Load Flow Analysis: Base Cases, Data, Diagrams, and Results

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APPENDIXES (available as separate documents); contact James A. Kavicky, Decision and Information Sciences Division, Argonne National Laboratory, phone: 630.252.6001, fax: 630.252.6037, e-mail: kavicky@dis.anl.gov

A: PTI Load Flow Input Data Dictionary

B: PECO Load Flow Input Data Dictionary

C: Coding Sheets for PECO Load Flow Input Data

D: Description of Conversion Programs

E: PTI Load Flow Simulation Results: Light-Load Case

F: PECO Load Flow Simulation Results: Light-Load Case

G: MAIN and ComEd Transmission Planning Criteria

H: Directory for Single-Line Diagrams and Load Flow Models: Light-Load Case

I: Information Query System Description

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NOTATION

ANL	Argonne National Laboratory
ASCII	American Standard Code for Information Interchange
ComEd	Commonwealth Edison Company
DBF	database file
kV	kilovolt
LTC	load tap changing
MAIN	Mid-America Interconnected Network
MVA	megavolt ampere
MVAR	megavolt ampere reactive
MW	megawatt
NERC	North American Electric Reliability Council
OH	overhead
PECO/LF	Philadelphia Electric Company/Load Flow
PSS/E	Power System Simulator for Engineering
PTI	Power Technologies Incorporated
SLD	single-line diagram
SVS	static VAR system

LOAD FLOW ANALYSIS: BASE CASES, DATA, DIAGRAMS, AND RESULTS

by

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ABSTRACT

This report describes how an electric utility system is modeled by using load flow techniques to establish a validated power flow case suitable for simulating and evaluating alternative system scenarios. Details of the load flow model are supported by additional technical and descriptive information intended to correlate modeled electrical system parameters with the corresponding physical equipment that makes up the system. Pictures and technical specifications of system equipment from the utility, public, or vendor are provided to support this association for many system components. The report summarizes the load flow model construction, simulation, and validation and describes the general capabilities of an information query system designed to access load flow parameters and other electrical system information.

1 INTRODUCTION

1.1 PURPOSE

This report summarizes the results of a load flow analysis case study performed by Argonne National Laboratory (ANL) for the Navy Engineering Logistics Office (NELO). This work was part of an overall energy systems modeling and analysis effort designed to develop a validated power flow study that facilitates understanding of power flow concepts. To simplify data collection requirements and illustrate key concepts, a representative power system in the United States — the Commonwealth Edison Company (ComEd) in northern Illinois — was chosen for the study. The analysis methodology used in this illustrative case study and the lessons learned from the study will assist NELO in conducting power flow studies of operational areas of interest.

1.2 OBJECTIVE AND ACCOMPLISHMENTS

The objective of the load flow analysis work was to apply a convergent power flow model to a representative electric power system to establish a validated power flow case study suitable for simulating and evaluating alternative system scenarios. The Philadelphia Electric Company/Load Flow (PECO/LF) model, which conforms to the model specifications provided

by NELO, was used in the analysis. The ComEd system was selected because of its technical complexity, which allowed all major concepts pertaining to power flow studies to be addressed, and its proximity to ANL, which facilitated site visits and access to data. The selection was also supported by the fact that a cooperative working relationship already exists between ANL and ComEd staff members.

In conducting the illustrative case study, ANL:

- Collected and validated ComEd load flow data, comprehensive technical data on generator characteristics, and slides of towers, substations, and generating stations.
- Completed the Power Technologies Incorporated (PTI)-PECO conversion program, including all pertinent auxiliary programs. These auxiliary programs included the bus renumbering program, boundary node extraction program, and bus and line comparison programs.
- Used PECO/LF to simulate the ComEd system, covering light load, summer peak load, and winter peak load conditions. Fine-tuned equipment settings to provide an excellent match between PECO results and published PTI output reports.
- Completed a directory that links the single-line diagrams (from the current year, 1995, and previous reporting year, 1994) to the 1995 load flow models by providing information on the specific location of nodes in the single-line diagrams.
- Prepared two sets of annotated, single-line diagrams. The larger diagrams (1994) show the connections between network elements in detail, with descriptive, readable labels that identify lines and stations and provide transformer and generator ratings. The smaller diagrams (1995) provide a better perspective of the connections between systems; each bus is numbered to correspond with its number in the PECO/LF model.
- Implemented a database and query system for the ComEd network and load flow information. The query system was written in FoxPro (version 2.6) and operates on a Windows 3.1 platform.

These accomplishments are described more fully in the subsequent sections of the report.

1.3 REPORT ORGANIZATION

The remainder of this report is organized as follows. Section 2 describes the data collection effort and provides a brief overview of the ComEd system. Section 3 describes data collection and translation steps that were needed in preparation for the load flow simulations. The focus of Section 4 is on efforts needed to represent interconnections between ComEd and neighboring systems. Section 5 summarizes convergence criteria and the behavior of the load flow model. In Section 6, simulation results are provided; these are followed by single-line diagram discussions in Section 7. Section 8 introduces the information query system developed specifically to assist in data access, browsing, and editing. Finally, Section 9 provides a brief overall summary of this work. Appendixes A through I contain the actual data items and images described in this report. The appendixes can be obtained by contacting James A. Kavicky, Decision and Information Sciences Division, Argonne National Laboratory; phone: 630.252.6001, fax: 630.252.6073; e-mail: kavicky@dis.anl.gov.

2 COLLECTION OF DATA FOR PECO/LF MODEL

Argonne collected three sets of load flow data: one set for the 1996 projected light load case, one for the 1995 summer peak load case, and one for the 1995 winter peak load case. The data were purchased directly from the Mid-America Interconnected Network (MAIN) region of the North American Electric Reliability Council (NERC). They were on three diskettes corresponding to the three load flow conditions mentioned above. Each diskette contained the following files in compressed American Standard Code for Information Exchange (ASCII) format:

- Load flow input data for MAIN in PTI-Power System Simulator for Engineering (PSS/E) format,
- Load flow simulation results for MAIN in PTI-PSS/E format, and
- Data dictionary (full names of all abbreviated substation names and symbols for the MAIN system).

The ComEd system is an integral component of the MAIN region and is tightly interconnected with neighboring utilities through 765-, 345-, and 138-kV lines. The embedding of the ComEd system within the MAIN data set is important, since the interconnections significantly affect ComEd's operations. Modeling the ComEd system as an isolated system required that ComEd-related information be extracted from the MAIN superset and that the surrounding network be represented as an electrical equivalent. This process of data preparation and translation is discussed in more detail in Section 4.

2.1 DESCRIPTION OF THE COMED SYSTEM

ComEd was founded in 1898 and has since grown to be a 25,400-MW utility with annual revenues of more than 6 billion dollars. With present assets of about 24 billion dollars, it serves a population of about 8.2 million people over a land area of 11,540 square miles. Its electrical customers include about 3,000,000 residential, 300,000 small commercial and industrial, 1,500 large commercial and industrial, and 12,000 other customers. The utility is headquartered in Chicago, Illinois. ComEd is an important component of the MAIN system. It is a predominantly nuclear-based utility; nuclear energy accounts for approximately 71% of its total annual energy output. The system's peak load (about 19,000 MW in 1995) occurs in the summer. ComEd has a total installed capacity of approximately 25,400 MW, of which 49% is nuclear, 31% is coal, 17% is oil, and 3% is natural gas. A number of small hydro generating stations exist, but they do not contribute significantly (on a percentage basis) to the overall capacity mix.

ComEd's overhead (OH) transmission system spans a total length of about 5,000 circuit miles and operates on the following voltage levels: 765, 345, 138, 69, 34.5, 18, and 12.5 kV. Its underground transmission system consists mainly of 69- and 138-kV lines covering a total

distance of about 375 circuit miles. The primary distribution uses 5-, 13-, and 35-kV circuits. ComEd's major interconnections are summarized in Table 2.1.

2.2 OVERVIEW OF COMED LOAD FLOW MODEL

The ComEd system model consists of about 650 buses and 820 lines. About 55 of the nodes are generator buses; of these, 15 are voltage-controlled, either directly or remotely, by load tap changing (LTC) transformers. The entire MAIN load flow model consists of about 10,000 buses and 35,000 lines.

An analysis of the ComEd system model at light-load conditions (April 1996) is presented in Table 2.2. About 26 of the 200 transformer entries in Table 2.2 are not stand-alone units but represent tertiaries of three-winding autotransformers. These tertiary windings contain mainly capacitor banks for controlling reactive power within the transformer. They are represented in the model as lines with negative reactance. About 10 transformers are clearly designated as LTC transformers with lower and higher limits to accommodate tap adjustments. The rest are specified as transformers with fixed turn ratios.

The buses may be further analyzed with respect to operating voltage, as shown in Table 2.3. As Table 2.3 shows, the ComEd system model is composed mainly of 138-kV substations. Most of the lower voltage buses (e.g., 12.5 to 13.8 kV) represent generator nodes at the primary end (low-voltage side) of step-up transformers.

TABLE 2.1 ComEd's Major Interconnections

Utility ^a	No. of Circuits	Voltage (kV)	Total Interconnection Capability (MVA)
AEP EQ	3	765,345	3,892
IOWA	4	345,138	3,125
CILCO	3	345,138	2,503
NIPSCO	7	345,138	4,748
IPCO	8	345,138	2,812
WUMS	4	345,138	3,509
CIPS	2	345	1,793

^a AEPEQ = American Electric Power (equivalent), IOWA = Iowa-Illinois Gas and Electric Company, CILCO = Central Illinois Light Company, NIPSCO = Northern Indiana Public Service Company, IPCO = Interstate Power Company, WUMS = Wisconsin and Upper Michigan Systems, and CIPS = Central Illinois Public Service Company.

TABLE 2.2 Elements That Compose the ComEd System

Element	Number of Elements
Bus (12.5-765 kV)	647
Generator unit	55
Line	820
Transformer	200
Phase shifter	9
Direct-current line	0

TABLE 2.3 Breakdown of Buses According to Operating Voltage

Operating Voltage (kV)	Number of Buses
765	3
345	95
138	475
69	32
25	10
24	18
13.8	3
13.2	3
12.5	8

3 FORMAT CONVERSION FROM PTI TO PECO/LF

Conversion of PTI-formatted load flow data to the PECO/LF structure involved three main processes: (1) extract ComEd data from the MAIN superset, (2) process ComEd-related information to comply with PECO/LF formats and specifications with regard to units of measure, and (3) modify the properties of ComEd's boundary nodes to account for the effects of systems externally connected to ComEd. These processes are described in Sections 3.2-3.4. Before these descriptions, Section 3.1 first explains the major differences between the PTI and PECO/LF input data formats and structures.

3.1 DIFFERENCES BETWEEN PTI AND PECO/LF

Conversion of load flow data from PTI to PECO was necessary for four main reasons. First, the programs use different formats. PTI-PSS/E uses free format with space and comma delimiters, while PECO/LF uses a fixed, space-delimited format. Second, the input data are grouped and sequenced differently in PTI and PECO. PTI has 13 data categories, while PECO/LF has 4. Third, the different software packages use different units of measure to model the same parameters. Finally, bus numbering standards are different. PTI-PSS/E uses a five-digit numbering scheme, while PECO/LF allows only up to four digits. The differences between PTI and PECO that are relevant to the data conversion process are summarized in more specific terms in Table 3.1.

TABLE 3.1 Major Differences between PTI and PECO/LF Input Data Formats

Item	PTI-PSS/E	PECO/LF
Input data in ASCII format	Free format, space- or comma-delimited	FORTTRAN fixed format, space-delimited
No. of data categories	13	4
Line resistance	Per unit	Percent
Line reactance	Per unit	Percent
Line charging	Per unit	Megavolt ampere reactive (MVAR)
Generator modeling	Several units can be connected to a single bus	Only one unit can be connected to a bus
Static capacitors	Three modeling options: discrete, fixed, and continuous	Two modeling options: fixed and continuous
Bus numbering	Uses five-digit numbers	Allows only up to four-digit numbers
Direct-current (DC) line	Models two-terminal or multiterminal DC lines	No logic for treating DC lines

The main data groupings for PTI and PECO input data are compared in Table 3.2. Clearly, the PTI-PSS/E code has a more finely decomposed set of data than does PECO/LF. The PECO/LF data set appears as a compressed version of PTI-PSS/E. Details on how specific PECO/LF parameters are derived by using PTI raw data are discussed in Section 3.3. Appendix A provides detailed descriptions of the items included within each data group. Appendix A, as well as all the other appendixes mentioned in this report, can be obtained by contacting James A. Kavicky, Decision and Information Sciences Division, Argonne National Laboratory; phone: 630.252.6001, fax: 630.252.6073; e-mail: kavicky@dis.anl.gov.

3.2 EXTRACTING ComEd DATA FROM THE MAIN DATA SET

Argonne acquired a large set of load flow data from MAIN. The data included all load flow information for the MAIN region, covering about 10,000 buses and 35,000 lines. ComEd accounts for about 650 (or about 6.5%) of the buses and 820 (or about 2.3%) of the lines.

Since the data ANL purchased were in ASCII files, the data had to be converted and stored in database files (DBFs) so they could be processed to derive PECO/LF values. A special program — EXTRACT1.PRG — was developed to extract ComEd data from the MAIN data set. The program captured all information contained in the MAIN data and stored the captured data in FoxPro DBFs. ComEd data were identified and segregated by using the area code number assigned to ComEd. The extracted data were stored in 13 DBFs according to the PTI data structure shown in Table 3.2. The field names of each of the 13 DBFs are described in

TABLE 3.2 Differences between PTI and PECO/LF Input Data Groupings and Sequencing

PTI-PSS/E	PECO/LF
1. Case identification	1. Case identification
2. Bus data	2. Bus data
3. Generator data	3. Line and transformer data
4. Branch data	4. Area interchange data
5. Transformer adjustment data	
6. Area interchange data	
7. Two-terminal DC line data	
8. Switched shunt data	
9. Trans impedance correction data	
10. Multiterminal DC line data	
11. Multisection line grouping data	
12. Zone data	
13. Area transaction data	

Appendix A. The extraction program also identified all boundary nodes and all tie lines connected to these nodes and stored this information in a separate DBF. The program used the conversion process described in Section 3.3 to derive PECO/LF values. Then the program stored the PECO/LF load flow input data in ASCII format. For the initial preparation of the PECO/LF input data, the effects of systems around ComEd were not taken into account.

A second program — EXTRACT2.PRG — was applied to process the ASCII file containing the PTI simulation results. Real and reactive power flow data on all tie lines connected to the ComEd system were captured by the program. The program used the captured information to adjust the properties of the boundary nodes so that flows through the tie lines were represented as local loads.

A third program — the RENUMBR.PRG — was employed to assign a new set of number labels to the nodes in accordance with the specifications of the PECO/LF model. Because ComEd was initially part of the large MAIN system, the numbers assigned to the buses were in five-digit formats. PECO/LF allows only four-digit numbers to be used to label the buses.

3.3 DERIVING PECO/LF PARAMETERS FROM PTI DATA

Deriving the PECO/LF parameters from PTI data involved an aggregation process in which several values from different data groups in PTI were combined to constitute a PECO/LF value. For example, to complete the branch data for PECO/LF, data from PTI's Branch Data Group, Transformer Adjustment Data Group, Transformer Impedance Correction Data Group, and Case Data Group had to be combined. To complete the PECO bus data, information had to be drawn from PTI's Bus Data Group, Generator Data Group, Two-Terminal DC Line Data Group, Multiterminal DC Line Data Group, and Switched Shunt Data Group.

Table 3.3 shows in detail how each parameter in the bus data group and branch data group of PECO/LF is derived by using PTI parameters. The parameters are presented and sequenced in the same manner as they appear in the PECO coding sheets shown in Appendix C. Appendix B gives the definition of columns appearing in the coding sheets. The PTI-PECO format conversion program, including the associated auxiliary programs, is described in Appendix D.

3.4 CAVEATS FOR RECONVERTING PECO/LF TO PTI

Converting load flow data from PTI to PECO is comparable to transforming a finely decomposed data set into a simpler one. The representation of data is simpler in PECO/LF format than in PTI, partially because the data represent lumped network parameter values. For example, the shunt MVAR in PECO/LF is actually the sum of the bus shunt reactance to ground and the switched shunt admittance (static capacitor banks) in PTI. Transforming the more detailed data into a more aggregated form is usually not a problem, because it is largely an integration task. The smaller pieces just have to be added together to form equivalent composite values. However,

the reverse operation is more difficult because clear guidelines on how to break down the data into smaller categories need to be in place.

Some PTI parameters may be difficult to reconstruct from a PECO/LF data set; they are listed here:

1. BL (reactive component of shunt admittance to ground) and BINIT (initial switched shunt admittance) from shunt MVAR values in PECO/LF: The number of steps per block and the admittance increment for each step cannot be reconstructed, because PECO/LF format does not provide guidelines for this.
2. Generator real power limits: PECO/LF does not provide this information.
3. Impedance correction table: PECO/LF does not provide this information.
4. Direct-current (DC) line parameters: PECO/LF does not have the capability to model DC lines.

On the other hand, the ComEd model may be reconstructed in PTI format by using the FoxPro DBFs that were used to store the PTI data during the conversion process. By using a program that writes data in free format, the load flow model for an isolated ComEd system may readily be recreated in PTI format.

TABLE 3.3 Derivation of PECO/LF Parameter Values from PTI Values

PECO Parameter ^a	Column	Unit	Process Used to Derive PECO Value	PTI Parameter ^a	Unit	PTI Data Group															
Bus Data																					
Bus number	1-4	NA ^b	PTI bus numbers were originally in five-digit format. A renumbering program assigned the PTI five-digit numbers to a new set of four-digit numbers. The new number set ranged from one up to the total number of buses.	I	NA	Bus data															
Bus type	8	NA	PTI codes correspond to PECO codes as follows: <table><tr><th>PTI</th><th>Description</th><th>PECO</th></tr><tr><td>1</td><td>Load bus (no generation)</td><td>0</td></tr><tr><td>2</td><td>Generator bus</td><td>1</td></tr><tr><td>3</td><td>Swing bus</td><td>2</td></tr><tr><td>4</td><td>Isolated bus</td><td>X</td></tr></table>	PTI	Description	PECO	1	Load bus (no generation)	0	2	Generator bus	1	3	Swing bus	2	4	Isolated bus	X	IDE	NA	Bus data
PTI	Description	PECO																			
1	Load bus (no generation)	0																			
2	Generator bus	1																			
3	Swing bus	2																			
4	Isolated bus	X																			
Bus name	10-21	NA	Formed by combining the first eight letters of NAME with the first four characters of BASKV, thereby creating a 12-character string. The last four characters of the bus name contained information on the base voltage as required by PECO.	NAME BASKV	NA	Bus data															
Voltage magnitude	23-26	Per unit	Taken directly from PTI values.	VM	Per unit	Bus data															
Voltage angle	27-30	Degree	Taken directly from PTI values.	VA	Degree	Bus data															
Generation MW	31-35	Megawatt	Taken directly from PTI values.	PG	Megawatt	Generator data															
Generation in MVAR	36-40	Megavar	Taken directly from PTI values.	QG	Megavar	Generator data															

TABLE 3.3 (Cont.)

PECO Parameter ^a	Column	Unit	Process Used to Derive PECO Value	PTI Parameter ^a	Unit	PTI Data Group
<i>Bus Data (Cont.)</i>						
Minimum generation limit	41-45	Megavar	Taken directly from PTI values.	QG	Megavar	Generator data
Maximum generation limit	46-50	Megavar	Taken directly from PTI values.	QT	Megavar	Generator data
Controlled bus	51-55	NA	Taken directly from PTI values.	IREG	NA	Generator data
Load MW	56-60	Megawatt	In general, taken directly from PTI values; however, for boundary buses, MW flows of all tie lines connected to the bus were aggregated and added to the local load. A negative resultant load implies MW import, while a positive value implies export of real power. Tie lines are lines that join ComEd with other utilities.	PL	Megawatt	Bus data
Load MVAR	61-65	Megavar	In general, taken directly from PTI values; however, for boundary buses, MVAR flows of all tie lines connected to the bus were aggregated and added to the local load. A negative resultant load implies MVAR import, while a positive value implies export of reactive power. Tie lines are lines that join ComEd with other utilities.	QL	Megavar	Bus data
Shunt	66-70	Megavar	Evaluated as the sum of BINIT and BL; it was noted that BINIT and BL are mutually exclusive; that is, whenever BINIT is not zero, BL is zero, and vice-versa.	BL	Megavar	Bus data
Capacitor/reactor				BINIT	Megavar	Switch shunt data
Area code	71-72	NA	Taken directly from PTI values.	IA	NA	Bus data

TABLE 3.3 (Cont.)

PECO Parameter ^a	Column	Unit	Process Used to Derive PECO Value	PTI Parameter ^a	Unit	PTI Data Group
Branch Data						
From bus number	1-4	NA	Taken directly from PTI values.	I	NA	Branch data
Continuation character	8	NA	Automatically inserted for phase shifters and load tap changing transformers.	NA	NA	NA
To bus number	9-12	NA	Taken directly from PTI values.	J	NA	Branch data
Circuit number	14	NA	Taken directly from PTI values.	CKT	NA	Branch data
Area	16	NA	Taken directly from PTI values.	IA	NA	Bus data
Resistance	18-23	Percent	Derived by multiplying R by 100%.	R	Per unit	Branch data
Reactance	24-29	Percent	Derived by multiplying X by 100%.	X	Per unit	Branch data
Line charging	30-35	MVA	Derived by multiplying B by 100 MVA base.	B	Per unit	
Transformer tap	36-40	Per unit	Taken directly from PTI values	RATIO	Per unit	Branch data
Minimum tap	41-45	Per unit	Taken directly from PTI values.	RMI	Per unit	Transformer adjusted data
Maximum tap	46-50	Per unit	Taken directly from PTI values.	RMA	Per unit	Transformer adjusted data
Phase shift angle	51-55	Degree	Taken directly from PTI values.	ANGLE	Degree	Branch data
Controlled bus number	56-60	NA	Taken directly from PTI values.	ICONT	NA	Transformer adjusted data
Normal MVA rating	61-64	MVA	Taken directly from PTI values.	RATEA	MVA	Branch data
Emergency MVA rating	65-68	MVA	Taken directly from PTI values.	RATEB	MVA	Branch data

TABLE 3.3 (Cont.)

PECO Parameter ^a	Column	Unit	Process Used to Derive PECO Value	PTI Parameter ^a	Unit	PTI Data Group
Branch Data (Cont.)						
MVA base	69-72	MVA	Taken directly from PTI values.	SBASE	MVA	Case identification data
Desired MVAR flow	35-40 2nd card	MVA	Taken directly from PTI values.	VMI	MVAR	Transformer adjusted data
Minimum LTC volts	35-40 2nd card	Per unit	Taken directly from PTI values.	VMI	Per unit	Transformer adjusted data
Minimum phase shift angle	41-45 2nd card	Degree	Taken directly from PTI values.	RMI	Degree	Transformer adjusted data
Maximum phase shift angle	46-50 2nd card	Degree	Taken directly from PTI values.	RMA	Degree	Transformer adjusted data
Desired MW flow	51-55 2nd card	Megawatt	Taken directly from PTI values.	VMI	Megawatt	Transformer adjusted data
Controlled line	57-65 2nd card	NA	No counterpart in PTI.	NA	NA	NA
Transformer available taps	67-70 2nd card	NA	Calculated by the formula: (VMA-VMI)/STEPS	VMA VMI STEPS	Per unit Per unit NA	Transformer adjusted data
Maximum LTC volts	71-75 2 nd card	NA	Taken directly from PTI values.	VMA	Per unit	Transformer adjusted data

^a See PECO/LF or PTI-PSS/E operations manual for complete description of parameters.

^b NA = not applicable.

4 MODELING THE ComEd SYSTEM

Modeling the ComEd system was a two-step process. First, data on the ComEd system were extracted from the MAIN data set. Then the boundary elements were modified to reflect the influence of the systems surrounding ComEd.

4.1 MODELING INTERNAL NETWORK ELEMENTS

By using the area code assigned to ComEd as a key, all ComEd-owned buses and lines were extracted from the MAIN "super set" and stored in 13 DBFs according to the PTI data structure presented in Table 3.2. No further modification of the internal buses and lines was made, since this task was straightforward. The extraction process automatically identified and segregated tie lines and boundary nodes. Finally, a valid set of data for the internal elements was formed by eliminating all nonactive lines and isolated buses. The values for PECO parameters were then derived by using the process shown in Table 3.3. In the PECO/LF model, DC lines were represented as a pair of supply and sink nodes with fixed values. However, since the ComEd system did not have any DC lines, no DC modeling activity was undertaken in this study.

4.2 MODELING BOUNDARY BUSES AND EXTERNAL SYSTEMS

Because the PECO/LF model is limited in terms of the size of the system that it can accommodate, it was not possible to model the entire MAIN system and use the PECO/LF network reduction software to make an equivalent of the external system buses outside the ComEd system. PECO's network reduction module could not accept the 10,000-bus system of MAIN. As a result, an alternative boundary approach was chosen to model the influences of external system buses.

The properties of boundary nodes had to be redefined to account for the influence of system interconnections. The main focus in modeling boundary buses is to properly represent interties. Interties provide channels through which electrical power may flow in or out of the ComEd system. More than one tie line may emanate from a boundary node. Both real (MW) and reactive power (MVAR) may flow through these lines. When the ComEd system is modeled as an isolated system, these tie lines disappear, but their effects are recognized by representing the power flow through them as local loads at the boundary buses. If more than one tie line connects to a boundary node, the MW and MVAR flows through all the lines are combined and added to the node's local load. A negative real power means that ComEd is importing real power, while a positive value implies that ComEd is exporting power. The same logic governs the convention for MVAR flows. In this modeling approach, the boundary buses that were originally designated as load buses remain classified as load buses even if their net load is negative. Negative loads are permitted in PECO/LF. Buses with negative net load can be reclassified as generation buses (in which case the voltage would be assumed to remain constant) only if the buses are known to be close to a very strong external generation center.

4.3 BUS RENUMBERING

As mentioned in Section 3.1, a renumbering program had to be run to convert PTI's five-digit bus numbers to four-digit numbers suitable for PECO/LF use. A new set of numbers was arbitrarily assigned to the buses. The new set was simply a sequential count of the buses from the first one up to the total number of buses in the ComEd load flow model. The final set was not completely consecutive, because one node was found to be isolated and had to be excluded from the valid set.

4.4 IMPLICATIONS OF THE ADOPTED MODELING APPROACH

By representing the MW and MVAR flows through the tie-lines as local loads at the boundary buses, the isolated model fixed the impact of the interties on ComEd's operation. The isolated ComEd model is valid only for exactly the same conditions as those that prevailed in the "pre-extracted" state of ComEd. In using the isolated model to examine outage contingencies and transient stability, one should adhere to the assumption that injections from the external system as well as the external voltages remain constant during disturbances within ComEd. If this assumption is not taken into account, the analysis may lead to inaccurate results, because the interties (represented as loads) are precluded from transmitting compensating or synchronizing power to ComEd during disturbances. For any major line outage within ComEd that occurs without a change in load, isolated ComEd model simulations could result in different line flows than those that would result if ComEd were simulated in the context of the full MAIN model. Because of this limitation, care must be exercised in using the isolated model for sensitivity analysis and stability studies. The isolated model now operates on the basis of the assumption that flows through the interties are either fixed or change proportionately with the loads.

4.5 VALIDATING THE CONVERSION PROCESS AND PECO/LF MODEL

As explained in Section 3.2, the conversion process essentially consists of executing the following programs: EXTRACT1.PRG, EXTRACT2.PRG, and RENUMBR.PRG. The analyst intervenes intermittently during the process to consolidate the outputs and assemble the PECO/LF-formatted data set. EXTRACT1.PRG captures and stores ComEd-related information from PTI-formatted MAIN data and generates initial PECO/LF-formatted load flow input data. EXTRACT2.PRG reads intertie and boundary node information from known PTI simulation results and then uses these data to modify properties of boundary nodes. RENUMBR.PRG completes the process by assigning four-digit number codes to the buses.

Two categories were tested to validate the conversion process. First, the accuracy of the units of measure (e.g., whether the values are per unit or percent) and format (e.g., whether the parameters are pasted in the appropriate columns and whether they should be floating point or integer type) was tested. Second, the ability to obtain a convergent solution with results consistent with the known PTI reference case was tested. The latter test is the ultimate validity check for the process. The converted data must be such that the PECO/LF program will lead to a

convergent solution within a reasonable number of iterations. In addition, the results must compare favorably with published PTI output.

Testing for correctness in units of measure and format was an iterative and tedious process. As errors were detected during initial iterations, incremental modifications were made in the programs to improve the results. The 1994 MAIN system, in PTI format, was a complex case consisting of about 10,000 buses and 35,000 lines. Errors were detected by comparing results of the program runs with the original values. Comparisons were conducted on a line-by-line and bus-by-bus basis. When necessary, manual calculations were performed to validate results.

Validity of the conversion process was first confirmed when the model run for the ComEd system converged. More important, results of the run compared favorably with the known reference data. The ComEd-related data had to be extracted, and effects of interties had to be incorporated in the model. Because of the huge volume of MAIN data, numerous other auxiliary programs were developed to automate the validation of results and minimize the number of trial runs. These included, among many others, the BUS_CHECK, COMPARE, and BALANCE programs. BUS_CHECK was used in conjunction with the renumbering program to make sure that all remotely controlled buses were consistently renumbered as the main nodes were assigned new numbers. The COMPARE program compared the PECO output with the PTI results on a line-by-line and bus-by-bus basis. The BALANCE program looked into the supply-demand situation of the model before a PECO/LF run, since a substantial imbalance in supply and demand due to erroneous data conversion could make convergence difficult.

Parameters of interest to analyze when comparing PECO/LF and PTI results are the following:

- From each originating node ("From Bus"):

1. MW flows,
2. MVAR flows,
3. MVA flows,
4. Power factor,
5. Voltage, and
6. Shunt MVAR.

- For each generator node:

1. MW dispatch,
2. MVAR dispatch,

3. Power factor, and
 4. Voltage.
- For each LTC transformer:
 1. Tap position,
 2. MVA flows,
 3. MW flows, and
 4. MVAR flows.
 - For phase shifters:
 1. Tap setting,
 2. Phase angle,
 3. MVA flows,
 4. Controlled MW flows, and
 5. MVAR flows.

5 OBTAINING CONVERGENCE IN THE PECO/LF ENVIRONMENT

5.1 CONVERGENCE CRITERIA AND PROGRAM CONSTANTS

Table 5.1 presents convergence tolerance and program constants used in the PECO/LF simulation runs. A desired performance standard was for the model to converge to a solution within 10 iterations.

5.2 GENERAL GUIDELINES FOR MINIMUM-ERROR RUNS

The following guidelines were developed on the basis of lessons learned from initial attempts to achieve convergence. They are presented in a list that can be reviewed before a PECO load flow run. They assume that PECO-formatted input data have been formed through the execution of the EXTRACT1.PRG, EXTRACT2.PRG, and RENUMBR.PRG programs. Using parameter values other than those displayed in this list may result in an aborted run or a nonconvergent case.

TABLE 5.1 PECO/LF Convergence Tolerance and Program Constants

Variable	Description	Value
P	Bus mismatch criterion for real power, per unit	0.001
Q	Bus mismatch criterion for reactive power, per unit	0.001
V	Voltage tolerance for automatic tap changers, per unit	0.005
M	Maximum number of network configuration changes before reoptimal ordering	40
L	Voltage criterion for table of exceptionally low voltages, per unit	0.95
H	Voltage criterion for table of exceptionally high voltages, per unit	1.05
PT	Total absolute mismatch for real power, per unit	a
QT	Total absolute mismatch for reactive power, per unit	b
A	Voltage delta criterion for table of excessive bus voltage changes, per unit	0.05
B	Percent of ratings used when listing monitored lines	100
MI	Maximum number of iterations	40.0

^a The criterion for total absolute mismatch for reactive power is determined by the formula: per-unit QT tolerance = $0.01 + (\text{no. of lines} + \text{no. of buses}) / (\text{maximum no. of lines} + \text{maximum no. of buses})$.

^b The criterion for total absolute mismatch for real power is determined by the formula: per-unit PT tolerance = per-unit QT $\times 0.6$.

The following steps outline the process for obtaining convergence:

1. In PECO/LF, choose Option 4 for the load flow solution approach. This option is intended for use with cases that are difficult to solve. Option 4 initiates a Newton-Raphson solution. The maximum MVAR limits for all nonfixed regulated buses will be increased by 1,000 MVAR until the case is close to convergence. When convergence is near, the limits will be restored to their original values.
2. Check if a swing bus has already been designated. The EXTRACT1.PRG and EXTRACT2.PRG programs do not automatically assign a swing bus. To be consistent with MAIN assumptions, chose the same generator unit as that chosen in the PTI data as the swing bus.
3. Check the data set for isolated buses (i.e., check if any bus is of type "X"). Although the PECO/LF program would normally identify an isolated bus during the initial run, a prior screening of the bus data would shorten turnaround times and avoid complications.
4. Check the dispatch schedule of generators marked "Gen Out." Although these generators have been relabeled as type "0" (load bus), their scheduled MW and MVAR outputs may still be nonzeros. If so, reduce all generation output to zero. Check all generator outputs again for consistency with original PTI data.
5. Set all static VAR system (SVS) buses (type "3") to type "0" buses to fix the shunt capacitor assignment. The type 3 designation does not work well in PECO, especially in conjunction with transformers with negative reactance.
6. Represent transformers as they originally were in PTI format. Fixed transformers should be modeled as fixed, and LTC transformers should be modeled as LTC transformers. Modeling all transformers as variable tap transformers could result in solutions requiring an excessive number of iterations (more than 70). Fixing all transformers, on the other hand, would result in nonconvergence, because of limitations imposed on availability of reactive power.

5.3 DIFFICULTIES ENCOUNTERED

Few difficulties were encountered before convergence was attained. Except for the light load case, which was the first case processed, all the cases attained convergence in, at the most, three attempts. More difficulties were encountered in matching results with PTI values than in attaining convergence. Some of the difficulties were as follows:

1. The use of type 3 buses for SVS buses would not allow convergence to occur. The type 3 bus has to be changed to a type 0 bus in order for the program to run without errors.
2. A convergence tolerance of 0.01 (default for small systems) for total Q and P mismatch led to about 70 iterations before convergence was obtained. Applying the formulas presented in Section 5.1 led to cases that converged within 15 iterations.
3. Failure to initially assign a swing bus suddenly halted program execution. The difficulty was that no message associated with this error was indicated in the printouts.

5.4 MAJOR DATA ADJUSTMENT TO MATCH PTI REFERENCE CASE

A comparison of initial PECO/LF simulation results with PTI reference case results indicated substantial differences in the magnitude and direction of power flows and dissimilarities in voltage magnitude and angles. Controlled MW flows through phase shifters were also substantially different. In some cases, the MVAR flows through the phase shifters were in directions opposite to those of the flows in the reference case. MVAR dispatch of generators was also substantially different. Some of the adjustments made to bring the initial PECO/LF simulation results closer to PTI's were as follows:

1. MW flow through phase shifters was adjusted. The difference in controlled MW flow stemmed from the fact that PTI allows the controlled MW to vary within a certain band, while PECO/LF defines a single specific value corresponding to the upper limit of the band. To enable the phase shifter to control exactly the same power as that controlled in PTI-PSS/E, solution values were specified for the phase shifters in PECO/LF.
2. MVAR flow through phase shifters was adjusted. Tap positions in phase shifters were noted to be substantially different in both programs, which caused a significant difference in VAR flows. The MVAR flow through phase shifters is very sensitive to transformer tap positions. A very small (e.g., 0.02 per unit) change in tap position could reverse the direction of MVAR flow. Magnitudes of MVAR flows could also be significantly altered by modifying the tap positions. To enable the phase shifters to indicate the same VAR flows as in PTI, the PECO/LF tap settings were gradually fined-tuned to match those in PTI. This effort involved a number of trial and error runs.
3. The LTC tap position was adjusted. For some reason, PECO/LF and PTI solutions for finding the final tap setting for some of the LTCs in the system differed. This difference resulted in different voltage levels in some buses and differences in MVAR flows as well. To attain an identical

voltage level at the pertinent voltage-controlled bus, PECO/LF lower or upper tap limits were changed to allow the tap setting to correspond to solution values found in PTI output.

4. An alternate swing bus was selected, particularly for the light load case. The choice of swing bus affects the levels of MW and MVAR flows in the system and the MW and MVAR dispatch among generators. The match between PTI and PECO solutions for MW and MVAR flows improved greatly when a new swing bus was selected. The swing bus originally indicated in PTI was Joliet 29;7u24. The alternate swing bus chosen was Joliet 29;8u24. This effort also involved a number of trial runs.

6 SIMULATION RESULTS

Appendix E presents the simulation results from PTI-PSS/E, and Appendix F presents those from PECO/LF. The PTI simulation results were obtained from MAIN and served as reference information for validating the results of the PECO/LF modeling and simulation. The information shown in Appendix F is an actual PECO/LF printout from a successful load flow simulation run. Simulation results shown in Appendix F cover the light load case only. Results for the winter and summer peak cases are also available from the Federal Energy Regulatory Commission bulletin board.

6.1 ComEd SYSTEM OPERATING CHARACTERISTICS

Results of simulations for the light, summer peak, and winter peak load conditions are summarized in Table 6.1. A breakdown of the major elements that make up the system is shown in Section A of the table for each scenario. The number of active elements varies for each case. Different loading conditions require a different number of dispatched generators, line connections, and equipment settings. For example, during peak load, about 36 generating units were on line, while about 12 were on line during light load. During peak load conditions, 14 transformers were set as LTCs, while only 10 were set as LTCs during light load.

Section B of Table 6.1 gives ComEd's supply-demand characteristics. The summer peak and light load cases represent the upper and lower bounds of ComEd's operation, respectively. ComEd's peak load in 1995 was about 18,500 MW. Minimum load was about 7,300 MW in 1996. Line charging MVA varies across the cases, although it is essentially a function of the number of lines and voltage. For a system of exactly the same configuration, the line charging MVA should be more or less constant regardless of the level of system load. Line losses also vary across cases. Line losses are mainly a function of load. On a percentage basis, the system losses range from about 1.5 to 2.0%, which is an excellent range for any system. Average power factor at load buses is about 0.897 to 0.917. ComEd's planning criteria target a base power factor of about 85-98% in load substations. The average operating power factor of generators ranges from 0.946 to 0.980.

During light load conditions, the line charging MVA predominates in the system, resulting in a relatively small amount of shunt MVARs (217 MVARs) and a negative (capacitive reactive power) loss of about 1,500 MVAR. It also results in the system tending to operate at higher voltage levels (95 buses violated the upper voltage constraint of 1.05 per unit). The highest voltage in the system is about 1.087 per unit or about 3.5% above the upper bound. In general, ComEd's planning criteria limit the voltage variation from 92% to 105% of the nominal voltage. In terms of power outflow from the system, ComEd exports about 170 MW and 400 MVAR during light load conditions.

TABLE 6.1 Summary of PECO/LF Simulation Results

Item ^a		1996 Light Load	1995 Summer Peak Load	1995 Winter Peak Load
A. System Components				
Total no. of buses		647	632	640
Total no. of lines		844	807	818
Total no. of transformers		200	188	201
No. of phase shifters		9	9	9
DC lines		0	0	0
Voltage levels (kV)		750, 345, 230, 69, 12.5	750, 345, 230, 69, 12.5	750, 345, 230, 69, 12.5
B. Supply-Demand Characteristics				
Generation	MW	7,280	18,426	15,061
	MVAR	4,341	6,291	3,037
Shunt static	MVAR	271	4,006	3,553
Load	MW	7,172	18,048	14,825
	MVAR	3,119	8,886	5,639
Losses	MW	108	378	236
	%	1.48	2.05	1.57
	MVAR	-1,508	3,611	954
Line charging	MVAR	3,384	3,056	3,304
Net export (import) MW		166	(252)	348
	MVAR	399	81	429
C. Violations				
No. of overloaded lines		1	0	1
No. of low-voltage buses		0	4	2
No. of high-voltage buses		95	3	0
D. Convergence Characteristics				
No. of iterations		9	13	11
Solution time (s)		10.5	14.56	14.1
Convergence tolerance		Default values	Default values	Default values
E. Simulation Accuracy Relative to PTI				
Line MW flows				
Percentage of lines within 2% dev		91	95	93
Percentage of lines within 5% dev		95	98	98
Average deviations (%)		0.31	1.12	0.16
Line MVA flows				
Percentage of lines within 2% dev		90	91	92
Percentage of lines within 5% dev		95	98	98
Average deviations (%)		1.14	0.26	0.10
Bus voltage magnitude				
Percentage of buses within 2% dev		100	100	100
Bus voltage angles				
Average deviations (%)		7.4	3.86	6.87

^a dev = deviation.

During the summer peak load conditions, ComEd imports about 252 MW but continues to export MVARs. System loss is about 3.5 times the amount experienced during light load, but these ratings remain at about a 2% level. Peak load conditions required the injection of about 4,000 MVARs from shunt capacitors across the system. The shunt capacitor banks supply nearly 40% of the total inductive VAR requirements of the system. The remaining 60% is supplied by the generators. Voltage in practically all buses is within the 0.95 to 1.05 operating band, which is consistent with the system planning criteria. No overloaded lines were identified.

ComEd's operation and planning criteria are described in detail in Appendix G. This appendix provides further information on how the system is designed and operated.

6.2 SIMULATION ACCURACY RELATIVE TO PTI RESULTS

A line-by-line and bus-by-bus comparison program was developed to compare PECO/LF results with the PTI solved reference case. Accuracy with respect to PTI was expressed in terms of the percentage of elements (either lines or buses) in PECO/LF whose values matched those of PTI's within a specified deviation tolerance. The results of this comparison are summarized in Section E of Table 6.1.

As can be seen in Table 6.1, 91-95% of the lines in PECO/LF model had MW flows within a 2% deviation of PTI values. Within a 5% deviation tolerance, the percentage of lines correspondingly increased to about 95-98%. This 95-98% set was composed mainly of significantly loaded lines (i.e., lines whose loading levels are above 5 MW). Similar observations can be made for MVA flows.

The voltage profile demonstrates an even better match; 100% of the buses had voltage magnitudes within a 2% deviation. For voltage angles, the average deviation was 3-7.4%. All generators had real power outputs within a 2% deviation, and 97-98% of them had power factors within a 2% deviation. However, deviations in MVAR dispatch among generators were substantial, ranging from 2.6% to 144%. A more detailed comparison of the outputs on a line-by-line basis (light load case) is presented in Appendix D. A detailed bus-by-bus comparison is presented in Appendix E.

Factors that most likely caused the discrepancies in MVAR flows follow:

1. The tap positions of LTCs need to be further adjusted to improve the voltage profile of remotely controlled nodes. Tap positions affect voltage magnitudes and consequently the amount of MVAR available in the system.
2. Round-off errors in MVAR loads can accumulate to as much as 30 MVARs and magnify the impact of these loads on individual generator dispatch.

3. Line shunts, which were modeled explicitly in PTI, were neglected in PECO/LF, because of their small values (less than 0.3 MVAR), but they can aggregate to as much as 30 MVARs.

Further adjustments to the magnitude of the generator terminal voltages can be made to alter MVAR dispatch. Increasing the magnitude of desired generator voltages will increase MVAR injection; doing the reverse will have an opposite effect.

7 SINGLE-LINE DIAGRAMS

7.1 DESCRIPTION OF SINGLE-LINE DIAGRAMS

To complement the load flow analysis, two sets of ComEd system single-line diagrams (SLDs) were submitted. The small diagrams (approximately 1 ft by 2 ft) represented the 1995 configuration of the ComEd system. The large diagrams (approximately 2 ft by 3 ft) depicted the ComEd system in 1994. The small diagrams, although more current, did not clearly present the labels and other details of system connections. However, their reduced scale allowed viewers to get a better perspective of the system. The large diagrams used much clearer and larger labels and symbols.

The set of small diagrams consisted of 22 sheets. Each sheet had a number and x and y labels to define the coordinates for any particular element on the sheet. The set included a directory page listing the names of the substations and generation stations, the number of the sheet on which each appears, and the x and y coordinates defining the location within the sheet. Annotations were made on the small diagrams to include PECO/LF bus numbers next to full bus names.

The original large diagram set consisted of 11 sheets without x and y labels. No directory page accompanied the set. To define locations of the various system elements, x and y labels were developed, with the x axis consisting of numbers and the y axis consisting of letters.

To make the diagrams even more usable, a directory was developed to link the various substations, taps, and generation stations to the load flow model and to provide a means of locating specific substations in the drawing more conveniently. This single-line diagram (SLD) directory is described in the next section.

7.2 DIRECTORY FOR SINGLE-LINE DIAGRAMS AND LOAD FLOW MODELS

The main function of the SLD directory is to associate the bus names (in all three base load cases) to their corresponding locations in the small and large diagrams. The directory contains the following information: (1) complete bus name, (2) PTI load flow model bus number, (3) PECO load flow model bus number, (4) abbreviated PECO bus name, (5) station number as assigned by ComEd, (6) location in small diagram, and (7) location in large diagram. The directory was developed by using information from the MAIN data dictionary, PECO/LF input data, PTI/LF input data, and x and y coordinates on the small and large diagrams.

Hard copies of the directory (light load case) are presented in Appendix F. The directory can appear in five forms, depending on the field used to index the data. The directory may be indexed by complete bus name, PECO/LF bus name, station number, voltage level, or PECO/LF bus number.

An electronic version of the directory with sort and search capabilities was also developed to enable the directory information to be used more efficiently. The electronic version is included as one of the modules of the information retrieval system developed for this study.

8 INFORMATION QUERY SYSTEM

An information query system was developed to support the power flow modeling and simulation work. The main purpose of the query system is to consolidate the various electronic data generated during the implementation of the project. It is also intended to format and organize the various outputs. The main function of the query system is to allow users to view and browse through information from pertinent databases and ASCII files. The system also includes limited editing functions. A search feature is included to allow for quick access to specific information.

The query system consists of four main modules: (1) PTI data structure, (2) PECO data structure, (3) SLD directory, and (4) system description. A more detailed description of the query system is presented in Appendix I.

9 SUMMARY AND CONCLUSIONS

This report summarizes the completion of validated load flow case studies that can now be used to assist NELO in applications for other operational areas of interest. Load flow data, which were originally in PTI-PSS/E format, were converted to PECO/LF format. Validation of the data and model were completed by using various auxiliary programs and information from known published sources. The model must be used with the understanding that the interties have been modeled as fixed local loads of the boundary buses. System simulations covering light, winter peak, and summer peak load conditions were undertaken. Overall, the model simulation results for 91-95% of the significantly loaded elements were accurate to within a 2% deviation from the reference values.

The annotated SLDs are an important aid in understanding the connections and bus designs of substations. The x and y coordinates developed for the diagrams are most useful for locating these substations, especially when they are used in conjunction with the SLD directory. Photographic images further assist users in understanding the nature and configuration of system components.

All relevant information pertaining to the power flow modeling and simulation of the ComEd system can be accessed via the information query system developed for the study. The query system provides a flexible foundation for even more comprehensive information retrieval or editing capabilities. In addition, the system can be easily adapted to represent any electrical system and its associated load flow and technical information.

Finally, as a result of the completion of the load flow cases and the accompanying software, a basis has been established for potential developments of "missing data heuristics." Data limitations are frequently very problematic with respect to constructing representative load flow simulations. However, the case study developed for this effort could provide sufficient logical links between known system component characteristics and visual images and thereby support heuristic estimates of the operating parameters for unknown or uncertain components.

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