230/115 kV autotransformer at Johnstown	PENELEC	$4.50
b1197.1	Reconductor the PSEG portion of the Burlington - Croydon circuit with 1590 ACSS	PSEG	$4.50
b1197	Reconductor the PECO portion of the Burlington - Croydon circuit, replaces some towers, and replace aerial wire at Croydon.	PECO	$4.40
b1906.2	Install a 2nd 230/115 kV TX at Yadkin	Dominion	$4.30

b1939	Reconductor the Barberton â€“ West Akron 138 kV line with 477 ACSS or greater (7.3 miles) + Terminal upgrades at Barberton	ATSI	$4.23
b1726	Create a ring at Fairfield 138 kV substation	DEOK	$4.23
b1906.4	Uprate Yadkin â€“ Chesapeake 115 kV	Dominion	$4.10
b1701	Reconductor Fredericksburg - Cranes Corner 230 kV	Dominion	$4.01
b2359	Wreck and rebuild approximately 1.3 miles of existing 230 kV line between Cochran Mill - X4-039 Switching Station	Dominion	$4.00
b2002	Northwood 230/115 kV Transformer upgrade	ME	$4.00
b1458	Install three new 345kV breakers at Bixby to separate the Marquis 345kV line and transformer #2. Operate Circleville - Harrison 138kV and Harrison - Zuber 138kV up to conductor emergency ratings	AEP	$3.73
b1938	Place a portion of the 138 kV Leroy Center 345/138 kV project into service by summer 2015	ATSI	$3.30
b2042	Add (6) 138 kV breakers + relaying at Leroy Center	ATSI	$3.30
b1467.1	Install a 14.4 MVar Capacitor Bank at New Buffalo station	AEP	$3.00
b2051	Install 3 138 kV breakers and a circuit switcher at Dorton station	AEP	$3.00
b2007	Install a 90 MVAR capacitor bank at the Frackville 230 kV Substation	PPL	$3.00
b1463	Reconductor the Bexley â€“ Groves 138 kV circuit	AEP	$2.90
b2263	Niles Generation Station - Relocate 138kV and 23kV controls from the generation station building to new control building	ATSI	$2.86
b1905.5	Whealton 230 kV breakers	Dominion	$2.10
b1733	Perform a sag study of the Bluff Point - Jay 138 kV line. Upgrade breaker, wavetrap, and risers at the terminal ends	AEP	$2.00
b1738	Perform a sag study of the Wolf Creek - Layman 138 kV line. Upgrade terminal equipment including a 138 kV breaker and wavetrap	AEP	$2.00
b1264	Replace 345 kV bus ties 1-2 and 1-9 at Plano to increase rating on line 16703 Upgrade	ComEd	$2.00
b1698.1	Install a 500 kV breaker at Brambleton	Dominion	$2.00

b1987	Reconductor the Osage-Collins Ferry 138 kV line with 795 ACSS. Upgrade terminal equipment at Osage and Collins Ferry	APS	$1.80
b1984	Install a 50 MVAR capacitor at the Boardman 138 kV	ATSI	$1.70
b1430	Install a new 138 kV circuit breaker at Benton Harbor station and move the load from Watervliet 34.5 kV station to West street 138 kV station	AEP	$1.50
b1265	Reconductor approximately 2 miles of Will County - Romeoville 138 kV portion of L1809 with ACSS conductor	ComEd	$1.50
b1905.2	Surry 500 kV Station Work	Dominion	$1.50
b1998	Install a 75 MVAR 115 kV Capacitor at Shawville	PENELEC	$1.50
b2306	Rebuild and Reconductor 1.67 miles ofÂ the US Silica #1 to W1-089 TAP69 kV circuit	AEC	$1.40
b1726.1	Split Circuit 3886 (Willey - Mulhouse 138 kV) and land both ends in Fairfield	DEOK	$1.38
b2462	Add two 138 kV circuit breakers at Fremont station to fix tower contingency '408_2'	AEP	$1.20
b2262	New Castle Generating Station - Relocate 138kV, 69kV, and 23kV controls from the generating station building to new control building	ATSI	$1.15
b2265	Ashtabula Generating Station - Relocate 138kV controls from the generating station building to new control building	ATSI	$1.15
b2118	Add 44 MVAR Cap at New Martinsville	APS	$1.10
b1978	Reconductor Inland â€“ Clinic Health Q-11 138 kV line	ATSI	$1.10
b2305	Rebuild and reconductor 1.2 miles of the US Silica to US Silica #1 69 kV circuit	AEC	$1.00
b1783	Add two 138 kV Circuit Breakers and two 138 kV circuit switchers on the Lonesome Pine - South Bluefield 138 kV line	AEP	$1.00
b2287	Loop in the Meadow Lake - Olive 345 kV circuit into Reynolds 765/345 kV station	AEP	$1.00
b1999	Replace limiting wave trap, circuit breaker, substation conductor, relay and current transformer components at Northwood	ME	$0.90

Appendix B - Polar Vortex Load Demand and Generation Dispatch Information

Load demand and generation dispatch information for the PJM control area during the polar vortex is provided in Table B.1 below. A positive generation number implies that the area is a net exporter of generation. Same rules apply for interchange. Similarly, a negative generation/interchange number implies that the area is a net importer of generation.

Table B.1 PJM Load and Generation Dispatch during Polar Vortex

Company	Generation		Load		Interchange
	MW	MVAR	MW	MVAR	MW
Public Service Electric and Gas Company	6,559	1,250	7,314	589	875
Philadelphia Electric Company	9,264	834	7,133	568	-2,015
Pennsylvania Power and Light Company	8,340	1,012	7,776	554	-423
Baltimore Gas and Electric Company	4,738	682	6,343	-587	1,708
Jersey Central Power and Light Company	1,721	36	4,013	89	2,346
Metropolitan Edison Company	2,831	48	2,761	-29	-4
Pennsylvania Electric Company	6,295	584	3,090	262	-3,050
Potomac Electric Power Company	3,226	483	5,501	668	2,360
Atlantic City Electric Company	993	199	1,812	99	846
Delmarva Power and Light Company	2,261	148	3,657	176	1,471
Allegheny Energy	7,084	1,465	8,935	917	2,219
Commonwealth Edison Company	19,506	3,836	16,719	3,608	-2,413
American Electric Power	24,717	3,102	22,013	3,363	-1,803
Dayton Power and Light Company	2,662	431	2,949	234	399
Virginia Electric and Power Company	19,716	764	19,065	-90	-227
Duquesne Light Company	1,501	253	2,391	437	917
American Transmission System Inc.	9,314	1,612	11,347	1,464	2,322
Duke Energy Ohio and Kentucky	2,660	588	4,652	90	2,0712
East Kentucky Power Cooperative	2,705	428	2,663	577	57
Total	136,269	17,756	140,608	12,986	7,977

Appendix C - Reliability Assessment

This Appendix lists facilities that overloaded under the study performed.

Overloaded Facilities under Contingency Category B

Table C.1 lists facilities that overloaded under contingency Category B (single contingency). The table lists the overloaded facilities, winter emergency rating of the facility in MVA, contingency under which the facility overloads and the overload percentage.

Table C.1 Overloaded Facilities under Contingency Category B

Overloaded Facility (Bus Number Bus Name Voltage Circuit Number)	Rating (MVA)	Contingency Name	Overload (%)
146752 SMAHWAH1 345 217063 WALDWICK 345 1	895	L_K-3411	121.24
146753 SMAHWAH2 345 217063 WALDWICK 345 1	908	L_J-3410	120.15
235108 01HATFLD 500 235774 01RONCO 500 1	3300	T157_TAP_01DOUBS	105.71
126265 COGNTECH 345 218529 G22_VFT345KV 345 1	358	L_A-2253	105.2
242512 05CLOVRD 765 242524 05CLOVRD 345 10	1587	7421_B3_05CLOVRD 765-141	105.14
253975 15BI 345 253999 15ARSENL 345 2	418	DLCO_305	101.08
253975 15BI 345 253999 15ARSENL 345 1	418	DLCO_306	101.08
213839 NEWLNVL3 35.0 213838 NEWLNVL3 230 1	126	NEWL260/* $ CHESCO $ NEWL260 $ K	135.41
237537 01STRASBRG 34.5 235513 01STRASB 138 1	25.8	APS_B_G609	130.34
224079 BETH T7 138 224086 O ST 138 138 1	192	PP81	124.7
242605 05CLNCHR 138 242700 05LEBANO 138 1	381	1375_B3	124.69

242788 05SALTV1 138 242827 05TAZEWE 138 1	296	1371_B2_TOR4	124.66
242693 05KEYWSS 138 242850 05WOLFH1 138 1	210	1375_B3	123
242811 05SPRING 138 242851 05WOLFH2 138 1	210	1375_B3	122.56
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	B_TRAN_SY_60B	120.12
242788 05SALTV1 138 246766 05ELKGAZ 138 1	382	1375_B3	118.81
243056 05NEWCOM 138 245252 NEWCMTEQ 999 1	69.2	5161_B2_TOR732	118.61
242566 05BROADF 138 242693 05KEYWSS 138 1	210	1375_B3	118.47
213439 BRADFRD1 35.0 213437 BRADFR13 230 1	92.4	220-31/* $ CHESCO $ 220-31 $ L	117.91
304070 6PERSON230 T 230 314697 6HALIFAX 230 1	756	LN 570	116.49
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	B_TRAN_SY_60A	116.17
235328 01ENONTP 138 235333 01GILBOA 138 1	229	37_B2_TOR12	114.6
235328 01ENONTP 138 235333 01GILBOA 138 1	229	6361_B3_05BELMON 765-1_woMOAB_woMOP	114.6
235328 01ENONTP 138 235333 01GILBOA 138 1	229	37_B2_TOR12	114.6
242605 05CLNCHR 138 242606 05CLNLFD 138 1	310	Base Case	110.9
235356 01KINGWD 138 235391 01PRNTY 138 1	213	01HATFLD _01RONCO _059	110.8
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	Base Case	110.74
200570 26CORRY E. 115 200622 26CORRY E. 34.5 3	20.9	B_PN115-LS-#16B	110.38
235428 01WINDSR 138 243131 05TILTON 138 1	320	Base Case	109.18
235381 01OSAGE 138	350	01HATFLD _01RONCO	109.13

235800 01COLLNS 138 1F		_059	
235356 01KINGWD 138 235391 01PRNTY 138 1	213	B_LINE_SY_058	108.43
243131 05TILTON 138 243143 05WBELLA 138 1	335	Base Case	108.24
235428 01WINDSR 138 243131 05TILTON 138 1	320	B_LINE_SY_058	107.79
272504 STATELINE;3B 138 272506 STATELINE;2S 138 1	253	170-L0708___	107.45
235428 01WINDSR 138 243131 05TILTON 138 1	320	01HATFLD _01RONCO _059	106.74
235381 01OSAGE 138 235800 01COLLNS 138 1F	350	B_LINE_SY_058	106.19
235296 01BAYS 138 235389 01POWELM 138 1	119	APS_B_G402	105.33
224084 VANN138 138 224086 O ST 138 138 1	235	PP18	105.21
242685 05J.FERX 138 242745 05PEAKCK 138 1	346	311_B2_TOR5_woMOP	105.03
235428 01WINDSR 138 243131 05TILTON 138 1	320	8319_B2_TOR587b	104.67
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	B_GENS_SY_043	104.26
243045 05MUSKNG 138 247319 05WOLFCK 138 1	258	37_B2_TOR12	104.21
272506 STATELINE;2S 138 272726 WASHINGTO; B 138 1	253	170-L0708___	103.8
235126 01WILLOW 138 235370 01MIDLBN 138 1	206	01BELMNT _01HARRSN _065	103.75
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	908_B2	103.57
235428 01WINDSR 138 243131 05TILTON 138 1	320	01FMARTN _01RONCO _074	103.28
235296 01BAYS 138 235389 01POWELM 138 1	119	APS_B_G372	103.24
235428 01WINDSR 138 243131 05TILTON 138 1	320	APS_B_G453	103.21

242700 05LEBANO 138 246766 05ELKGAZ 138 1	452	1375_B3	103.08
242605 05CLNCHR 138 242700 05LEBANO 138 1	381	5296_B2_TOR97b_MOAB	103.01
242788 05SALTV1 138 242827 05TAZEWE 138 1	296	311_B2_TOR5_woMOP	102.95
235428 01WINDSR 138 243131 05TILTON 138 1	320	APS_B_G452	102.46
235428 01WINDSR 138 243131 05TILTON 138 1	320	AP_B2_571	102.45
235356 01KINGWD 138 235391 01PRNTY 138 1	213	01FMARTN _01RONCO _074	102.42
235120 01ALBRIG 138 235356 01KINGWD 138 1	213	01HATFLD _01RONCO _059	102.08
235428 01WINDSR 138 243131 05TILTON 138 1	320	01 502 J _01KAMMER _081	101.23
235428 01WINDSR 138 243131 05TILTON 138 1	320	5037_B3_05KAMMER 765-1	101.23
235428 01WINDSR 138 243131 05TILTON 138 1	320	5037_B3_05KAMMER 765-1	101.23
243070 05OHIOCT 138 243094 05SCOSHC 138 1	250	Base Case	101.01
243161 05ZANESV 138 245423 ZANESVIL 69.0 1	90	5163_B2_TOR739_woMOAB	100.95
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	913_B2	100.92
235428 01WINDSR 138 243131 05TILTON 138 1	320	APS_B_G166	100.8
235296 01BAYS 138 235389 01POWELM 138 1	119	APS_B_G373	100.67
235381 01OSAGE 138 235800 01COLLNS 138 1F	350	01FMARTN _01RONCO _074	100.56
235450 01CARROL 138 235463 01TANEY 138 1	143	B_ME230-SX-#9	100.33
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	37_B2_TOR12	100.31
238915 02LRN Q2 138	273	6361_B3_05BELMON 765-	100.31

239728 02BLKRVR 138 1		1_woMOAB_woMOP	
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	37_B2_TOR12	100.31
226831 STA_C_PAR 230 224004 C23069T6 230 1	800	LN 533	100.21

Table C.2 provides a list of facilities that overloaded under contingency Category C (multiple contingencies). The table lists the overloaded facilities, winter emergency rating of the facility in MVA, contingencies under which the facility overloads and the overload percentage.

Table C.2 Overloaded Facilities under Contingency Category C

Overloaded Facility Bus Number Bus Name Voltage Circuit Number	Rating (MVA)	Contingency Name	Overload (%)
135277 FALCONER 115 200579 26WARREN 115 1	136	C5_PN230-TW-#2A	116.84
216901 ATHENIA_3 138 217014 FAIRLAWN_3 138 1	266	BF_BERG_1-E	113.54
226831 STA_C_PAR 230 224004 C23069T6 230 1	800	560T571	111.96
235120 01ALBRIG 138 235356 01KINGWD 138 1	213	AP_SB_467	102.08
235296 01BAYS 138 235389 01POWELM 138 1	119	5031_C2_05KAMMER 765-PP2	108.67
235328 01ENONTP 138 235333 01GILBOA 138 1	229	5031_C2_05KAMMER 765-PP2	126.5
235356 01KINGWD 138 235391 01PRNTY 138 1	213	AP_SB_467	110.8
235363 01MAHNSL 138 243127 05TIDD 138 1	286	4743	100.76
235381 01OSAGE 138 235800 01COLLNS 138 1F	350	AP_SB_467	109.13
235428 01WINDSR 138 243131 05TILTON 138 1	320	Base Case	109.18
235450 01CARROL 138 235463 01TANEY 138 1	143	PJM11BG	101.48

237537 01STRASBRG 34.5 235513 01STRASB 138 1	25.8	AP_SB_420	152.54
238521 02NAOMI 138 239070 02RICHLD 138 1	194	C1-BUS-WR002B	105.57
238551 02AVON 345 238552 02AVON 138 92	602	C2-BRK-NR007A	103.38
238552 02AVON 138 238646 02CW TP3 138 1	316	C2-BRK-NR006	104.26
238586 02BRKSID 138 239168 02WELNGT 138 1	86	C2-BRK-SR055	107.97
238915 02LRN Q2 138 239728 02BLKRVR 138 1	273	Base Case	110.74
242542 05ATKINS 138 242803 05SMYTH 138 1	286	2916_C2_05J.FERR 765-A	102.01
242566 05BROADF 138 242693 05KEYWSS 138 1	210	1528_C2	122.72
242567 05BROADX 138 242803 05SMYTH 138 1	251	2916_C2_05J.FERR 765-A	124.8
242580 05CARBND 138 242689 05KANAWH 138 1	317	5031_C2_05KAMMER 765-PP2	102.48
242605 05CLNCHR 138 242606 05CLNLFD 138 1	310	Base Case	110.9
242605 05CLNCHR 138 242700 05LEBANO 138 1	381	1528_C2	131.29
242685 05J.FERX 138 242745 05PEAKCK 138 1	346	8480_C2_05CLOVRD 765-_woMOP	105.03
242693 05KEYWSS 138 242850 05WOLFH1 138 1	210	1528_C2	127.26
242700 05LEBANO 138 246766 05ELKGAZ 138 1	452	1528_C2	108.64
242788 05SALTV1 138 242827 05TAZEWE 138 1	296	2916_C2_05J.FERR 765-A	117.04
242811 05SPRING 138 242851 05WOLFH2 138 1	210	1528_C2	125.54
242972 05BTHL Z 138 243135 05W DOVE 138 1	289	4831_C2_05KAMMER 765-NN	100.57
242983 05CHANDR 138	286	4831_C2_05KAMMER 765-	107.05

243074 05PHILO 138 1		NN	
243045 05MUSKNG 138 247319 05WOLFCK 138 1	258	5031_C2_05KAMMER 765-PP2	130.82
243070 05OHIOCT 138 243094 05SCOSHC 138 1	250	Base Case	101.01
243131 05TILTON 138 243143 05WBELLA 138 1	335	Base Case	108.24
243533 05LAYMAN 138 247319 05WOLFCK 138 1	258	5031_C2_05KAMMER 765-PP2	126.06
243664 05HAZARD 161 243693 05HAZRD2 138 1	208	8345	108.83
304070 6PERSON230 T 230 314697 6HALIFAX 230 1	756	570T509	141.27
304451 6GREENVILE T 230 314574 6EVERETS 230 1	478	511T595	114.96
313802 6PRINCE EDW 230 314268 6BRIERY 230 1	608	511T595	136.42
313802 6PRINCE EDW 230 314692 6FARMVIL 230 1	608	511T595	135.47
314265 3FIVEFORKSDP 115 314584 3LITTLTN 115 1	147	511T595	120.08
314265 3FIVEFORKSDP 115 314673 3BCHWD90 115 1	147	511T595	122.26
314268 6BRIERY 230 314686 6CLOVER 230 1	608	511T595	137.16
314310 6JUDES F 230 314322 6MDLTHAN 230 1	692	511T595	108.22
314333 6POWHATN 230 314747 6BREMO 230 1	792	511T595	102.19
314435 6SAPONY 230 314563 6CLUBHSE 230 1	637	511T595	103.66
314559 3CAROLNA 115 314585 3L GASTN 115 1	147	511T595	108.63
314563 6CLUBHSE 230 314583 6LAKEVEW 230 1	399	511T595	121.21
314579 6HORNRTN 230 314583 6LAKEVEW 230 1	470	511T595	100.6

314584 3LITTLTN 115 314585 3L GASTN 115 1	147	511T595	115.36
314673 3BCHWD90 115 314702 3KERR 115 1	147	511T595	127.83
314677 6BUCKING 230 314692 6FARMVIL 230 1	595	511T595	118.51
314677 6BUCKING 230 314747 6BREMO 230 1	608	511T595	112.16
314686 6CLOVER 230 314697 6HALIFAX 230 1	924	570T509	113.63
314912 8LEXNGTN 500 314854 6LEXNGT1 230 1	396.5	555TH3	107.45
314912 8LEXNGTN 500 314856 6LEXNGT2 230 1	387.6	555TH1	109.36