DISTRIBUTION NETWORK CONTINGENCY ANALYSIS AND CONTINGENCY DETECTION WITH THE CONSIDERATION OF LOAD MODELS

by

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ABSTRACT

DISTRIBUTION NETWORK CONTINGENCY ANALYSIS AND CONTINGENCY DETECTION WITH THE CONSIDERATION OF LOAD MODELS

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The electric utility market environment has changed quite radically during recent years due to the process of deregulation. This has changed the asset management towards a capital controlled business where owners are trying to maximize their profits with cost optimization. To keep up with the increase demands on high reliability and high quality delivery systems, many utilities endeavor to rationalize their system operations with more intelligent control schemes and facilities.

A lot of issues under uncertainty such as load growth, quality of supply and environmental impact affect the reliability of the distribution system. Power outage is the most serious challenge that might affect the reliability of the distribution system, which normally leads to onerous financial losses as customer reimbursements and faulty equipment fixing or replacement. Hence, utility companies are obligated to assess their distribution network security, improve their service quality, and prevent potential power outage. An important aspect of this is contingency analysis, which involves understanding and mitigating potential failures in the network.

More accurate and efficient contingency analysis was implemented in this study based on comprehensive ZIP load model, which estimates the actual customer demand from the nominal demand and the actual voltage level. Considering the realistic characters of loads, low voltage load cut off function was introduced to acquire more credible analysis result. Field surveys were conducted to determine the load composition based on 18 separate device categories. To improve the computing efficiency, macro coefficients were derived. Based on this comprehensive ZIP model, load reconciliation was then integrated to power flow program to improve the analysis accuracy. The application of comprehensive load model and load reconciliation gives operators more accurate and credible indication than constant load.

Online contingency detection is another key function to improve the distribution network reliability. This study implements an effective detection system for contingencies such as transformer outages, open mains or other incidents using statistical approaches. Based on periodic network transformers loads readings, any transformer load change exceeds the normal load change boundary will be listed as suspect event to be analyzed. Sensitivity analysis is performed to verify the contingencies based on the actual real time transformer load changes and pre-calculated values for transformer load changes for each expected incident in the network. All the sensitivity matrices are calculated automatically on HP-UX environment and with the consideration of comprehensive ZIP load model.

Eventually, distribution network contingency analysis under different contingency levels is performed and detailed analysis results were given. The practical feasibility of the analysis method and the accuracy of the comprehensive ZIP load model greatly improve the accuracy and credibility of the contingency analysis. The validation of the online contingency detection system is also implemented on real distribution network and the test results match the actual event. All of these studies prevent potential cascade power outage, provide more accurate support for decision maker, facilitate an immediate repair of the faulty part and eventually improve the distribution system reliability.

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INTRODUCTION

1.1 Background

The continuous increase for dependency on electrical energy to run most of their activities makes it necessary to regularly improve the distribution systems. This improvement not only involves served area and system capacity increase, but also includes service quality and system reliability enhancement. The security assessment plays an important role in the power distribution networks since it offers power system engineers a theoretical framework to measure the power supply quality served by the utilities, and provide a decision-aid tool at emergency situation. Contingency analysis is a key function of security assessment, which involves predicting and mitigating potential failures in the distribution network.

Basically there are two stages in contingency analysis: contingency selection and contingency evaluation [1, 2]. At the contingency selection stage, to speed up the analysis process, usually fast and approximate load flow calculation methods are used to select a list of severe contingencies for further evaluation [3]-[7]. At the contingency evaluation stage, the selected candidate contingencies are evaluated by a more detailed analysis to check for violations. Especially when a power system network has serious reactive power or voltage problems, a fast and accurate power flow solution must be used to solve for the resulting flows and voltages if an outage occurs.

The accuracy of load modeling has an important impact on the load flow calculation results. Load is one of the most important electric components in power system operation and control. Grid planning and operating decisions rely on simulations of dynamic behavior of the power system. Both technical and commercial segments of the industry must be confident that the simulation models and database are accurate and up to date [8]-[10]. At the present time, most utility companies treat customer demand as a constant load when performing secondary-network power distribution load-flow analysis. Substantial changes in the nature of the electrical load in the past ten years have made it clear that a more accurate load representation is essential [11].

Components reliability is also an important factor that affects the security of the distribution network. The electrical distribution network is a very complex system, consisting of thousands of various components, such as: wires, insulators, posts, connectors, distribution transformers, cables, etc. Each of these components has a different life expectancy and failure distribution function. Some failures that affect the reliability of distribution system happen more often in most of systems due to the similarity in the installation. Singularity of some networks due to the system design, load demand intensity, equipment aging, area weather or repeated upgrading and extensions not only brings up some types of faults more often than they should, thereby affecting the reliability of the system, but also makes it difficult to locate or diagnose the problem due to the difficulty in figuring out the present system configuration. In such cases, increased hours are needed to restore the system, a matter that deeply affects the reliability according to the common consideration used to evaluate the network reliability.

The accumulation of undetected contingencies is one of the most challenging fault incidents in underground distribution systems, especially without implementation of suitable monitoring mechanism to provide early indications about such incidents occurrence. One of the most wellknown underground distribution systems in the world is the Consolidated Edison Company of New York, Inc (Con Edison). Though Con Edison has implemented many new algorithms and installed equipments to improve the components reliability in recent years, the cascading contingenies are still the most serious challenge that might affect the reliability of their distribution system [12].

Due to all above reasons, this dissertation was particularized to develop an accurate, efficient, and realistic distribution network contingency analysis and contingency detection system to protect the distribution system such as Con Edison from possible troublous incidents that may affect the most important and high crowded areas in the world.

1.2 Networked Distribution System

Unlike other utility distribution systems that radial or near radial structure with large number of branches/nodes, prominent features of electrical distribution system of Con Edison are closely networked. In order to perform the desired functions of a Distribution Management System (DMS), some special features must be implemented to accommodate the requirements of the distribution system of Con Edison.

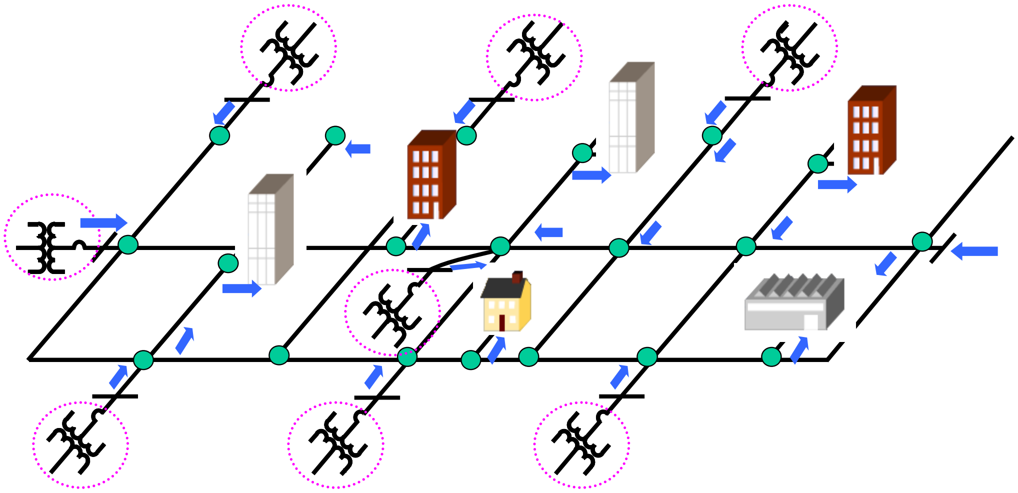


Figure 1.1 Example of Part of the Con Edison's Distribution Network

Con Edison operates one of the most complex electric power systems in the world. It also maintains the most reliable electric service in the world. In 2006, PA Consulting Group named Con Edison the most reliable electric utility for the northeast region. The system performs at a level that is seven times above the national average.

Con Edison delivers electricity to more than 3 million customers through a huge transmission and distribution network. The company has built the world's largest system of underground electric cables to accommodate the congested and densely populated urban area it serves. The system's underground network features approximately 94,000 miles of cable, 263,000 manholes and service boxes, and 34,000 underground transformers. Con Edison's nearly 36,000 miles of overhead electric wires complement the underground system. In 20XX, annual electric usage reaches almost 55 billion kilowatt hours in Con Edison's service area. The total consumption is growing steadily. Customers in the Con Edison service area are using 20 percent more electricity than they did 10 years ago. Demand is expected to rise another 10 percent in the next decade. It is anticipated that more than 1 million room air conditioning units will be added in the Con Edison service area over the next 5 years.

1.3 Poly-voltage Load Flow (PVL)

Poly-voltage Load Flow (PVL) is a collection of distribution systems analysis, data management, and report generating programs available under a single user interface. PVL is Con Edison’s principle distribution system design and analysis tool and it helps Con Edison remain a leader in reliable electric power. It is a balanced three-phase load flow analysis program with the additional features such as demand estimation, feeder ratings, short circuit calculations, and feeder maintenance. PVL is capable of identifying overload of transformers, primary feeder sections, and secondary mains, low voltage of primary and secondary buses, and provides detailed reports showing the loading and voltages of each and every component in the system [13].

Most, if not all, Con Edison’s network distribution systems have a “N-2” (also known as second contingency) design criteria. Customers’ peak electric demand would be met without stressing network components beyond design limits when any two network feeders are out of service. Based on PVL, load flow analyses are performed during design stage to make sure no loads are dropped or reduced, and no equipment in the system is overloaded in each of the following cases:

- Base-case
- All (N-1) or first contingency cases
- All (N-2) or second contingency cases

PVL provides Con Edison's reliability-planning program and monitor-operating program with critical data such as:

- Feeder cable section data and transformer data
- Feeder load and rating data
- Load shift information for all FIRST and SECOND contingencies
- Feeder load pickup information for all FIRST and SECOND contingencies

1.4 Secondary Distribution Network Challenges

Some times and especially in high load seasons, the operation of secondary distribution network encountered by internal or external incidents that affect the whole distribution system reliability and performance, below some of them are explicated.

1.4.1 Multiple Contingency Analysis

Power systems security control is necessary to smooth power system operation within secure regions. Contingency analysis is useful in understanding power system conditions in advance before taking preventive control. However, an accurate and detailed analysis method in a near real-time manner is still a great challenge due to the high nonlinearity and high dimensionality of power systems. The combinational nature of multiple contingencies in fact makes it impossible to scan all combinations of contingencies in a reasonable time frame. Traditionally system security analysis is carried out on lower level contingencies in the time interval of several minutes (e.g., most of N-1 and some of the important N-2 contingencies). In many instances the hazardous impacts of multiple contingencies are easily ignored until their occurrence, because their probabilities of occurrence are quite low. However, multiple contingencies do occur, and when they do, consequence can be very severe.

1.4.2 Load Modeling and Load Reconciliation

The load behavior is a function of the system voltage and different electric apparatuses act differently. It is important to include the load model and perform distribution load reconciliation in the simulation program when studies the contingency conditions where the system is under stress and system voltages at certain areas are depressed. Con Edison has performed load testing and established load models for different category of devices. However, current development is under Microsoft Windows environment and the load composition is limited. One of the tasks in this dissertation is to integrate and implement comprehensive load models into PVL for performance evaluation in the HP-UNIX environment.

1.4.3 Estimation of High-Tension (HT) and 4kV Loads

Many of Con Edison's networks have high-tension (HT) loads supplied at 13 kV or 27 kV level. A typical high-tension load is usually supplied by multiple feeders through a common bus. Although Con Edison knows the feeder loading at the station (and the network loads), no real-time readings for the HT loads is available in the load flow applications now. Further more, in addition to network loads and HT loads, feeders also supply 4 kV loads (4 kV unit stations) in some Con Edison's networks. This means 4 kV loads and HT loads need to be adjusted according to feeder loads and network loads in some fashion.

1.4.4 Network outage

Outage is a harmful event that affects the reliability of the distribution system. It normally takes place as a response for certain operation abnormality in one or more of network equipments or as a result of external factors. Some of the most common causes of outages include:

- Dig-in cable area.
- Flood.
- Power shortage.
- Power equipment failure.
- Human control and operation mistakes.
- Protection system action.

1.4.5 Effects of Open Main / Blown Limiter incident

If the open main incidents are not detected and fixed in time, long term secondary distribution network performance will be affected due to the appearance of the following serious challenges:

- If one or more transformer are out of service for any reason, the load flow through secondary mains will be redistributed in a different way than that the network is initially designed to.
- Loading of transformers around the incident location exceed their KVA rating, especially during peak load time that may trigger the transformer protection into operation.

$$\sum_{\substack{n \neq T.out \\ n=1}}^{N} (\Delta S_{T.n})(P.F_{T.n}) = (S_{T.out})(P.F_{T.out}) + \Delta P_{losses} \qquad (1.3)$$

$$[S_{T.n} + \Delta S_{T.n}] \geq S_{T.n.Rated} \Rightarrow \text{ Over heat / Protection device operation} \qquad (1.4)$$

$\Delta S_{T.n}$: Transformer (n) total power (KVA) change due to transformer (*T.out*) outage.

$P.F_{T.n}$: Power factor for transformer number (n).

$S_{T.out}$: Total power (KVA) for the disconnected transformer by blown limiter (*T.out*)

ΔP_{losses} : Network power losses change due to transformer (*T.out*) outage.

$S_{T.n.Rated}$: Rated KVA of transformer *T.n*.

- Open Main incidents in heavy load conditions lead to overloading the network equipments like underground cables and transformers, which may last for a long period and may eventually cause manhole fire.

1.4.6 Utility Financial Losses as Customers Reimbursements

Utility is responsible for providing uninterrupted and high quality service for its customers all the time regardless of the season or how high the demand is. Therefore, the utility may have to reimburse the customers for their losses as a result of the service interruption or irregularity referred to control malfunction, equipment failure or employees negligence. As an example, according to regulations and rules for Con Edison; the company will compensate each residential customer for his/her losses due to lack of refrigeration up to maximum of $350 and up to maximum of $7000 for each commercial customer for any one incident, limited to $10,000,000 per incident as company's total liability.

1.4.7 Blackout in Distribution System

Blackout incidents are rare, but the huge effects that they usually leave in the economic, security and psychical life of the individuals, plants, companies and utility itself make it essential to investigate any possible causes for such events, in addition to particularize many researches to enhance the operational environments, equipment specifications, protection schemes and faulty parts early detection monitoring. These requirements aim to minimize the future possibility for same incidents repetition and eventually to improve the service quality currently supplied.

Con Edison supplies one of the most important and highly loaded areas in the world that explicates company's concern to maintain a high reliability system. The system has experienced several local blackout incidents in the past. For example, after 8 of 14 feeders dropped off in Washington Heights Network on July 6th, 1999, Con Edison shut down the whole network concerning the remaining cables may be unable to carry the electric loads at that time. The power outage took place during high heat and humidity wave where approximately 170,000 customers experienced service outage for different periods of time that reached to 19 hours in some areas.

According to a report from the Office of the Attorney General to the people of the state of New York on March 9, 2000 [14] [15]:

- They concluded that the cause of this outage mainly was due to the increase in system demand during that hot weather days while the distribution system suffering from inadequate or defective components.

- Also the report mentioned to the long period of time taken to restore the failed parts and cables in the outage area.

The “shut down” decision was made based on the contingency analysis results at that time, and this decision has been questioned till now. Is it too early to shut down the system and the rest network may sustain without causing any further damage? Or is it too late and the incident has caused permanent damage to the network already? Without accurate load models, all of these are left unanswered because of lacking of reliable contingency analysis.

This report also shows the need for a detection mechanism which is capable of detecting and locating the incoming failure or open circuit in the secondary network. The repeated undetected incidents might lead to load redistribution in the mains and network transformers in a way completely different from that the network was designed to operate with. This may lead to overload some network components at high load situation and possibly cause transformer cascade outages.

Experiencing such emergency is still possible in the future. It is very important to implement contingency analysis and contingency detection for the distribution network with the consideration of load models to provide credible indication and figure out an effective mechanism for such incidents to mitigate the undesired consequences and make the restoration process faster and easier.

1.5 Study Objectives

The distribution network of Con Edison has experienced several power outages. As continuous efforts for Con Edison to maintain reliable and high quality service, constant P-Q load model is a weakness for accurate contingency analysis and effective contingency detection.

Based upon Con Edison present system operation experiences, the actual network configuration, and the available data source, this dissertation aims to develop a novel contingency analysis and contingency detection system with the consideration of comprehensive ZIP load model.

Taking all of these challenges into consideration, study objectives can be summarized as:

- Implement detailed contingency analysis based on Poly-voltage Load Flow (PVL) under HP-UX environment to provide operators up-to-date and accurate indication.
- ZIP load model will be taken into studies because many nonlinear loads demand are voltage dependent. Low voltage cutoff function will be incorporated and macro load model coefficients will be derived to realize more realistic and efficient evaluation result.
- Load reconciliation will be performed based on load sensitivity matrix and base case customer demand for real time and accurate analysis.
- Least square error method will be used to estimate the high-tension loads and the 4kV loads to improve the accuracy of power flow calculation.
- Implement contingency detection system to identify the contingency accidents such as transformer outage or open main accidents. Develop programs based on HP-UNIX to calculate required sensitivity matrices automatically.
- Integrate the contingency analysis, comprehensive ZIP load model and load reconciliation with PVL and keep tracing the open main or transformer outage information to improve the distribution network reliability.

1.6 Synopses of Chapters

The material in this dissertation is organized as follows:

Chapter 1 introduces the general background of the distribution network contingency analysis, contingency detection and load model issues, and illustrates the importance, motivation, and objective of this dissertation.

Chapter 2 introduces the basic idea and the framework of the contingency analysis and contingency detection. The difficulty of multiple contingency analysis, the cascading features of power outage and the contingency selection and contingency evaluation are presented. The statistical approaches to detect the abnormal change in the transformer load are shown and transformer outage and open main sensitivity analysis process are also explained in details.

Chapter 3 investigates the comprehensive ZIP load model and load reconciliation. Loads are grouped into 18 categories, low voltage cut off function is provided and macro load model coefficients are also derived. Real time customer demand estimation algorithm based on load sensitivity matrix is presented. The High-tension and 4kV load estimation is also implemented by using least square error algorithm.

Chapter 4 performs system integration of contingency analysis and comprehensive ZIP load model compared with constant P-Q load. Detailed analysis results under different contingency levels are given.

In chapter 5, distribution network contingency detection algorithm is evaluated based on Con Edison's real network. Graphical user interfaces are introduced and detailed detection results are also illustrated.

Chapter 6 states the summary and contributions of this dissertation and discusses the opportunity for further research.

CHAPTER 2

CONTINGENCY ANALYSIS AND CONTINGENCY DETECTION

2.1 Contingency Analysis

Contingency analysis is a software application run in an energy management system to give the operators an indication of what might happen to the power system in the event of an unplanned (or unscheduled) equipment outage [16]. In other words, the contingency analysis application allows the operator to ask “what if’ questions such as: “What will be the state of the system if we have an outage on part of our distribution network?” The answer to this question might be that the system power flows and voltages will readjust and remain within acceptable operating limits, or the severe overloads and undervoltages will occur so that the system’s ability to survive is in question. The use of a contingency analysis application in an energy management system is predicated upon the idea that when forewarned, the operator can take some action before or after the event to help the system avoid outage events.

Typical contingencies on a distribution network consist of outages such as loss of feeders, distribution lines, or transformers. Contingencies can occur in the form of single equipment outages or in the form of multiple outages. The causes of equipment removal and short circuits can be classified as internal or external. Internal causes arise from phenomena such as insulation breakdown, over temperature relay action or simply incorrect operation of relay devices. The external causes result from some environmental effects such as lightning, high winds and ice conditions or nonweather related events such as vehicle or aircraft coming into contact with equipment, or even human or animal direct contact. All of these causes are treated as unscheduled, random events which the operators do not expect to occur, but for which the operators must be prepared.

The fact that the power system is designed to account for outages does not mean power system operators can passively assume the system will withstand all such events. There is a great difference between the system planners design and the actual system the operations department must use to deliver power. Construction can be delayed or denied by regulatory agencies, load patterns can shift in unforeseen ways or generator outages can necessitate purchasing power and transmitting it over long distances. The result is a situation wherein operators must play an active role in maintaining the system security.

The first step in this active role is to run a contingency analysis application program at frequent enough time intervals to guarantee that system conditions have not changed significantly from the last execution. The output of the contingency analysis is a series of warnings or alarms to the operators stating something like this:

Feeders out: [F001, F002, F003, F004, F005]

Reducing demand on bus: ABCDEF by 1000.00 + j 2000.00 kVA

Overload transformers: HHH1, III2, JJJ3, KKK4, LLL5, MMM6

Voltage Drop to: 0.xx PU at LYYYY

To achieve an accurate picture of the system's vulnerability, several issues need to be addressed:

- *System model*: Contingency analysis is carried out using a steady-state or power flow model of the power system. If stability is to be assessed as well, then additional information concerning the dynamic aspects of the system needs to be added.
- *Contingency Definition:* Each contingency to be modeled must be specified. The simplest form of contingency definition is to name a single component. This implies that when the model of the system is set up, this contingency will be modeled by removing the single component specified. How the component outage is specified is also an important consideration.

- *Contingency List:* Usually contingency analysis programs are constructed to run from a list of valid contingencies. Part of the technical difficulty involved in creating a contingency analysis program that functions usefully can be seen when such a list is compiled.
- *Performance:* How fast should the contingency analysis application program execute? Generally, utility operators wish to have results from a contingency analysis program in the order of a few minutes up to fifteen minutes. Anything longer means that the analysis is running on a system model that was updated too long ago for the results to be reliable.
- *Modeling Detail:* The detail desired by most utility operating engineers for a contingency case is usually the same as that used in a study power flow. That is, each contingency case requires a fully converged power flow that correctly describes each transformer's load rating and each load's estimation.

2.1.1. N-k Contingency

The "N-1" criterion is an "abstraction" representing equivalently a single contingency (element kept out of service for maintenance, generating unit not scheduled, etc.), or the tripping of one element following a normative incident, like a three phase short circuit. An N-k contingency means a contingency resulting in loss of k components where it is implicit that k>1.

The difficulty of N-k contingency analysis lies in its combinatorial nature. The number of credible contingencies may vary depending on the level of analysis, number of elements (N), and level of contingency. That is, first level of contingency corresponds to N-1, second level of contingency corresponds to N-2 and so forth. Thus, the total number of k^{th} contingencies can be given by C_{Nk} for $k=0, 1, 2,\ldots, N$. Then the total number of all possible contingencies, TC_{Nk}, can be given as:

$$TC_{Nk} = \sum_{k=0}^{N} C_{Nk} \tag{2.1}$$

where, C_{Nk} can be given as:

$$C_{Nk} = \frac{N!}{k!(N-k)!} \tag{2.2}$$

Even for a small size network with N=100, there are 4950 N-2 contingencies, 161700 N-3 contingencies, 7842450 N-4 contingencies, 14304628800 N-5 contingencies, and so on. The data dimensionality problem in fact makes it almost impossible to scan all combinations of contingencies in a reasonable time frame. Traditionally system dynamic security analysis is carried out on a few pre-selected contingencies in the time interval of several minutes (e.g., most of N-1 and some of the important N-2 contingencies). In many instances the hazardous impacts of contingencies can be easily ignored until their occurrence, because their probabilities of occurrence are quite low. However, multiple contingencies do occur, and when they do, consequences can be very severe, and these very practical facts motivate the objective of this research, to analyze high risk N-k contingencies for online security assessment.

2.1.2 Cascading Blackout

Fortunately, most cascading process can be relatively slow in the initial stages that may allow time for online contingency analysis.

Figure 2.1 presents the timeline of August 14th US-Canada blackout [17]. At initial stage, from 15:05 to 16:08, there were five lines tripped successively, and the system operators did have 27 min, 9 min, 4 min and 29 min to take remedial action. If an efficient contingency analysis method had been performed and reliable analysis result could be provided to system operators in several minutes, this blackout could have been prevented. However, the large number of N makes the N-5 contingency analysis very difficult. System operators had no sufficient online information to arm preventive or corrective controls in order to ensure system security in the dangerous initiating event. System oscillations then grew so large the system could not rebalance and stabilize. Finally the blackout took place.

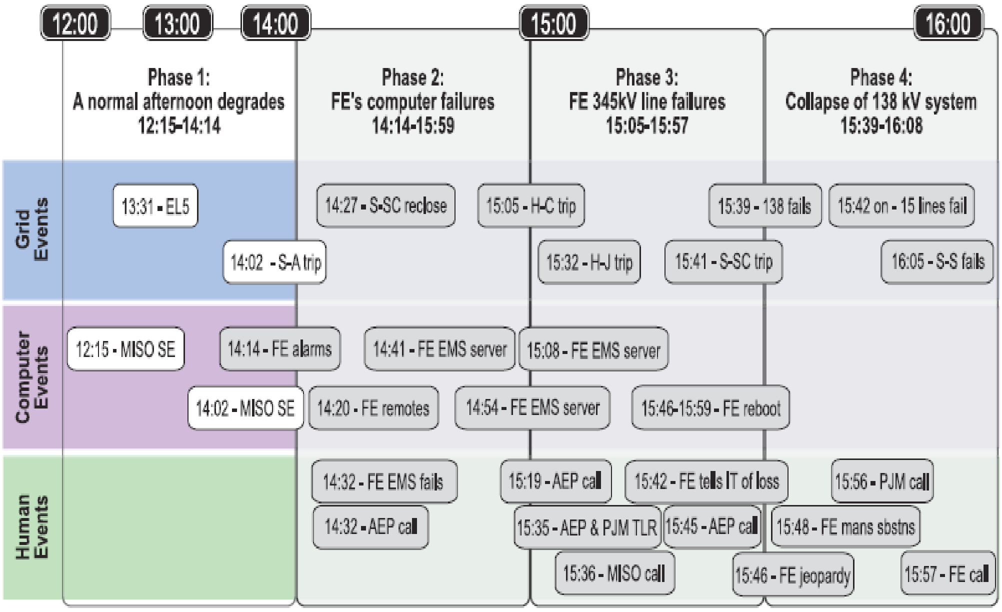


Figure 2.1 The timeline of August 14th US-Canada blackout

Therefore, it is essential to analyze contingencies that may cause further system cascading failure and determine remedial actions to prevent the outages, so as to ensure system stability during initial stage. It's significant to take advantage of these cascading intervals and accurately evaluate the system to provide sufficiently fast prediction results in case of critical contingencies.

2.1.3 Contingency Selection

For a large power system, there are a large number of credible contingencies which need to be analyzed. Thus, there are two important approaches for online contingency analysis. First, reduce computational time for contingency calculation. Many researchers have addressed this problem and have tried to reduce the computational time by taking advantage of computer hardware such as parallel computing and distributed computing [18]-[22]. However, to some extent, some existing computing methods cannot meet the requirements of the increased system complexity in the deregulated environment owing to the precision and accuracy of system modeling or the speed and efficiency of computing process. Others have tried to do severity based contingency selection and build a reduced contingency list by modeling detailed system into simplified one [23]-[25]. This approach does reduce computational effort, but may not classify system's contingencies accurately, which may cause false alarms or miss to detect harmful contingencies.

Contingency analysis is difficult because of the conflict between the accuracy with which the power system is modeled and the speed required to model all the contingencies. If the contingencies can be evaluated fast enough, then all cases specified on the contingency list are run periodically and alarms reported to the operators. This is possible if the calculation for each outage case can be performed very fast or else the number of contingencies to be run is very small.

Considering distribution networks are comparatively small to generation and transmission systems, this study employs a simple but accurate contingency selection. The basic idea of this contingency selection is, when contingency occurs, based on present system contingency level N-k (where k≥1 is implicit), run N-1 contingency analysis, which is actually (N-k)-1 contingency. The analyses are always based on latest system configuration information and only run N-1 contingency analysis. With this analysis method, the total number of contingencies for analysis turns to be:

$$TC_{Nk} = N - k \tag{2.3}$$

Apparently, this method is good for the cases such as the incident in the Washington Height and it releases computing burden dramatically and improves the analysis speed efficiently. If the time interval between latest event and next element tripping is longer than the analysis time, system operator could have enough time to take remedial actions, which may reduce the probability and severity of next event or prevent following cascading failure. For small or medium systems, analysis based proposed method may be implemented within one second. With the continuous system configuration tracing, the analysis program could update the required data in time and improve the evaluation accuracy, which makes it particularly suitable for online assessment. Figure 2.2 presents the flowchart depicting the whole contingency analysis process.

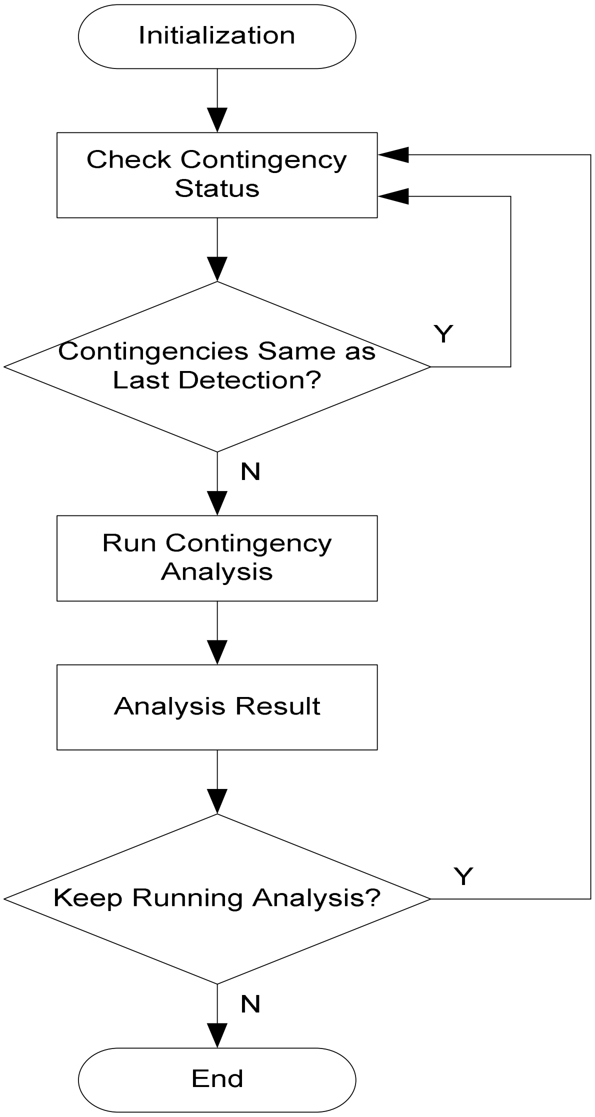


Figure 2.2 Flowchart of Contingency Analysis

2.1.4 Contingency Evaluation

There are two parts in the contingency evaluation, one is post contingency analysis and the other one is N-1 pre-contingency analysis. Each post contingency scenario is evaluated in order to detect operational problems and the severity of violations. The most common operational problems are line overloading, transformer overloads, and inadequate voltage levels at system buses. N-1 pre-contingency analysis is also performed to identify potentially harmful contingencies and reduce the risk of false alarms.

Both the post contingency evaluation and N-1 pre-contingency evaluation involve fast and accurate load flow. A number of algorithms for fast contingency analysis such as fast decoupled load flow [26] (based on sparse matrix techniques [27], such as refactorization [28] or compensation [29]), or localization methods [30] are studied by many researchers.

To improve the evaluation accuracy, several load flow techniques such as the Newton Load Flow (NLF) [31][32] are reported. Despite its obvious qualities, the NLF suffers drawbacks such as the time consuming factorization of the Jacobian matrix. All the above approaches are only focused on the improvement of the algorithms of the load flow, however, the load model, which plays an important role in the load flow, is normally neglected.

Based on Poly-voltage Load Flow (PVL), this dissertation is dedicated on the accuracy improvement of distribution network load model. PVL adopts sparse matrix method to realize a fast contingency analysis, and the analysis accuracy is guaranteed by implementing the comprehensive ZIP load model, which will be depicted in Chapter 3 in details.

2.2 Contingency Detection

The contingency detection has a significant impact on distribution network reliability. Transformer outage or open main events are very common contingencies that frequently take place in the secondary distribution systems. Most of the time, these accidents may cause unreliable operation for the surrounding subsystem that could extend to involve surrounding areas leading to partial or complete blackout if such incidents are not detected and corrected.

A lot of researches have focused on improving the reliability of the system by concentrating on transformers and other distribution system components [33]-[36]. However, very few have focused their research on transformer outage and open main incident detection as early as possible to reduce the hazardous impacts. Besides, the complexity of actual configuration of Con Edison underground distribution system makes it difficult to implement any research that addresses challenges if it is not familiar with the circumstances of Con Edison.

Developing a comprehensive and effective contingency detection system is essential for all distribution systems with the underground networks for following reasons:

- The previous outage incidents took place in some networks and caused by open main incidents.
- The high reimbursement value paid to the customers in case of outage incident.
- The long period needed to repair the affected equipment and to restore the system without this mechanism.
- Psychological, convenience and security side effects may impact the inhabitants during the period of possible outage especially if it involves early night hours.

Dr. Abed Athamneh proposed a novel open main detection approach based on Con Edison’s secondary distribution network with the considering of transformer change rates and sensitivity analysis [12], however, the exhaustive labor cost of all the sensitivity matrix calculation limits the feasibility of this proposed detection system.

This research implements a statistical contingency detection approach by automatically calculating all the sensitivity matrices on HP UNIX environment, observing any abnormal or unexpected change in the transformer load by comparing the previous transformer load profile and the present one, analysizing any suspect one based on the sensitivity matrices and giving detection result.

2.2.1 Offline Calculation

To declare a suspect incident as a confirmed outage incident, nearby transformers load change sensitivity analysis should be implemented. To formalize transformer outage sensitivity matrix, a series of programs integrated with PVL based on HP UNIX are developed to calculate the nearby transformers load changes for every case of a transformer outage incident. The network transformers show most load change will be listed as nearby transformers. All the programs can run automatically on HP UNIX environment without any manual operation.

All the offline calculations are based on such assumption: The transformer currents will redistribute when transformer outage or open main/blown limiter occurs. Its change rate may exceed the normal RMS variations.

2.2.1.1 Transformer Outage Nearby Transformer List (TONTL)

For each network transformer, all the nearby transformers are listed to show where most load changes will be experienced as a result of that individual outage incident. The list can be generated by running a program named TONTL.c. This program was developed by ESRC and based on HP UNIX environment. In the calculation process, transformers are taken out one at a time while the load response at the other transformers is being observed and compared with the actual values in base case (perfect network).

The top 10 network transformers show the most load change will be listed as nearby transformers.

$$\Delta I_{R.xfr.NBn} = I_{R.xfr.NBn} - I_{R.xfr.NBn-} \tag{2.4}$$

$$\Delta I_{R.xfr.event} = I_{R.xfr.event} - I_{R.xfr.event-} \tag{2.5}$$

Because the number of considered nearby transformers is not the total number of the network transformers, the expected lost load by one transformer outage will be greater than the changes in the ten nearby transformers in most cases.

$$\left|\Delta I_{R.xfr.event}\right| > \left|\sum_{n=1} \Delta I_{R.xfr.NBn}\right| \text{, where} \tag{2.6}$$

$\Delta I_{R.xfr.NBn}$: Load change for nearby transformer *n.*

$I_{R.xfr.NBn}$: Load of nearby transformer *n* at the event time.

$I_{R.xfr.NBn-}$: Load of near by transformer *n* at previous reading.

$\Delta I_{R.xfr.event}$: Load Change for the transformer at which over boundary change detected.

The list indicates the top ten most affected transformers that show the highest load changes due to outage at one transformer. The size of each transformer should be taken into consideration if transformer rating load ratio is used as load unit instead of current value in Amperes. The list is prepared to show the nearby transformer information (names and values of load change) for every transformer to be used later in investigating pre-exist open main in the transformer outage area.

Table 2.1 TONTL Pattern

Transformer Outage at	Names and Change Values of Nearby Transformers			
	1st	2nd	……	10th
xfr $_1$	xfr NB.A: $\Delta I_{C.A}$	xfr NB.B: $\Delta I_{C.B}$		xfr NB.J: $\Delta I_{C.J}$
….	…	…	…	…
xfr $_n$	xfr NB.I: $\Delta I_{C.I}$	xfr NB.II: $\Delta I_{C.II}$		Xfr NB.X: $\Delta I_{C.X}$

$\Delta I_{C.A}$: Calculated load change for transformer (A)

Since the regular real time reading received by the RMS system is a percentage of the transformer full load, transformer Size Factor (Ks) has to be used to rectify the actual load change contribution ratio for different size nearby transformers with respect to the one at which the abnormal load change is detected (event).

$$K_s = \frac{Nearby.Transformer.size(KVA)}{Event.Transformer.Size(KVA)} \tag{2.7}$$

$$P_{xfr.NBn}(unified) = P_{xfr.NBn}(load.percent) \times K_s \tag{2.8}$$

2.2.1.2 Open Main Nearby Transformer List (OMNTL)

For every suspicious open main incident, load response for all network transformers is observed by using a program named OMNTL.c, which was developed by ESRC and based on

HP UNIX environment. Network secondary mains are opened once at a time while the load response at the transformers is being observed and compared with the actual values in base case (perfect network). Nearby transformers that show most load changes are listed beside that main in descending order to form a complete list that has a number of rows equals to that of network secondary mains.

Table 2.2 OMNTL Pattern

Secondary Main	Affected Nearby Transformer					
	Affected xfr No.	1st	2nd	3rd	…	10th
Main $_1$	i	xfr NB.A	xfr NB.B	xfr NB.C	…	…
….	…	…	…	…	…	…
Main $_m$	k	xfr NB.I	xfr NB.II	xfr NB.III	…	…

In Table 2.2, the second column specifies the total affected nearby transformer number. All the mains and all the transformers are shown with related index number (starting from “0”) for computing convenience. This list considers ten most affected transformers. However, in some cases, the whole number of the nearby transformers which are affected by this open main incident is less than ten transformers. If the total affected nearby transformer number is less than ten, index number “-1” will be shown as complements at the rest of columns.

2.2.1.3 Most Sensitive Transformer List (MSTL)

According to OMNTL, almost every network transformer is listed one time or more as the most affected nearby transformer due to open main location. In MSTL, for each network transformer, all possible open mains at which this transformer shows the maximum load change are listed in one row. Therefore MSTL number of column is different from transformer row to another depending on how sensitive this transformer is to the different open main incidents.

The MSTL calculation part is also included in the program of OMNTL.c. In the first step, this program will allocate a space with the size of N*(M+1) for this matrix, where N is the total number of transformers and M is the total number of mains. Once the MSTL calculation is completed, a matrix with the column number of maximum affected mains plus one will be generated. Like OMNTL, the second column will specify the total affected nearby transformer number; all the mains and all the transformers are shown with related index number (starting from “0”) for computing convenience; if the total affected main number is less than maximum, “-1” will be taken as complements.

Table 2.3 MSTL Pattern

Transformer	Secondary mains lead to max. load change at this transformer				
	Affected Main No.	1st	2nd	3rd	…
xfr $_1$	i	Main $_A$	Main $_B$	Main $_C$	…
…	…	…	…	…	…
xfr $_n$	k	Main $_I$	Main $_{II}$	Main $_{III}$	…

2.2.1.4 Round-off Error

A round-off error, also called rounding error, is the difference between the calculated approximation of a number and its exact mathematical value. The input data for the open main detection system prepared by this study are mainly the RMS readings for the network transformers loads with a current percentage format. For all the above sensitivity matrix calculation, directly using load percentage information might cause great round-off error, especially for the OMNTL and the MSTL calculation. In an open main situation, the change rates of the nearby transformers are not very big comparing the transformer size. Most transformer sizes are range from 500 kVA to 2500 kVA, which means a few kVA variations may be taken as the same as a lot of kVA variations if load percentage is used for calculation. For example, when one main is open, suppose all the transformer sizes are 2500 kVA, and the change reates of several nearby transformers are as following:

Transformer 1: 37.5 kVA

Transformer 2: 50 kVA

Transformer 3: 62.4 kVA

Apprarently, in MSTL, the sequence should be T3, T2, and T1. But if load change rates are taken into calculation with percentage, the result will be different:

$$
\begin{aligned}
CR1 &= \frac{37.5}{2500} \times 100 = 1.5\% \approx 2\% \\
CR2 &= \frac{50}{2500} \times 100 = 2\% \\
CR3 &= \frac{62.4}{2500} \times 100 = 2.4\% \approx 2\%
\end{aligned}
\tag{2.9}
$$

in this way, all these three transformers have the same change rate and the sequence in MSTL turns to be T1, T2, and T3.

Seen from the above example, taking percentage change rates may result in the transformer that changes the most is not on the top list of OMNTL. Moreover, such round-off error can further affect the MSTL and cause severe error that some mains should be on the list are not on but some ones should not be on the list appear. Therefore, for all the sensitivity matrix calculation, real load change in kVA format is taken into calculation to achieve a more accurate result. For TONTL value, to match the percentage format of RMS data, the load change will be transferred to percentage format after sort processing.

2.2.2 Initial Detection Procedure

Table 2.4 Real Time Network Transformer Load Change Calculation

Reading (n)	Time/Date	Transformer Load			Change Rate		
		Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	T_1/D_1	I_{A1}	I_{B1}	I_{C1}	-	-	-
2	T_2/D_1	I_{A2}	I_{B2}	I_{C2}	$I_{A2}- I_{A1}$	$I_{B2}- I_{B1}$	$I_{C2}- I_{C1}$
3	T_3/D_1	I_{A3}	I_{B3}	I_{C3}	$I_{A3}- I_{A2}$	$I_{B3}- I_{B2}$	$I_{C3}- I_{C2}$

As listed in Table 2.4, for each phase in every network transformer, the difference between the just received load value reading from RMS and the previous one is calculated, to be compared with typical change for normal day load.

$$\Delta I_n = I_n - I_{n-1} \tag{2.10}$$

This comparison is implemented between two values:

- The value of real time load change.
- The prerecorded normal day load change value.

The predetermined values for transformer normal load change can be presented by two boundary curves (positive and negative) indicates the moving standard deviation for this load; where the real time transformer load change values are in-between.

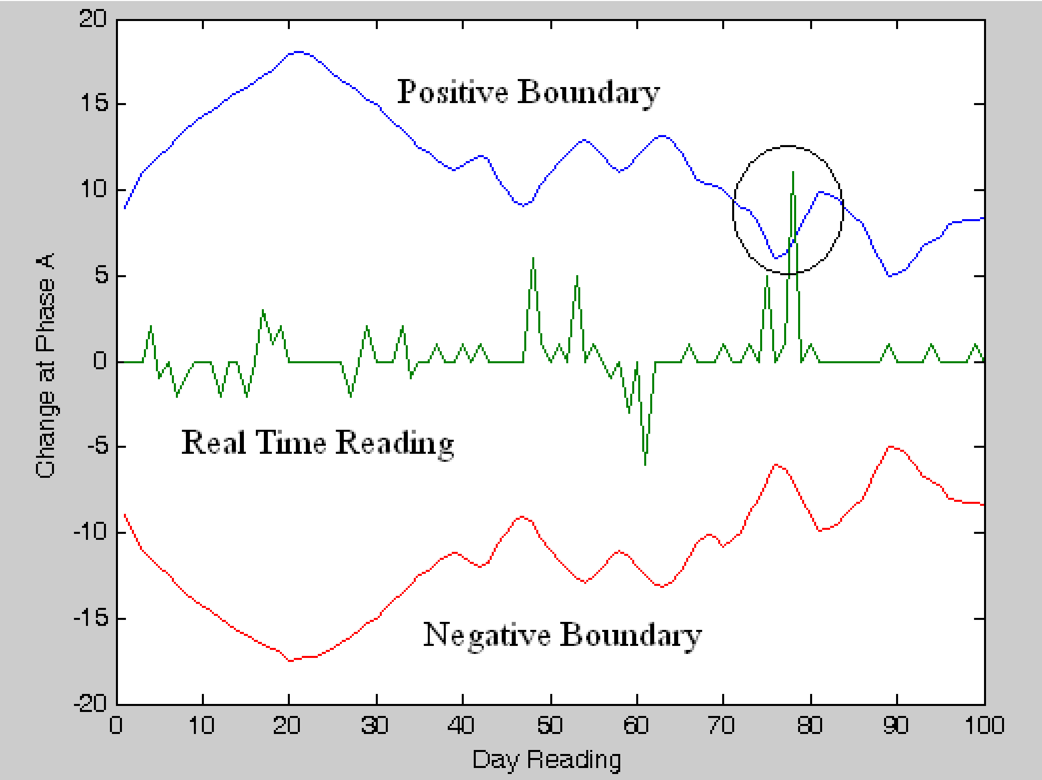


Figure 2.3 Real Time Load Change and Boundary Curves for One Day

Once a change in real time reading value exceeds the boundary, this event will be added to the suspect list to be refined latter.

Each value in the boundary curve can be calculated using moving standard deviation for specific number of normal day samples (Ns=7), which includes the event time normal reading plus (Ns-1) readings before.

$$Q_n = \sqrt{\frac{1}{Ns}\sum_{i=b}^{n}(L_i - \bar{L})^2} \qquad (2.11)$$

Where:

Q_n : Standard Deviation for Ns normal day readings started by reading # b and terminated by n.

Ns: Number of samples included by standard deviation calculation.

L_i: Normal load reading # n in sequence.

$\bar{L}$: Arithmetic mean of Ns readings of transformer normal day load = $\frac{1}{Ns}\sum_{i=b}^{n} L_n$

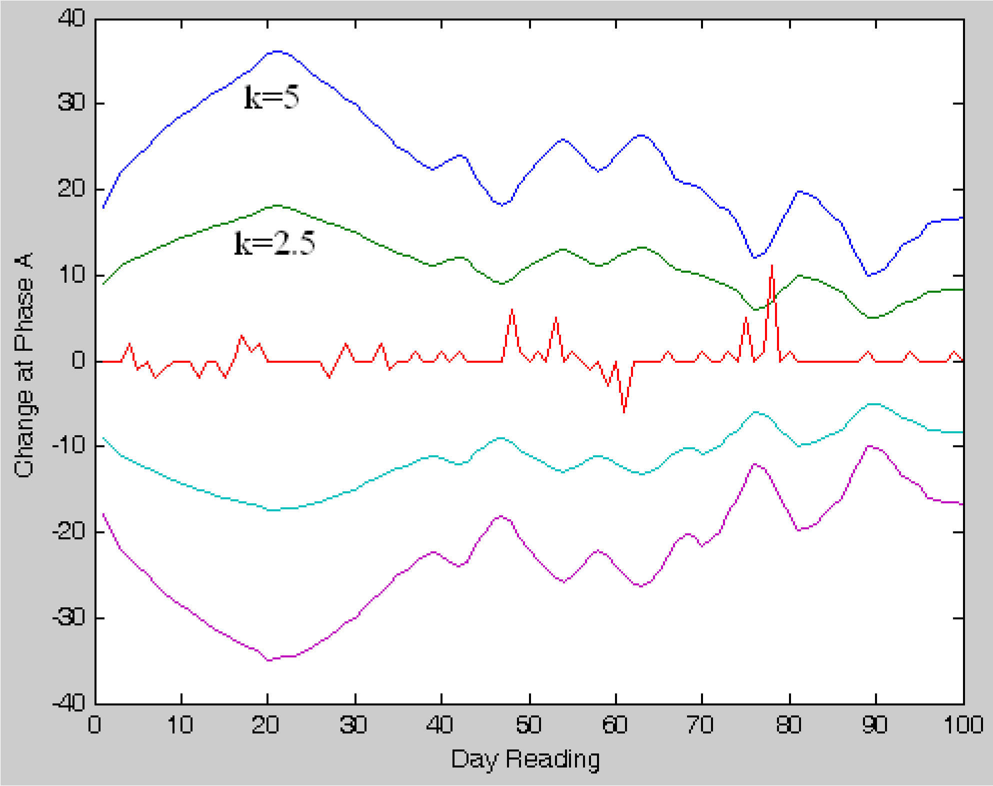


Figure 2.4 Effect of Curve Factor k on Detection Sensitivity

Detection sensitivity can be adjusted to discover lower or upper change level for transformer load by multiplying the standard deviation boundary curve by proper curve level factor (K) to expand or shrink the area enclosed between the positive and negative curves. Therefore the detection process will be more sensitive when (k) factor value goes down.

For positive curve: $Qc_{at.point.n} = k \times STD_n$ (2.12)

For negative curve: $Qc_{at.point.n} = -k \times STD_n$ (2.13)

Qc_n : Normal load curve value at day reading *n.*

k : Boundary curve level factor.

STD_n : Standard deviation for Ns normal load readings ended by reading n.

The Boundary curve values are calculated for each phase from the correspondent transformer normal load change values. A similarity in the shape of the boundary curves for different phases may be noticed, which refers to the similarity of the transformer normal load of the different phases at that period. This is a considered criterion used while selecting a normal load change period for STD calculation, unless the nature of the connected loads always show different values for the different transformer phases.

The event listed in the initial suspect list by one or more detection approaches is not necessarily a real incident that requires immediate attention, such fallacious event may referred to one of the followings reasons:

- Prescheduled transformer switching (in/out) operation.
- Erroneous current readings.
- Urgent change in transformer load that does not coincide with the normal day load profile.

2.2.3 Refining Detection Procedure

In order to investigate the type of the incident that might cause the detection of an abnormal load change event by one of the statistical approaches; a refinement process for this event will be implemented. Refinement process depends on the sensitivity analysis for the load change at the transformer at which the change detected, in addition to the response of the load at nearby transformers.

Sensitivity analysis is implemented first for transformer outage detection purposes. If the suspect event is not transformer outage incident according to this sensitivity results; open main sensitivity analysis should be launched.

Once the transformer incident is confirmed, if we have considerable mismatch between real time responses of the nearby transformers and those are obtained from PVL program for "perfect" network, possible pre-exist open main situations should be checked.

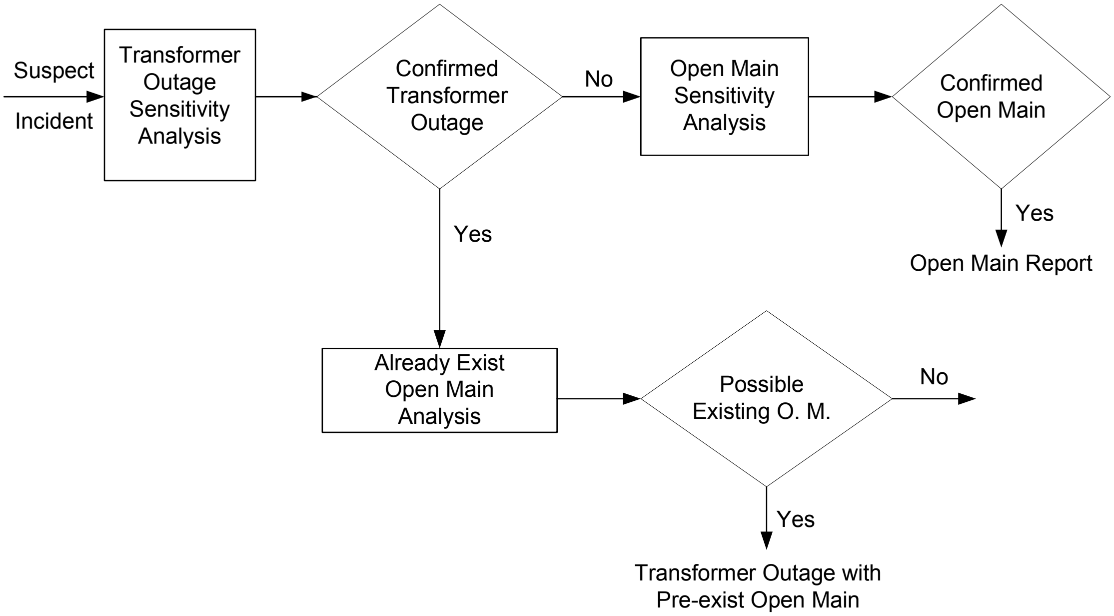


Figure 2.5 Sensitivity Analysis Procedure

2.2.3.1 Transformer Outage Sensitivity Analysis

Once the initial suspect event is refined and approved as suspect incident, transformer outage analysis will be started. Two main purposes for implementation of transformer outage detection analysis in this study:

- To recognize the real outage incident that leads to transformer power flow interruption from other misleading information apparently indicating outage but actually is not.
- In order to utilize the outage decision in open main incident analysis. The open main detection process requires that no outage incident is confirmed from one of the nearby transformers involved in this process.

For suspect events detected by the mentioned statistical approaches and confirmed as real events through the initial detection procedure, the presence of zero-load value reading is an indication for highly suspected transformer outage incident due to possible protection device operation or due to feeder outage.

In order to determine if the suspect incident actually is a transformer outage or an open main incident, transformer outage sensitivity analysis will be implemented first on the suspect incidents. If it is confirmed as an outage incident, the possibility of pre-exist open main around could be dropped or embraced according to how close the real time nearby transformers load changes ($\Delta I_{R.n}$) are from the calculated values ($\Delta I_{C.n}$).

Any detection for unusual transformer load change should be refined by going through the following steps that includes the primary refinement:

- Is there a scheduled maintenance operation for this transformer at this time? which is enough reason to exclude this event from the suspect list (S_m):(1:No maintenance, 0:maintenance)
- Does the present real time reading ($I_{R.event}$) show zero value in any of the three phases? If it does not, this event will be refined through open main incident process.
- Does the load change at this transformer ($\Delta I_{R.event}$) happen together with other changes ($\Delta I_{R.n}$) at certain transformers listed in Nearby Transformers List for Transformer Outage (TONTL)? if it does not, this load change does not reflect a real transformer outage and mostly is an erroneous reading.

Once abnormal change in one of the network transformers ($\Delta I_{R.event}$) is detected and primarily refined, transformer outage sensitivity analysis will be initiated, if the present load shows zero value. Outage analysis depends on how close the summation of real time changes in nearby transformers loads ($\sum \Delta I_{R.NBn}$) are from the load change at the event transformer

($\Delta I_{R.event}$). From the Nearby Transformer List for Transformer Outage (TONTL), we can know the nearby transformers to compare the sum of their real time load changes ($\sum \Delta I_{R.NBn}$) to that of event transformer $\Delta I_{R.event}$, taking into consideration:

- Transformer size ratio, $K_s = \frac{Nearby.Transformer.size(KVA)}{Event.Transformer.Size(KVA)}$. This serves to adjust the effect of different network transformers sizes on the sensitivity calculations. For every nearby transformer involved in the sensitivity calculation process, correspondent transformer size factor K_s will be used.

Sometimes, the distribution system parameters implemented in the power flow calculation do not exactly conform to those actually installed in the system due to continuous grid extensions that have not been updated to power flow program yet or due to undetected faulty equipment, which usually redistribute the load at the nearby transformers in a way different from that calculated by PVL. For this reason, the number of nearby transformers to be analyzed in the sensitivity process is chosen to be ten most affected nearby transformers in TONTL to include such possible redistribution case, where the summation of real time load change for these transformers should be close to the load change at that transformer shows zero load value. Most of the time, the sum is not close to this value for the previous mentioned causes, therefore mismatch tolerant value (MIS_{tol}) is used in this study. Cases with mismatch values summing less than MIS_{tol} will approved as transformer outage incident.

$$\left| \frac{\Delta I_{R.event} - \sum_{i=1}^{10} \Delta I_{R.NBi}}{\Delta I_{R.event}} \right| \leq MIS_{tol} \Rightarrow Trans.Outage \qquad (2.14)$$

MIS_{tol}: The maximum tolerant mismatch absolute value between $\Delta I_{R.event}$ and $\sum_{i=1}^{10} \Delta I_{R.NBi}$ as ratio of $\Delta I_{R.event}$.

The selected value for MIS_{tol} mainly depends on how different the actual network configuration is from that used in PVL by which the ten nearby transformers selected. The default value for MIS_{tol} is chosen as 0.6.

2.2.3.2 Transformer Outage with Pre-exist Open Main

Once a transformer outage decision is confirmed, another sensitivity analysis will be implemented in this study to determine if this transformer is close to a pre-exist open main or not. This brief decision implies the implementation of another sensitivity analysis process that compares the RMS real time load change ($\Delta I_{R.n}$) for the most affected five nearby transformer in TONTL to the calculated change values ($\Delta I_{C.n}$). To confirm that this transformer outage took place around an already existing open main, two conditions should be satisfied:

1. The maximum mismatch value between real time and calculated load change that shows up in one of the five nearby transformers must exceed a predetermined value ($MIS_{EXISTING}$), taking into consideration:
   - Interrupted load ratio (between the interrupted transformer load in power flow program case and that actually interrupted in real time case).

     $K_i = \frac{I_{C.event(from.power.flow.calculation)}}{I_{R.event(from.real.time.values)}}$, So, for specific event sensitivity calculation, we have one interrupted load ratio factor (K_i).

For any abnormal load change event taking place at network transformer (xfr_{event}), transformer real time interrupted load ($\Delta I_{R.event}$) and the same load calculated in power flow program ($\Delta I_{C.event}$) should be considered in addition to the changes for the most affected five nearby transformers ($xfr._{NB1}, xfr._{NB2}, ..., xfr._{NB5}$),

Table 2.5 Real Time and Calculated Nearby Transformers Load Changes

Outage at TR. (xfr.event), Load change ($\Delta I_{R.event}$)			
Nearby TR.	Real Time TR. Load Change(ΔI_R)	Calculated TR. Load Change (ΔI_C)	Mismatch ΔI_R-ΔI_C
$Xfr._{NB1}$	$\Delta I_{R.NB1}$ x Ks_1 x Ki	$\Delta Ic._{NB1}$ x Ks_1	$\Delta 1$
$Xfr._{NB2}$	$\Delta I_{R.NB2}$ x Ks_2 x Ki	$\Delta Ic._{NB2}$ x Ks_2	$\Delta 2$
….	…	…	…
$Xfr._{NB5}$	$\Delta I_{R.NB5}$ x Ks_5 x Ki	$\Delta Ic._{NB5}$ x Ks_5	$\Delta 5$

2. None of the present loads ($I_{R.NBn}$) at the five nearby transformers should be zero.

$$\Delta_n = \left|\Delta I_{R.n} - \Delta I_{C.n}\right| \tag{2.15}$$

If: $$((\Delta_{mx} = \left|\Delta I_{R.mx} - \Delta I_{C.mx}\right| \geq MIS_{existing}).AND.(I_{R.NBn} \neq zero)) \tag{2.16}$$

$\Rightarrow$ Possible Pre-Existing Open Main.

$xfr_{NB.mx}$: The nearby transformer at which (Δn) is the max.

$MIS_{EXISTING}$: is chosen to be 15 as tentative value.

2.2.3.3 Open Main Incident Sensitivity Analysis

As soon as an abnormal load change is detected at the present RMS reading on one of the network transformers ($\Delta I_{R.event}$) by any of the statistical approaches explained earlier, transformer outage detection system checks the response of nearby transformers to determine whether it is a transformer outage or not. If it is not a transformer outage; open main detection procedure is initiated to locate the possible open main incident. Some logical events should be confirmed to declare the incident occurrence:

- One of the network transformers should show abnormal load change ($\Delta I_{R.event}$) that overmatches the normal day load change limit ($\Delta I_{Boundary.event}$) for that transformer at this time of day $\Delta I_{R.event} > \Delta I_{Boundary\ .event}$
- No transformer outage $(T.O)$ is recorded as a response for this over limit transformer load change. If so; the cause for the change is already known and no need to plunge into open main detection process.
- As one of the distinctive feature for transformer load change response in case of open main over that for transformer outage case, it is necessarily that at least another nearby transformer shows opposite load change (increase or decrease) regardless of ratio value (k),

$$\Delta I_{R.n} = -k(\Delta I_{R.event})$$
$$k = \frac{|\Delta I_{R.n}|}{|\Delta I_{R.event}|} \tag{2.17}$$

For transformer (xfr_{event}) that shows maximum over limit load change ($\Delta I_{R.event}$), the possible open main incidents that lead to maximum load change at this transformer (xfr_{event}), can be found from Most Sensitive Transformer List (MSTL), where every incident (SM_n) from these will also affect a number of nearby transformers ($xfr_{OMNB.n}$) listed in OMNTL. The detection sequence goes through these possible secondary mains (SM_n) one by one to examine the real time response for its nearby transformers ($xfr_{OMNB.n}$).

Every proposed open main in OMNTL, that its nearby transformers load changes ($\Delta I_{R.OMNBn}$) fulfill the three conditions mentioned following will be a possible open main location, on which a sensitivity analysis will be implemented.

- $\Delta I_{R.event} > \Delta I_{Boundary.event}$
- No transformer outage decision $(T.O)$
- Another nearby transformer shows opposite load change.

Sensitivity analysis should be implemented here to exclude those main locations that do not satisfy nearby transformers load changes feature and to determine which location has higher possibility than the others. The following open main locations should be excluded first:

- The main location that one of the nearby transformers ($xfr_{OMNB.n}$) shows zero load in the present reading (Off-switch.) or zero load in the previous reading (ON-Switch.),

  $I_{R.OMNBn} = zero$,or $I_{R.OMNB.n-} = zero$ in the same time that:

  $$\Delta I_{R.OMNBn} \geq \Delta I_{Boundary.OMNBn} \tag{2.18}$$

- The main location with nearby transformers loads changes summation greater than predetermined level value (LEV_{tol}).

  $$\left|\sum_{n} \Delta I_{R.OMNB.n}\right| \geq LEV_{tol} \tag{2.19}$$

The selection of (LEV_{tol}) value depends on how sensitive we need the detection process to be, also how close network actual configuration to the ideal one used in PVL calculation to Identify the ten nearby transformers. A value of 5 is chosen as tentative tolerant value.

Sensitivity analysis on the rest possible open main locations should be implemented to determine which location has higher possibility than the others as shown in Table 2.6.

Table 2.6 Open Main Incident Analysis

Possible Open Main (POM$_j$)		Open Main Nearby Transformer Load Change			
	$xfr_{R.OMNB.1}$	$xfr_{R.OMNB.2}$	$xfr_{R.OMNB.3}$	$xfr_{R.OMNB...}$	Sum
POM$_1$	$\Delta I_{R.OMNB.a}$	$\Delta I_{R.OMNB.b}$	$\Delta I_{R.OMNB.c}$	…	$\sum_{n=a} \Delta I_{R.OMNBn}$
…	…	…	…	…	…
POM$_m$	$\Delta I_{R.OMNB.A}$	$\Delta I_{R.OMNB.B}$	$\Delta I_{R.OMNB.C}$	…	$\sum_{n=A} \Delta I_{R.OMNBn}$

The most probable location is the main that shows least summation value for it’s nearby transformers load changes.

$\min(\sum_{n=1} \Delta I_{R.n}) \Rightarrow$ Most Probable Open main Location. (2.20)

CHAPTER 3

LOAD MODEL AND LOAD RECONCILIATION

Load modeling has a significant influence on power systems operation, simulation, and analysis. It is shown that the evaluation of the distribution network performance, which plays a critical role in electric power systems operations, is affected by the power network parameters, including load parameters, and that presence of parameter errors can lead to unreliable evaluation results [37]-[42].

A load model is a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) or current flowing into the bus load [8]. Load modeling is essential to provide secure and economic planning and operation of a power system. Much progress in the load modeling has been made over the past three decades. Various static and dynamic models based on mathematical and physical representations have been studied to describe the load characteristics. There are some standard models recommended by IEEE for power flow and dynamic simulation programs. Many articles published on load model subject discuss the relationship between the power system load and its supply voltage and frequency [9] [10]. Considering many non-linear loads whose demands are voltage dependent, ZIP load model is taken into study.

3.1 The Most Common Load Models

The most commonly used load models found in the literature are described as follows:

Constant impedance: In the constant impedance model, the active and reactive power injections at a given load bus vary directly with the square of the nodal voltage magnitude. This model is also called constant admittance model:

$$P = f(V^2) \tag{3.1}$$

where P is the active power injection and V is the voltage magnitude at the load bus.

Constant current: In this model, the active and reactive power injections at a given load bus vary directly with the nodal voltage magnitude:

$$P = f(V) \tag{3.2}$$

Constant power: Here, the power of the load bus is assumed to be constant and does not vary with the nodal voltage magnitude:

$$P = k \tag{3.3}$$

where k is a constant.

Frequency dependent model: In this case, the active and reactive power injections of the load bus are related to the bus voltage frequency through an equation as follows.

$$Facter = [1 + a_f (f - f_0)] \tag{3.4}$$

where:

a_f is the model sensitivity parameter;

f is the nodal voltage frequency;

f_0 is the nominal frequency.

3.2 ZIP Load Model

3.2.1. Traditional ZIP Load Model

Usually, the power system loads are modeled as constants. However, this kind of model is inadequate for some studies like power system dynamic studies and voltage collapse studies. To have better prediction on the performance of distribution system, system studies have to be developed with better models for the systems components including better load models. A nonlinear load model, ZIP model, which is a combination of constant current, constant power and constant impedance, is popular in modeling the nonlinear behaviors of loads.

$$P = P_0 \left[Z_p \left(\frac{V}{V_0} \right)^2 + I_p \left(\frac{V}{V_0} \right) + P_p \right] \tag{3.5}$$

$$Q = Q_0\left[Z_q\left(\frac{V}{V_0}\right)^2 + I_q\left(\frac{V}{V_0}\right) + P_q \right] \quad (3.6)$$

In Equation 3.5 and 3.6, P_0, Q_0 are the rated real and reactive powers; *Z, I, P* are the constant "impedance", "current" and "power" coefficients; V_0 is the rated voltage; *V* is the actual load voltage. It is noted that the sum of the coefficients, *Z+I+P*, is unity.

3.2.2. ZIP Load Model with Considering Cutoff Voltage

Every load has its own operating voltage range. To incorporate functional-cutoff voltage V_{min}, the ZIP load model was modified using the following multiplier function [12]:

$$Y_v = 0.5\{1 + \tanh[(\frac{V}{V_0} - \frac{V_{\min}}{V_0}) * K]\} \quad (3.7)$$

Y_v is shown graphically in Figure 3.1 for the case $V_0 = 120V$, $V_{\min} = 90V$ and $K = 80$. It has the special property that it is nearly 0 when $V < V_{\min}$ and nearly 1 when $V > V_{\min}$.

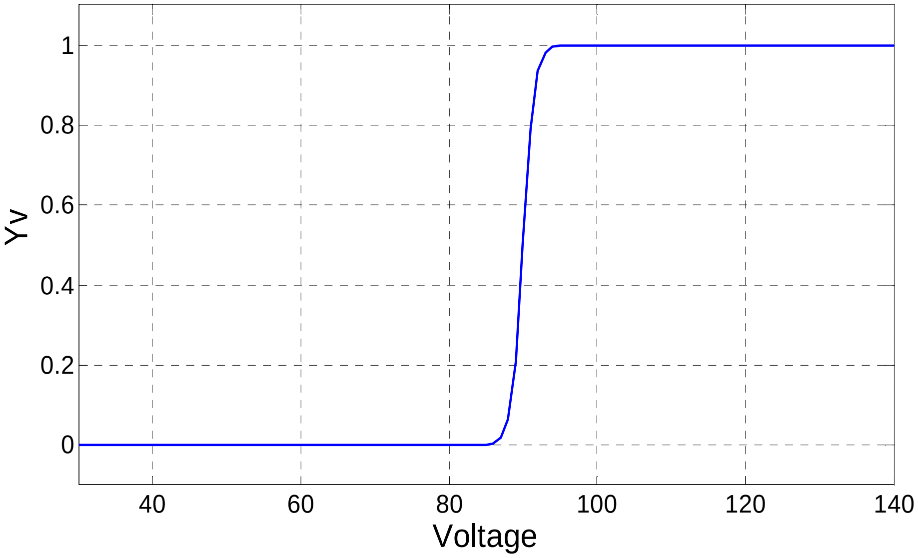


Figure 3.1 Behavior of Multiplier Y_v as a Function of Load Voltage

Then the modified ZIP equations will be:

$$P = P_0\left[Z_p\left(\frac{V}{V_0}\right)^2 + I_p\left(\frac{V}{V_0}\right) + P_p\right] \bullet Y_v \tag{3.8}$$

$$Q = Q_0\left[Z_q\left(\frac{V}{V_0}\right)^2 + I_q\left(\frac{V}{V_0}\right) + P_q\right] \bullet Y_v \tag{3.9}$$

3.2.3. Example of the ZIP Load Model with Cutoff Function

As a sample, we picked a single load-unit from Hajagos' paper [38]: load 3b, "adjustable frequency drive 2," from Table II. In the paper P and Q are given by quadratic equations that use an impedance coefficient Z, a current coefficient I, and a power coefficient P. The data given for that load are: $V_0 = 120V$; $S_0 = 1780VA$; $Pf = 0.79$; $V_{\min} = 90V$; for active power: $Z = 3.19$, $I = -3.84$, $P = 1.65$ (the sum $Z + I + P = 1$); for reactive power: $Z = 1.09$, $I = -0.18$, $P = 0.09$. (again, the sum $Z + I + P = 1$). The modified equations are:

$$P(V) = 1780 \cdot 0.79[3.19(\frac{V}{120})^2 - 3.84(\frac{V}{120}) + 1.65] \cdot 0.5\{1 + \tanh[(\frac{V}{120} - 0.75) \cdot 80]\} \tag{3.10}$$

$$Q(V) = 1780 \cdot \sqrt{1 - 0.79^2}[1.09(\frac{V}{120})^2 - 0.18(\frac{V}{120}) + 0.09] \cdot 0.5\{1 + \tanh[(\frac{V}{120} - 0.75) \cdot 80]\} \tag{3.11}$$

Figure 3.2 below illustrates the behavior of the above equations. Below the minimum voltage, $120 \cdot 0.75 = 90V$, $P(V)$ and $Q(V)$ become zero. The dashed lines show how the curves would look if original equations were used; that is, if the hyperbolic function $0.5\{1 + \tanh[(\frac{V}{120} - 0.75) \cdot 80]\}$, were absent from Equations 3.10 and 3.11.

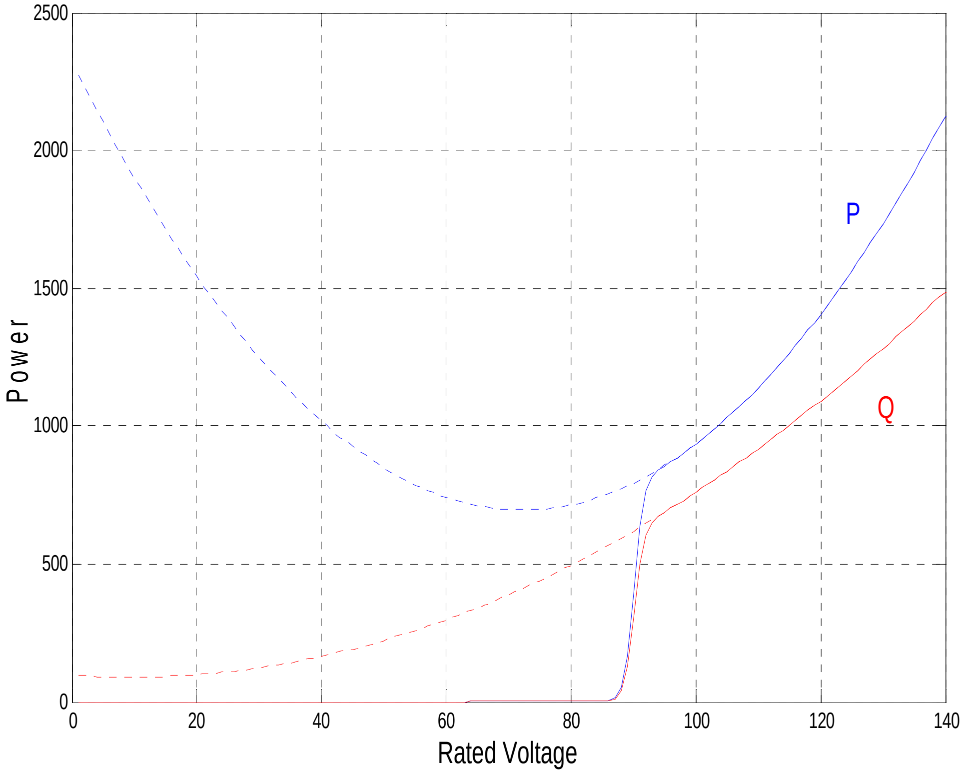


Figure 3.2 Power Curves for a Single Appliance as a Function of Voltage

It is seen that the modified ZIP model approaches the practical load situation better than the traditional load model. The complete list of the individual devices tested and their nominal ratings is given in Appendix A [11].

All the load equipments were then grouped into 18 separate categories such as air conditioners, compressors, fans, lights, computers, elevators and so on, and each has its own individual type of electrical characteristic [11]. This list is given in Table 3.1, which also includes the ZIP coefficients derived from curve fitting, and the minimum operation voltages. Like traditional ZIP model, the sum of the coefficients, $Z + I + P$, is equal to unity. One typical difference between the new model and the traditional model lies in the range of the coefficients, which is not between 0 and 1 but makes better curve fitting result.

Table 3.1 Load Categories and Load ZIP Model Coefficients

Devices	PF	V_{min}	Active Power			Reactive Power		
			Z	I	P	Z	I	P
D1	0.96	0.81	5.55	-11.13	6.58	10.21	-17.05	7.84
D2	0.90	0.65	1.10	-1.65	1.55	7.49	-12.08	5.59
D3	0.90	0.87	0.85	-1.40	1.56	1.09	-0.18	0.09
D4	1.00	0.91	-35.5	75.71	-39.25	0.00	0.00	0.00
D5	0.69	0.25	0.61	0.42	-0.04	0.83	0.17	0.00
D6	0.98	0.65	-0.96	3.05	-1.09	-8.21	14.27	-5.06
D7	0.86	0.70	1.55	-3.32	2.77	3.48	-4.96	2.48
D8	0.82	0.85	0.40	-0.41	1.01	-0.93	2.89	-0.96
D9	0.86	0.70	1.55	-3.32	2.77	3.48	-4.96	2.48
D10	0.99	0.70	-5.24	10.71	-4.47	-5.68	12.27	-5.59
D11	0.99	0.60	-7.42	13.97	-5.55	7.42	-10.59	4.18
D12	0.97	0.60	-0.30	1.27	0.04	-9.23	16.64	-6.40
D13	0.82	0.70	-0.64	2.17	-0.53	-1.02	2.80	-0.78
D14	1.00	0.00	0.48	0.57	-0.05	0.00	0.00	0.00
D15	1.00	0.00	0.43	0.64	-0.08	0.00	0.00	0.00
D16	0.86	0.50	0.27	-0.61	1.34	-0.11	0.02	1.08
D17	0.99	0.60	0.55	1.86	-1.40	19.74	-31.30	12.56
D18	0.76	0.77	0.13	-0.14	1.01	-0.62	1.84	-0.22

3.3 Load Composition

3.3.1 Definition of "Commercial" and "Residential" Load

In order to answer the questions: What kinds of electrical equipments are actually used today? How much power do they consume? What part of the day are they in operation? A number of field surveys were made at commercial and residential sites within Con Edison's distribution networks. At each site, the electrical equipments were inventoried [11].

3.3.1.1 Commercial Site Surveys

The large commercial sites that were surveyed are listed below:

(1) D. Building – xxxx P. Ave.

(2) R. U. T. Building – xxxx Y. Ave.

(3) B. – xxth Street and L. Ave.

(4) G. M. Building – xxxx xth Ave.

Similarly, several ”small” commercial sites were visited:

(1) E. G. M. S. - xxxx B. Street

(2) G. store - xxxx V. Ave.

(3) C. store – xxxx L. Ave.

(4) xxx/xxx East xxth Street – B.

(5) K. T. and S. Restaurant – xxxx M. Ave.

The collected data were consolidated to define the terms: “large commercial load” (see Table 3.2) and “small commercial load” (see Table 3.3).

Table 3.2 Survey Results: Large Commercial Load

Equipment	4 bldg.’s [kW]	kW per 1,000 ft^2	kW in %
D1	0	0	0
D2	950.46	0.3650	6.27
D3	2217.74	0.8517	14.63
D4	64.2	0.0247	0.4
D5	3699.3	1.4206	24.4
D6	1225.5	0.4706	8.1
D7	1044.2	0.4010	6.9
D8	332.6	0.1277	2.2
D9	273.5	0.1050	1.8
D10	1179.3	0.4529	7.8
D11	1753.3	0.6733	11.6
D12	113.9	0.0437	0.8
D13	126.9	0.0487	0.8
D14	969	0.3721	6.4
D15-1	66.7	0.0256	0.4
D15-2	342.1	0.1314	2.3
D16-1	207.1	0.0795	1.4
D16-2	572.2	0.2197	3.8
D17	20.2	0.0078	0.1
D18	13.6	0.0052	0.1

Table 3.3 Survey Results: Small Commercial Load

Equipment	4 bldg.'s [kW]	kW per 1,000 ft^2	kW in %
D1	0	0	0
D2	28.8	1.31508	12.54
D3	67.2	3.06852	29.26
D4	0	0	0
D5	66	3.0137	25.2
D6	0	0	0
D7	9.3	0.4247	3.4
D8	0	0	0
D9	0.6	0.0274	0.9
D10	16.6	0.758	7.5
D11	4.8	0.2192	2.2
D12	0	0	0.4
D13	4.4	0.2009	1.6
D14	13.5	0.6164	8.0
D15-1	0	0	0.5
D15-2	1.4	0.0639	6.7
D16-1	1.3	0.0594	0.5
D16-2	3.1	0.1416	1.3
D17	0.3	0.0137	0.1
D18	3.8	0.1735	1.4

3.3.1.2 Residential Site Surveys

In the same manner, a number of "large" residences were visited, and their electrical equipments inventoried.

(1) R. Apartments – xxxx West xxth Street

(2) C. – xxx/xxx East xxth Street

"Small" residences that were inventoried were:

(1) Brownstone – xxx East xxrd Street

(2) Brownstone – xxx East xxth Street

Data for the large residences were consolidated to define the term "large residential load" (see Table 3.4). Similarly the small residences data were combined to define the term "small residential load" (see Table 3.5).

Table 3.4 Survey Results: Large Residential Load

Equipment	2 bldg.'s [kW]	kW per 1,000 ft^2	kW in %
D1	183.2	0.7090	15.84
D2	122.1	0.4727	10.56
D3	305.3	1.1817	26.4
D4	0	0	0
D5	172.7	0.6684	14.9
D6	0	0	0
D7	0	0	0
D8	102	0.3948	8.8
D9	0	0	0
D10	12	0.0464	1.0
D11	17	0.0658	1.5
D12	0	0	0
D13	3.2	0.0124	0.3
D14	21	0.0813	1.8
D15-1	93.4	0.3615	8.1
D15-2	91.8	0.3553	7.9
D16-1	9	0.0348	0.8
D16-2	5.4	0.0209	0.5
D17	18	0.0697	1.6
D18	0	0	0

Table 3.5 Survey Results: Small Residential Load

Equipment	2 bldg.'s [kW]	kW per 1,000 ft^2	kW in %
D1	4.95	0.4091	19.14
D2	0.0	0.0	0.0
D3	11.55	0.9545	44.66
D4	0	0	0
D5	3.1	0.2562	12.0
D6	0	0	0
D7	0	0	0
D8	0	0	0
D9	0	0	0
D10	0.08	0.0066	0.3
D11	0	0	0
D12	0	0	0
D13	0	0	0
D14	1.5	0.124	5.8
D15-1	2.1	0.1736	8.1
D15-2	1.4	0.1157	5.4
D16-1	0.3	0.0248	1.2
D16-2	0.4	0.0331	1.5
D17	0.5	0.0413	1.9
D18	0	0	0

3.3.2 Customized Load Composition and Macro Load Model Coefficients

The composition of the load is strongly dependent on the time of day, month, season, and weather condition. Limiting all the load types to only four types such as typical large commercial, small commercial, large residential and small residential load is still not as accurate as expected. Customized loads are provided and could be updated any time with the real load composition changing. For each load, all the electrical equipments were inventoried with kilo watt percentage format like Table 3.6.

Table 3.6 Customized Load Composition Format

No.	Devices	KW %
1	Air Conditioners (Window)	0.20
2	Refrigerators	0.05
3	Compressors	0.10
…	……	…
18	UPS’	0.09
	Total	1.00

For a load, suppose the rated complex power is S and the total power factor is PF, the percentage for each equipment is PER_i with a power factor of Pf_i, then the load expression will be:

$$P = \sum_{i=1}^{18} S \bullet PF \bullet PER_i \bullet \left[Z_{p_i}\left(\frac{V}{V_0}\right)^2 + I_{p_i}\left(\frac{V}{V_0}\right) + P_{p_i} \right] \bullet Y_{V_i} \tag{3.12}$$

$$Q = \sum_{i=1}^{18} S \bullet PF \bullet PER_i \bullet \frac{\sqrt{1-Pf_i^{\,2}}}{Pf_i} \bullet \left[Z_{q_i}\left(\frac{V}{V_0}\right)^2 + I_{q_i}\left(\frac{V}{V_0}\right) + P_{q_i} \right] \bullet Y_{V_i} \tag{3.13}$$

For a distribution network, there may be hundreds of or thousands of loads. It's very time consuming if every load is calculated through this way in the process of the performance evaluation. For active power, besides the basic ZIP function calculation, there are more than four multiplication and one complex cutoff function calculation. Then all of the above calculation need be repeated 18 times. It will cost more time for reactive power calculation. To improve the computing efficiency and keep the load model accuracy, macro ZIP load model coefficients was derived, and the load model expression turns to be:

$$P = ZP_k \left(\frac{V}{V_0} \right)^2 + IP_k \left(\frac{V}{V_0} \right) + PP_k \tag{3.14}$$

$$Q = ZQ_k \left(\frac{V}{V_0} \right)^2 + IQ_k \left(\frac{V}{V_0} \right) + PQ_k \tag{3.15}$$

Where

$$ZP_k = \sum_{i=1}^{k} S \bullet PF \bullet PER_i \bullet Z_{p_i} \tag{3.16}$$

$$ZQ_k = \sum_{i=1}^{k} S \bullet PF \bullet PER_i \bullet \frac{\sqrt{1 - Pf_i^{\ 2}}}{Pf_i} \bullet Z_{q_i} \tag{3.17}$$

IP_k, PP_k, IQ_k and PQ_k have the similar expression as them and k=1, 2, …, 10.

After getting the load composition information, all the macro ZIP load model coefficients could be pre-calculated. From Table 3.1, there are totally 10 different minimum voltages for all these 18 equipments. To include the low voltage cut off function, 10 sets of macro coefficients could be derived. The evaluation program will pick up the related macro coefficients depended on voltage. This procedure is relative simple in programming, and a "switch-case" command can implement this smoothly. Applying macro coefficients dramatically improve the efficiency of the load model calculation together with the whole assessment computing.

3.4 Load Reconciliation

From Equation 3.8 and 3.9, it's apparent that the accuracy of the load model also rely on the rated active power and reactive power P_0 and Q_0. To achieve a precise load model together with a realistic distribution network evaluation result, the analysis program must make sure the rated power data is accurate and up to date. Based on periodic network transformers loads readings provided by Remote Monitoring System (RMS) and load sensitivity analysis, load reconciliation is considered to keep the accuracy of the rated power.

A sensitivity analysis is performed to calculate the shift factor of each individual load with respect to the transformer loadings. Firstly, increase 20% on a particular load, and then calculate the contribution of each transformer. Secondly, sort the transformers with change rates, and pick up the top 5 transformers and record related change rates with percentage. Finally, apply this procedure to all loads. A typical load sensitivity matrix with the load number of n and transformer number of m is listed as following:

Table 3.7 Typical Load Sensitivity Matrix

Load	Names and Contributed Percentage of Nearby Transformers			
	1st	2nd	…	5th
L_1	T_a: S_{1a}	T_b: S_{1b}	…	T_h: S_{1e}
L_2	T_o:S_{2h}	T_p: S_{2i}	…	T_q: S_{2l}
….	…	…	…	…
L_n	T_i: S_{nu}	T_j: S_{nv}	…	T_k: S_{ny}

S_{ij}: The sensitivity value between load *i* and transformer *j*.

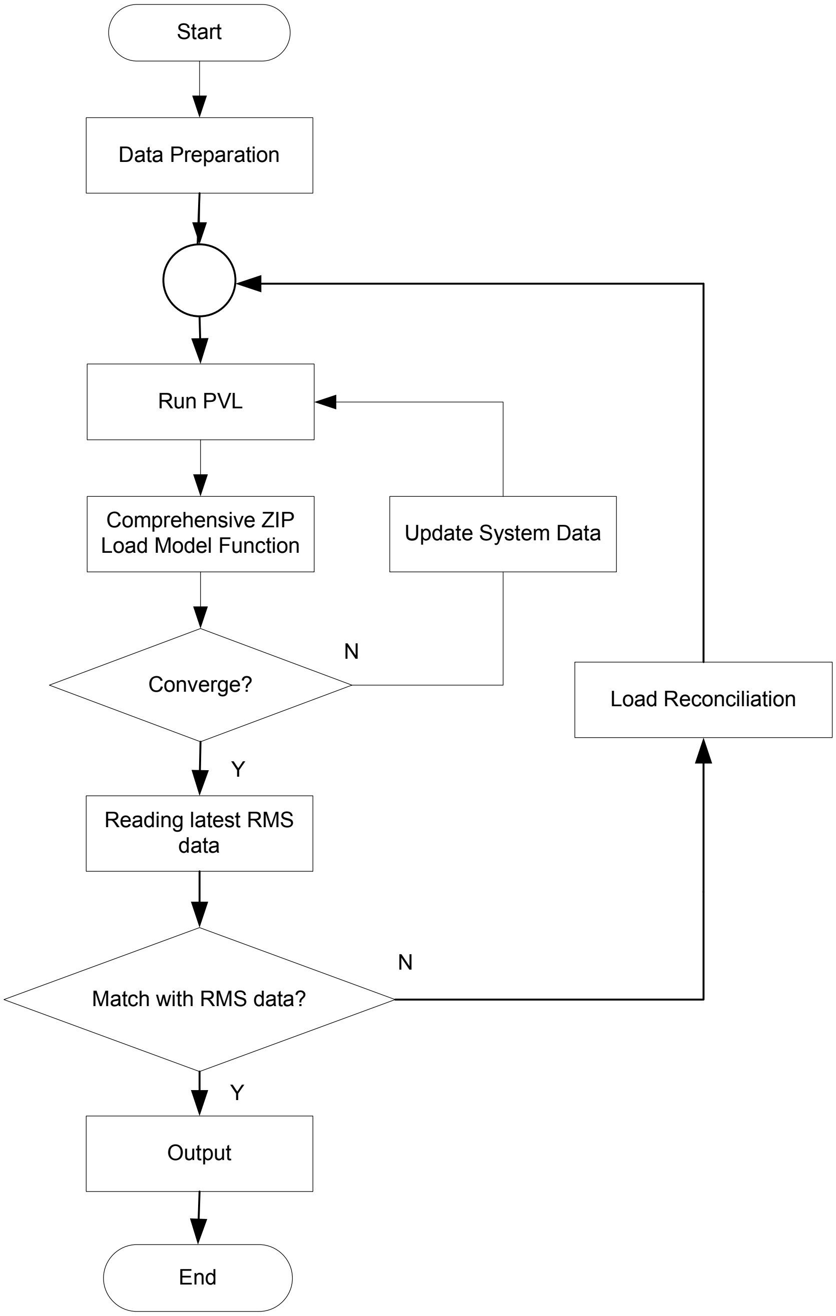


Figure 3.3 Flowchart of Comprehensive ZIP Load Model and Load Reconciliation

Figure 3.3 illustrates the flowchart of part of the program with comprehensive ZIP load model and load reconciliation. Several data processing procedures are performed in the data preparation part like acquiring initial rated power information of all loads, calculating macro ZIP load model coefficients, reading all the required files for PVL running and calculating all the initial transformer loads. Load model part is in the inner loop with PVL application, comprehensive ZIP load model function and system data update. Load data for PVL running will be updated with latest calculated data till program converge. By comparing current load voltage value with previous one, load model program could determine if the calculation progress is converged.

After load model application, if the calculated transformer voltages differ from the RMS ones, load reconciliation will be performed in the outer loop. Real transformer loads will be compared with initial transformer loads and the change rate will be recorded as percentage format:

$$\Delta T_j = \frac{T_{Cj} - T_{Ij}}{T_{Ij}} \cdot 100 \qquad (j=1, 2, \ldots, m) \qquad (3.18)$$

According to sensitivity matrix and transformer change rate, the rated load demand could be estimated by this:

$$L_{Ri} = L_{Ii} + \sum_{j=1}^{m} \Delta T_j \cdot S_{ij} \qquad (i=1, 2, \ldots, n) \qquad (3.19)$$

ΔT_j : The load change rate of transformer *j*.

T_{Cj} : The present load of transformer *j*.

T_{Ij} : The initial load of transformer *j*.

L_{Ri} : The rated power of load *i*.

L_{Ii} : The initial rated power of load *i*.

Load reconciliation will dramatically increase the load model accuracy and improve the whole distribution network analysis result. Although the presented load model is a static load model, it also has dynamic features with the load conciliation approach.

3.5 High-Tension and 4kV Customer Loads Estimation

In Con Edison power distribution system, high-tension (HT) loads supplied at 13 kV or 27 kV level are also very common in the distribution network. One typical high-tension load is usually supplied by multiple feeders through a common bus. Although the feeder loads reading and network laods reading are available at the station, no real-time readings for HT loads in the load flow applications now. Furthermore, in some Con Edison's networks, feeders supply network loads, HT loads, and 4 kV loads at the same time. This means 4 kV loads and HT loads need to be adjusted according to feeder loads and network loads.

For high-tension customer loads and 4kV customer loads, following solution will be carried to estimate their demand based on least square algorithm. Suppose the relationship between feeders and HTV&4kV loads are illustrated as following.

Table 3.8 Relationship between HTV/4kV Loads and Feeders

	Fdr1	Fdr2	Fdr3	……
HTV1	X	X		
HTV2	X	X	X	
…	X		X	
HTVn				
4kV1		X		X
…	X			
4kVm		X		X

The total power of HTV and 4kV loads from certain feeder ΔP_{F1}, ΔP_{F2}, …, which can be acquired by subtracted all the basic network customer loads from the total power of certain feeder.

Firstly, run PVL, then get the pre-estimated high-tension load or 4kV load value P'_{HTV1}, P'_{HTV2}, $P'_{HTV3}\cdots$

Secondly, based on every high-tension or 4kV load should get equal power from every supported feeder,

$$P'_{H1F1}=\frac{1}{2}P'_{HTV1}, P'_{H1F2}=\frac{1}{2}P'_{HTV1}$$

$$P'_{H2F1}=\frac{1}{3}P'_{HTV2}, P'_{H2F2}=\frac{1}{3}P'_{HTV2}, P'_{H2F3}=\frac{1}{3}P'_{HTV2} \tag{3.20}$$

Thirdly, least square error algorithm should be performed and find a right value for *x* to qualify the following formula,

$$\min\left[\left(\sum_{F1}\left(x\bullet P'_{HiF1}\right)-\Delta P_{F1}\right)^2+\left(\sum_{F2}\left(x\bullet P'_{HiF2}\right)-\Delta P_{F2}\right)^2+\ldots\right]$$

$$i=1, 2, \ldots n+m \tag{3.21}$$

Then high-tension or 4kV load estimation will be performed by applying the following equation:

$$P_{HTVn}=x\bullet(P'_{HnFi}+P'_{HnFj}+..P'_{HnFk}) \tag{3.22}$$

ΔP_{Fi} : Total high-tension and 4kV load power supplied from feeder i.

P'_{HTVj} : Pre-estimated power of high-tension or 4kv load j.

P'_{HjFi} : Pre-estimated power supplied by feeder i to high-tension or 4kv load j.

P_{HTVj} : Estimated power of high-tension or 4kv load j.

CHAPTER 4

SYSTEM INTEGRATION OF CONTINGENCY ANALYSIS AND LOAD MODEL

In this chapter, system integration of contingency analysis is implemented based on the distribution networks of Con Edison. All the analysis programs were developed on HP UNIX environment with C language and a single computer with a model of HP9000/785/C3000 was taken into test.

4.1 HP UNIX

To realize every desired function, the contingency analysis programs need integrate a power flow software Poly-voltage Load Flow (PVL), which was developed on HP UNIX. Due to the compatibility issue, the contingency analysis programs were also developed on HP UNIX environment. Comparing to the Microsoft Windows system, the UNIX operating system has the following advantages:

Stability:

UNIX system is hands-down the winner in this category. There are many factors here but to name just a couple of big ones. UNIX handles high loads better than Windows and UNIX machines seldom require reboots while Windows constantly need them. Programs running on UNIX enjoy extremely high up-time and high availability.

Reliability:

Individuals and subsystems running on Windows crash far more frequently than a UNIX system. UNIX has been reliable for years due to its dependable software and technology.

Efficiency:

UNIX is usually more proficient in the use of its memory, especially when dealing with network services. Because UNIX requires less memory and processor time than Windows, a UNIX based system has more memory and processor power for other computer functions.

When it comes to compatibility, UNIX is not as good as Windows. A lot of program designing software is only based on Windows, which makes the programming on UNIX not as convenient. To integrate PVL into the evaluation program, an execution function “EXECL” was implemented with the following format:

*int execl(const char *path, const char *arg0, ..., const char *argn, (char *)0);*

The EXECL function creates a new process image from a regular, executable file. However, there is no return from a successful call to an EXECL function, because the calling process is functionally replaced by the new process, which means the program will be terminated after calling PVL.

The evaluation program, especially for sensitivity matrix calculation, need keep calling PVL for hundreds even thousands of times, so another important function “FORK” was taken into application. Basically, the FORK call, inside a process, creates an exact copy of that process somewhere else in the memory (meaning it will copy variable values, etc...), and runs the copy from the point the call was made (it means that the relative value of the next instruction pointer is also copied). By using FORK function, when one process for PVL calling is terminated, the evaluation program could wait for the other child process starting and realize next PVL calling again and again.

4.2 Contingency Analysis Procedure

4.2.1 Input Data Preparation

Besides all the input data for PVL running, the input data for the contingency analysis prepared by this study are the load composition form, the contingency list and the RMS readings. They are all based on HP UNIX environment and need to be ready before analysis program running.

Load Composition Form:

It is a “.txt” file based on Con Edison’s field survey results, which may be updated according to weather, season, or time of day at any time. Two available modes like typical compositon or customized compositon are provided. Analysis progras will first read the typcal load composition. If the sum of the four typical loads is equal to 100, analysis program will only take the typical load composition data no matter what the customized data is. Otherwise, if the sum of typical loads is not equal to 100, analysis program will only consider the customized load data. This following form shows the detailed information for each load’s composition format:

Table 4.1 Example of Load Composition File

Load Name	Typical Loads				Customized Loads			
	LC (%)	SC (%)	LR (%)	SR (%)	Air Conditioners (%)	Compressors (%)	…	UPS (%)
L0001	25	25	25	25	0	0	…	0
L0002	0	0	0	0	12	22	…	2
…	…	…	…	…	…	…	…	…
Labcd	20	30	20	30	21	8	…	0

LR: large commercial,

SC: small commercial,

LC: large resident,

SR: small resident.

Contingency List:

It is a “.txt” file based on contingency detection result and confirmed by operators. Contingency analysis program will keep tracing the update of this list to determine if perform further contingency analysis with the consideration of load models. Analysis program will also update the PVL auto-running imputs based on the reading of this list. The format of the contingency list is as following:

Table 4.2 Example of Contingency List

Time (YYYYMMDDHHMMSS)	Feeder out
20100102030405	F001
…	…
20100607080910	Fabc

RMS data:

It is a ".dms" file based on the realtime network transformers loads, prepared for load reconciliation. The contingency analysis program will automatically pick up the latest RMS data required in the analysis process.

Table 4.3 Sample of RMS Data

Time(YYYYMMDDHHMMSS)	Transformer	I(A)	I(B)	I(C)	Schedule Maintenance
20100102030405	Xfr 1	26	24	24	0
20100102030405	Xfr 2	14	16	15	0
…	…	…	…	…	…
20100102030405	Xfr n	22	22	22	0

4.2.2 Analysis Program Integration, Compiling and Running

In order to investigate the affect of the contingencies efficiently and accurately, a comprehensive contingency analysis process with the consideration of load models will be implemented. The analysis program includes several functions as data preparation, contingency selection, PVL auto-running, comprehensive ZIP load model and load reconciliation. The whole flowchart is shown in Figure 4.1.

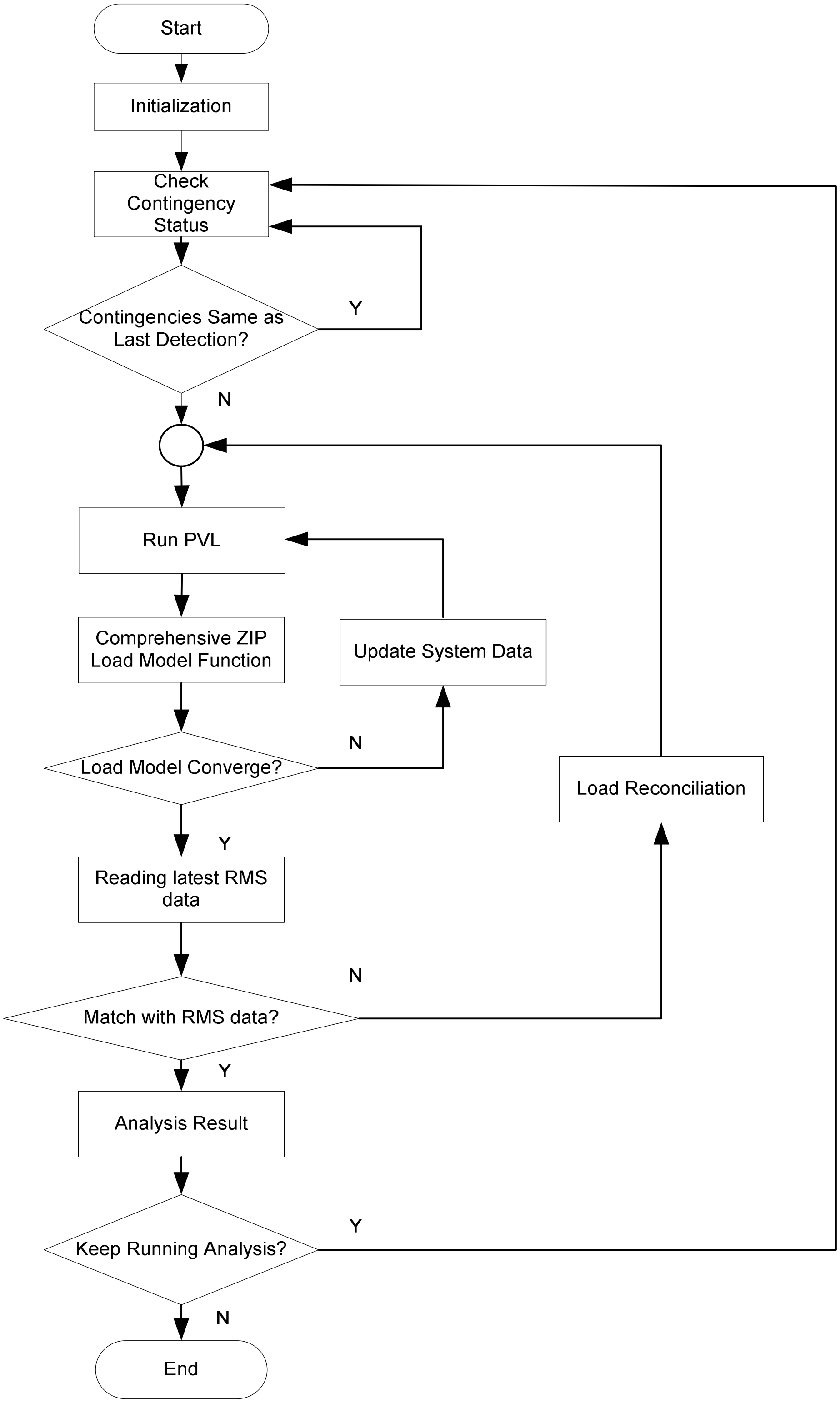


Figure 4.1 Contingency Analysis Flowchart

After the data preparation, analysis program will keep reading the contingency list file to check if there is any contingency status change. If new contingencies do happen, run PVL with the rated load data and get the voltage information for each load. Based on latest voltage information, comprehensive ZIP load model function will be applied to optimize the analysis till load model function converges. By comparing RMS data, load reconciliation is taken into analysis program to improve the analysis accuracy. Contingency analysis results will be given after the load reconciliation and operators could determine if keep running the analysis program according to the real situation.

The whole evaluation program was developed on HP UNIX environment. A math liabrary is used and the compiling of the program should follow this format:

```
#cc –lm –o objectivefile contingency_analysis.c
```

To run the objective file, just input:

```
#./objectivefile.o
```

4.3 Contingency Analysis with Comprehensive ZIP Load Model

A Con Edison's distribution network with 12 feeders is used in test for verifying the efficiency and feasibility of the proposed contingency analysis method. The following conditions are introduced in the test:

- N-1 to N-7 contingency analyses with constant load models
- N-1 to N-7 contingency analyses with comprehensive ZIP load models

For each operational condition, testing was performed with real distribution network data to replicate as closely to field conditions as possible. The following aspects were taken into account while analyzing the contingencies of the distribution network:

- Computational cost
- Validation of the load model
- Practical feasibility
- Realistic analysis result

4.3.1 Validation of Computational Efficiency

Because of the fast and direct contingency selection, both analyses based on constant load representation and analyses based on comprehensive ZIP load models are very efficient. With comprehensive ZIP load model, the computational time will be a little longer than that with constant load, but the time cost is still within acceptable range.

Table 4.4 Comparisons of Computational Cost (mm:ss)

Constant Load		Comprehensive ZIP Load Models	
Contingency Level	Time	Contingency Level	Time
1	00:33	1	00:34
2	00:21	2	00:24
3	00:33	3	00:36
4	00:26	4	00:30
5	00:18	5	00:21
6	00:18	6	00:21
7	00:17	7	00:42

The load model converging threshold is set to 0.01.

4.3.2 Analysis Result Comparison

The contingency analysis result is different between constant load model and comprehensive ZIP load model. The following typical example will show all the details.

N-1 contingency: Feeder out: [20M01].

Table 4.5 Comparisons of N-1 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	140933.2
Minimum Load Voltage (PU)	0.966	0.968
Overloaded Transformers	No	No
Reduced Loads	No	No

N-2 contingency: Feeder out: [20M01 20M07].

Table 4.6 Comparisons of N-2 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	140628.4
Minimum Load Voltage (PU)	0.953	0.960
Overloaded Transformers	No	No
Reduced Loads	No	No

N-3 contingency: Feeder out: [20M01 20M07 20M02].

Table 4.7 Comparisons of N-3 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	140062.9
Minimum Load Voltage (PU)	0.953	0.960
Overloaded Transformers	Yes (7)	No
Reduced Loads	No	No

N-4 contingency: Feeder out: [20M01 20M07 20M02 20M08].

Table 4.8 Comparisons of N-4 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	139487.8
Minimum Load Voltage (PU)	0.935	0.946
Overloaded Transformers	Yes (14)	No
Reduced Loads	No	No

N-5 contingency: Feeder out: [20M01 20M07 20M02 20M08 20M09].

Table 4.9 Comparisons of N-5 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	138947.3
Minimum Load Voltage (PU)	0.935	0.946
Overloaded Transformers	Yes (16)	Yes (1)
Reduced Loads	No	No

N-6 contingency: Feeder out: [20M01 20M07 20M02 20M08 20M09 20M04].

Table 4.10 Comparisons of N-6 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	137574.4
Minimum Load Voltage (PU)	0.889	0.918
Overloaded Transformers	Yes (34)	Yes (11)
Reduced Loads	No	No

N-7 contingency: Feeder out: [20M01 20M07 20M02 20M08 20M09 20M04 20M05].

Table 4.11 Comparisons of N-7 Contingency Analysis

Load Model	Constant Load	Comprehensive ZIP Load Models
Total Load Demand (kVA)	176996.7	139487.8
Minimum Load Voltage (PU)	0.796	0.849
Overloaded Transformers	Yes (39)	Yes (19)
Reduced Loads	Yes (1)	No

From the above tables, for both constant load analysis and comprehensive ZIP load model analysis, the load voltage decreases with the contingency level increasing. For constant load analysis, the total load demand is always the same at any contingency level, however, for comprehensive ZIP load model, the total load demand has the same changing trend with the load voltage as the contingency level changes. Besides the load flow program converging, one important factor operators will concern is overloaded transformers. For constant load analysis, there will be seven overloaded transformers when N-3 contingency occurs. However, no overloaded transformers are shown till N-5 contingency occurs with the comprehensive ZIP load model.

Actually, when contingencies occur, load voltage will drop too much to supply some equipments, the total load demand will be lower than normal and the chance of overloaded transformers will be lower, which proves the analysis result with comprehensive ZIP load model is a more convincing result. The proposed load models can accurately model dynamic behaviors of reactive power as well as real power, especially in multiple contingency conditions.

CHAPTER 5

VALIDATION OF CONTINGENCY DETECTION

In this chapter, contingency detection algorithms were tested on one of the distribution networks of Con Edison. The graphical user interface was developed on Microsoft Windows environment with Visual Basic programming language, and the sensitivity matrix calculation programs were developed on HP UNIX environment with C language and a single computer with a model of HP9000/785/C3000 was taken into test.

5.1 Sensitivity Matrix Calculation

The accuracy of the sensitivity matrices has a significant impact on the quality of the contingency detection. Con Edison has 60 distribution networks, most of which have hundreds of transformers and thousands of mains and the network configurations are keeping changing. When it comes to the sensitivity matrices, it is impossible to calculate them without automatically computing programs. Two sensitivity matrix calculation programs based on C language were developed on HP UNIX environment, and Table 5.1 shows the information of these two programs.

Table 5.1 Programs for Sensitivity Matrix Calculation

Program	TONTL.c	OMNTL.c
Related Sensitivity Matrix	TONTL	OMNTL, MSTL
Compiling Information	`cc –o tontl tontl.c`	`cc –lm –o omntl omntl.c`
Running	`# ./tontl.o /addr/config.txt`	`# ./omntl.o /addr/config.txt`

Both of these two programs run with configuration files, so users don’t need to update the source code. Every configuration file is related to one network, and Table 5.2 presents an example for configuration file. The two programs have friendly user interfaces and user can easily change specified file name and file contents to calculate other network data.

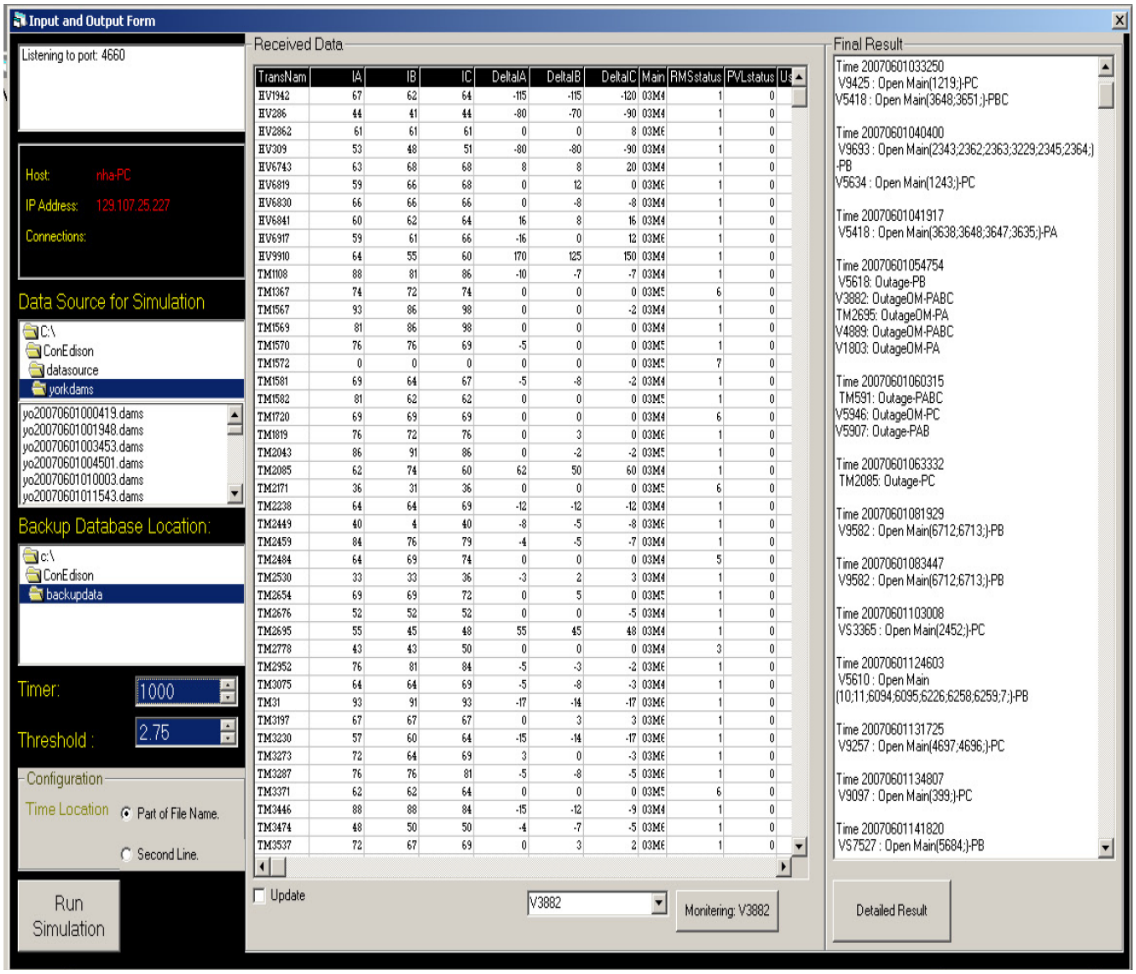
Table 5.2 Configuration File Illustration

addr_case=*/addr/base.case*	Address to save all the nxfr files' directory.
addr_xps=*/addr/base.xps*	Address of base.xps report.
addr_pvlautosh=*/addr/pvlauto.sh*	Address of PVL automatically running file.
addr_output=*/addr/data/*	Folder address to save all the output files like Trnumbering.txt, TRsize.txt, TONTL.txt, OMNTL.txt, MSTL.txt, TONTLvalue.txt, TONTL_xfrname.txt, OMNTL_xfrname.txt and MXTL_xfrname.txt.
addr_databackup=*/addr/backup/*	Folder address to backup all the .nxfr files and .usn files.

The efficiency of sensitivity matrix calculation is improved dramatically over the manual methods. For a network with 519 transformers and 6809 mains, the time cost for TONTL is less than 40 minutes and that for OMNTL and MSTL is also within three hours. Without using the percentage information for transformer loads, round-off error is eliminated and the accuracy of the sensitivity matrices is also ensured.

5.2 Contingency Detection Module

Figure 5.1 shows the front panel of the graphical user interface for the contingency detection. There are three parts in the main interface. The left part presents Input information such as data source of network, data acquiring timer and threshold for boundary, and users can also select online or offline mode. All the information of the transformers is detailed in the middle part and users can detail all problems. The right part provides the alarms detected by the software.



Listening to port: 4660

Host: nha-PC
IP Address: 129.107.25.227
Connections:

C:\
ConEdison
datasource
yorkdams

yo20070601000419.dams
yo20070601001948.dams
yo20070601003453.dams
yo20070601004501.dams
yo20070601010003.dams
yo20070601011543.dams

c:\
ConEdison
backupdata

Timer: 1000
Threshold : 2.75

Time Location ● Part of File Name. ○ Second Line.

TransNam	IA	IB	IC	DeltaA	DeltaB	DeltaC	Main	RMSstatus	PVLstatus	Us
HV1942	67	62	64	-115	-115	-120	03M4	1	0	
HV286	44	41	44	-80	-70	-90	03M4	1	0	
HV2862	61	61	61	0	0	8	03M6	1	0	
HV309	53	48	51	-80	-80	-90	03M4	1	0	
HV6743	63	68	68	8	8	20	03M4	1	0	
HV6819	59	66	68	0	12	0	03M6	1	0	
HV6830	66	66	66	0	-8	-8	03M4	1	0	
HV6841	60	62	64	16	8	16	03M4	1	0	
HV6917	59	61	66	-16	0	12	03M6	1	0	
HV9910	64	55	60	170	125	150	03M4	1	0	
TM1108	88	81	86	-10	-7	-7	03M4	1	0	
TM1367	74	72	74	0	0	0	03M5	6	0	
TM1567	93	86	98	0	0	-2	03M4	1	0	
TM1569	81	86	98	0	0	0	03M4	1	0	
TM1570	76	76	69	-5	0	0	03M5	1	0	
TM1572	0	0	0	0	0	0	03M5	7	0	
TM1581	69	64	67	-5	-8	-2	03M4	1	0	
TM1582	81	62	62	0	0	0	03M5	1	0	
TM1720	69	69	69	0	0	0	03M4	6	0	
TM1819	76	72	76	0	3	0	03M6	1	0	
TM2043	86	91	86	0	-2	-2	03M5	1	0	
TM2085	62	74	60	62	50	60	03M4	1	0	
TM2171	36	31	36	0	0	0	03M5	6	0	
TM2238	64	64	69	-12	-12	-12	03M4	1	0	
TM2449	40	4	40	-8	-5	-8	03M6	1	0	
TM2459	84	76	79	-4	-5	-7	03M4	1	0	
TM2484	64	69	74	0	0	0	03M4	5	0	
TM2530	33	33	36	-3	2	3	03M4	1	0	
TM2654	69	69	72	0	5	0	03M5	1	0	
TM2676	52	52	52	0	0	-5	03M4	1	0	
TM2695	55	45	48	55	45	48	03M4	1	0	
TM2778	43	43	50	0	0	0	03M4	3	0	
TM2952	76	81	84	-5	-3	-2	03M6	1	0	
TM3075	64	64	69	-5	-8	-3	03M4	1	0	
TM31	93	91	93	-17	-14	-17	03M6	1	0	
TM3197	67	67	67	0	3	3	03M6	1	0	
TM3230	57	60	64	-15	-14	-17	03M6	1	0	
TM3273	72	64	69	3	0	-3	03M6	1	0	
TM3287	76	76	81	-5	-8	-5	03M6	1	0	
TM3371	62	62	64	0	0	0	03M5	6	0	
TM3446	88	88	84	-15	-12	-9	03M4	1	0	
TM3474	48	50	50	-4	-7	-5	03M6	1	0	
TM3537	72	67	69	0	3	2	03M6	1	0	

☐ Update

V3882

```
Time 20070601033250
 V9425 : Open Main(1219;)-PC
V5418 : Open Main(3648;3651;)-PBC

Time 20070601040400
 V9693 : Open Main(2343;2362;2363;3229;2345;2364;)
-PB
V5634 : Open Main(1243;)-PC

Time 20070601041917
 V5418 : Open Main(3638;3648;3647;3635;)-PA

Time 20070601054754
 V5618: Outage-PB
V3882: OutageOM-PABC
TM2695: OutageOM-PA
V4889: OutageOM-PABC
V1803: OutageOM-PA

Time 20070601060315
 TM591: Outage-PABC
V5946: OutageOM-PC
V5907: Outage-PAB

Time 20070601063332
 TM2085: Outage-PC

Time 20070601081929
 V9582 : Open Main(6712;6713;)-PB

Time 20070601083447
 V9582 : Open Main(6712;6713;)-PB

Time 20070601103008
 VS3365 : Open Main(2452;)-PC

Time 20070601124603
 V5610 : Open Main
(10;11;6094;6095;6226;6258;6259;7;)-PB

Time 20070601131725
 V9257 : Open Main(4697;4696;)-PC

Time 20070601134807
 V9097 : Open Main(399;)-PC

Time 20070601141820
 VS7527 : Open Main(5684;)-PB
```

Figure 5.1 Front Panel of Contingency Detection User Interface

For any network transformer chosen from the combo box at the middle upper corner of the front panel, real time load change on each phase can be monitored in the online monitoring system panel for the last two hours. The chart also explicates the boundary curve for the normal load and recent incident history as shown in the Figure 5.2.

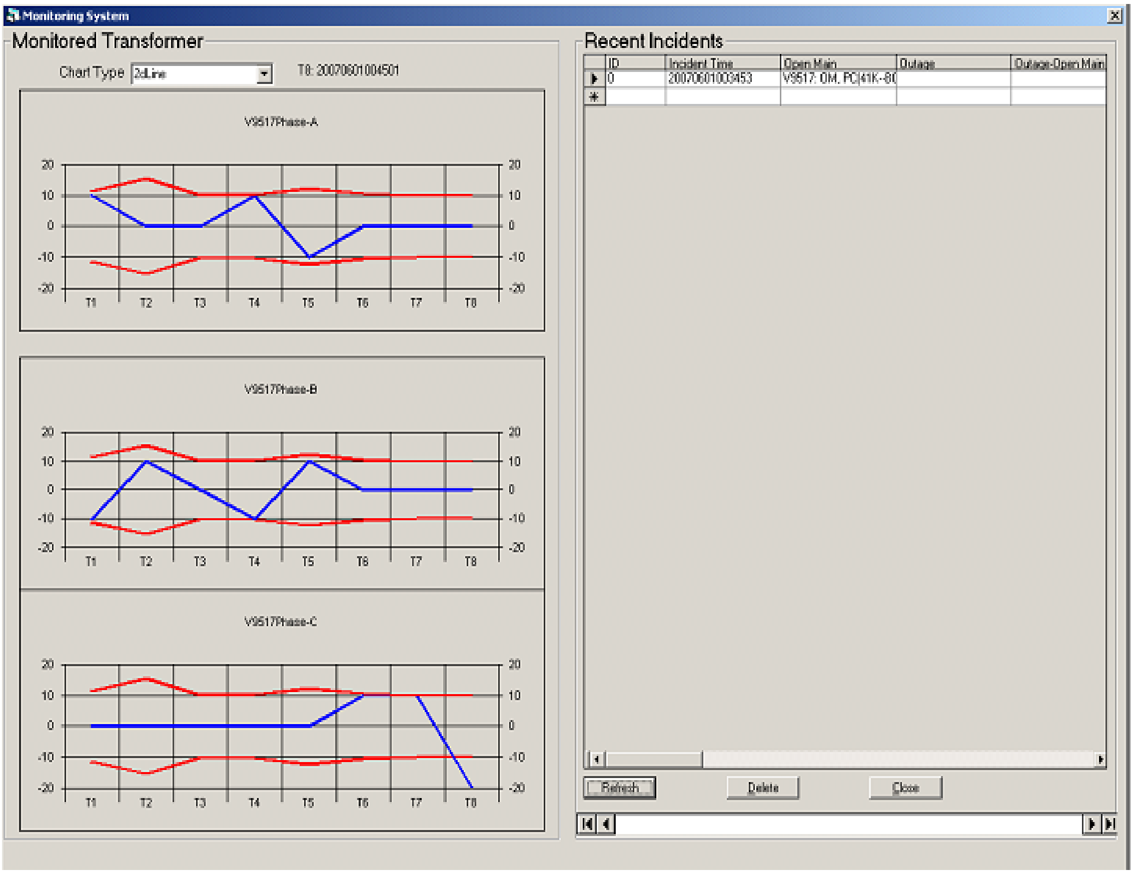


Chart Type 2dLine

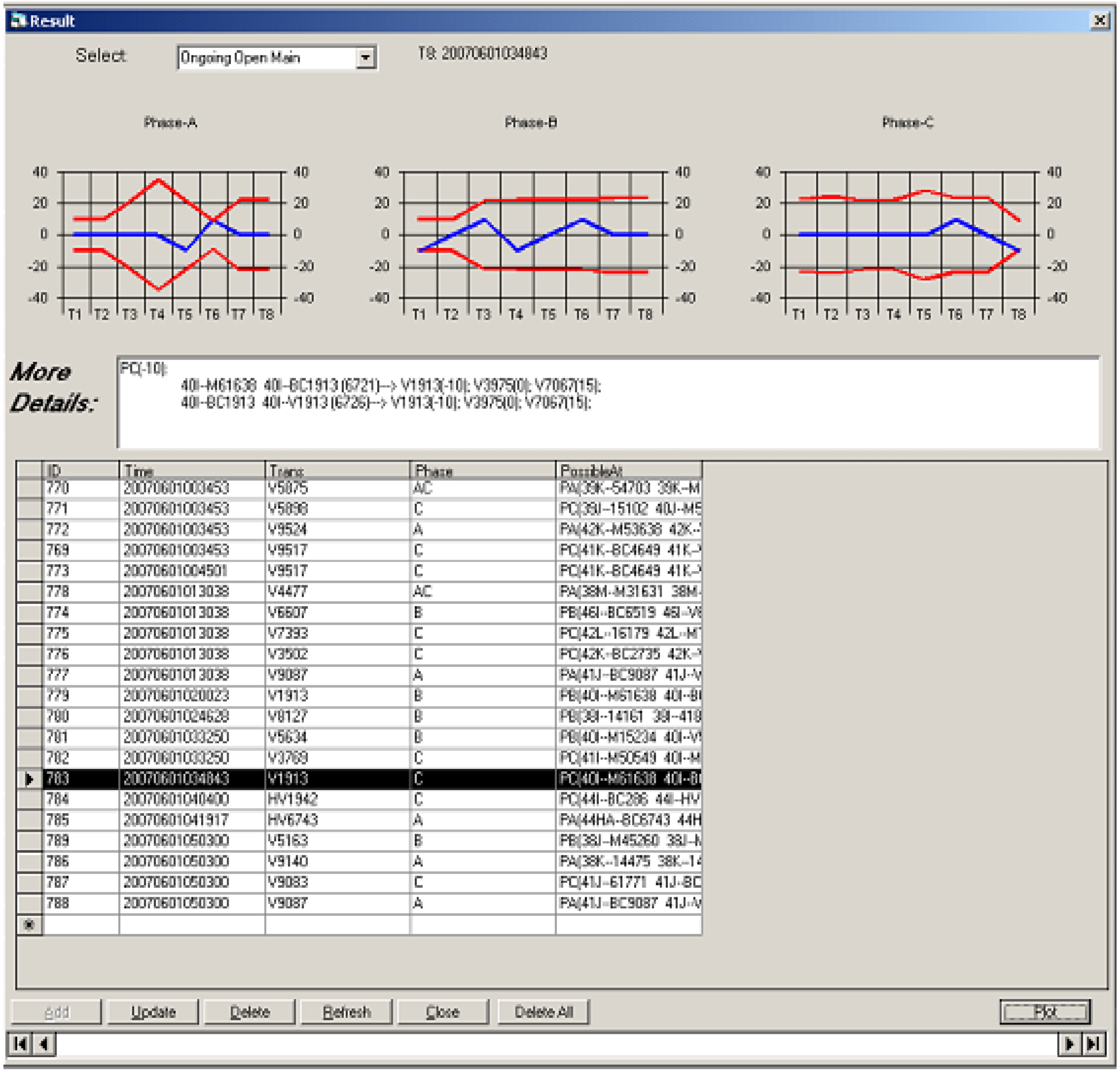
T8: 20070601004501

ID	Incident Time	Open Main	Outage	Outage-Open Main
0	20070601003453	V9517: OM, PC|41K-80		

Figure 5.2 Detailed Information for Monitored Transformer

5.3 Test Results

All the detected events are listed in the detection result panel. By selecting either transformer outage or open main, users can get all recent events under each category and each one indicates the time of occurrence according to RMS system. After clicking them, users will get the three phase data plots of corresponding event.



Select: Ongoing Open Main

T8: 20070601034843

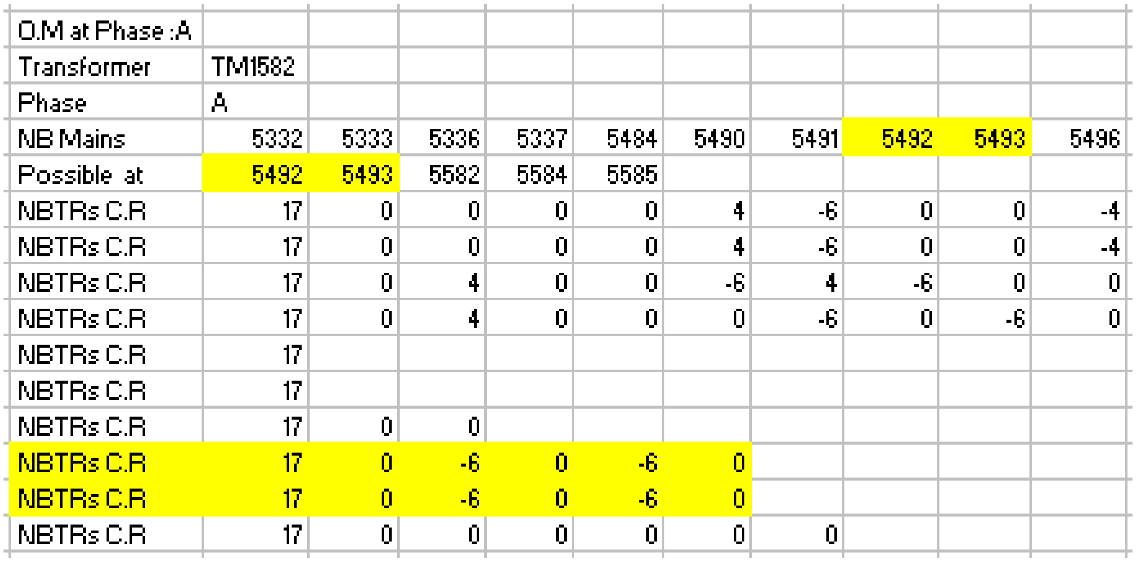
More Details:

PC(-10):
40I-M61638 40I-BC1913 (6721)--> V1913(-10); V3975(0); V7067(15);
40I-BC1913 40I-V1913 (6726)--> V1913(-10); V3975(0); V7067(15);

ID	Time	Trans	Phase	PossibleAt
770	20070601003453	V5075	AC	PA(39K-54703 39K-M
771	20070601003453	V5898	C	PC(39J-15102 40J-M5
772	20070601003453	V9524	A	PA(42K-M53638 42K-
769	20070601003453	V9517	C	PC(41K-BC4649 41K-
773	20070601004501	V9517	C	PC(41K-BC4649 41K-
778	20070601013038	V4477	AC	PA(38M-M31631 38M-
774	20070601013038	V6607	B	PB(46I-BC6519 46I-V
775	20070601013038	V7393	C	PC(42L-16179 42L-M
776	20070601013038	V3502	C	PC(42K-BC2735 42K-
777	20070601013038	V9087	A	PA(41J-BC9087 41J-V
779	20070601020023	V1913	B	PB(40I-M61638 40I-B
780	20070601024628	V8127	B	PB(38I-14161 38I-41
781	20070601033250	V5634	B	PB(40I-M15234 40I-V
782	20070601033250	V3769	C	PC(41I-M50549 40I-M
783	20070601034843	V1913	C	PC(40I-M61638 40I-B
784	20070601040400	HV1942	C	PC(44I-BC286 44I-HV
785	20070601041917	HV6743	A	PA(44HA-BC6743 44H
789	20070601050300	V5163	B	PB(38J-M45260 38J-N
786	20070601050300	V9140	A	PA(38K-14475 38K-14
787	20070601050300	V9083	C	PC(41J-61771 41J-BC
788	20070601050300	V9087	A	PA(41J-BC9087 41J-V

Figure 5.3 Detailed Detection Result Panel

The open main detection software performs well on Con Edison's distribution networks and the test results identify the actual event. For example, checking with historical data, an event was detected with Main 5492 and Main 5493 from the abnormal change rates of Transformer TM1582 on 6/16/2007 (IOM_TM1582_20070616_124732). Actually, the same event was reported on 6/19/2007 and was fixed on 8/27/2007. Figure 5.4 indicates the detailed detection results.



O.M at Phase :A										
Transformer	TM1582									
Phase	A									
NB Mains	5332	5333	5336	5337	5484	5490	5491	5492	5493	5496
Possible at	5492	5493	5582	5584	5585					
NBTRs C.R	17	0	0	0	0	4	-6	0	0	-4
NBTRs C.R	17	0	0	0	0	4	-6	0	0	-4
NBTRs C.R	17	0	4	0	0	-6	4	-6	0	0
NBTRs C.R	17	0	4	0	0	0	-6	0	-6	0
NBTRs C.R	17									
NBTRs C.R	17									
NBTRs C.R	17	0	0							
NBTRs C.R	17	0	-6	0	-6	0				
NBTRs C.R	17	0	-6	0	-6	0				
NBTRs C.R	17	0	0	0	0	0	0			

Figure 5.4 Details of a Detection Result Example

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 Concluding Remarks

Contingency analysis and contingency detection are the essential components for distribution network operation and control. This study improves the accuracy of the contingency analysis and contingency detectioin by applying accurate load models.

A novel contingency analysis model for multiple contingency, with the consideration of comprehensive ZIP load model, is proposed in this dissertation. This model is computationally efficient and particularly suited for online assessment. The comprehensive ZIP load model improves the accuracy of contingency analysis significantly. The load model part might increase the time for computing, however, distribution network is relatively small, and it is still possible to complete all the calculation within an acceptable time. The proposed approach is clear and simple in nature, yet it provides an efficient, accurate, and feasible contingency analysis method.

Besides contingency analysis, contingency detection is also taken into consideration. The implementation of the contingency detection algorithm makes it possible to detect the occurrence of an incident and to identify the most possible incident location, which facilitates the mission of repairing team and provides up-to-date information to improve contingency analysis accuracy.

Based on the proposed algorithm, tests were performed on Con Edison’s real distribution network, and the evaluation efficiency, accuracy and practical feasibility are confirmed.

6.2 Dissertation Contribution

This study presents a novel mechanism to analyze and detect contingencies of a underground distribution system. The major contributions of this work are:

- Implemented an efficient contingency analysis model to perform online high order contingency analysis without increasing computational burden or simplifying distribution network,
- Integrated the modified ZIP load model into the power flow software PVL to improve the accuracy of contingency analysis.
- Implemented the low voltage cutoff function with modified ZIP load model to obtain a more realistic load representation.
- Developed the macro ZIP load model coefficients to improve the load model computing efficiency.
- Developed the algorithms for high-tension and 4kV load estimation.
- Developed the automatic running programs for sensitivity matrix calculation to reduce the labor cost, which is used to be so onerous that it is almost impossible to calculate the sensitivity matrices for all the distribution networks.
- All the above evaluation programs are developed based on HP UNIX environment to realize the compatibility with Con Edison’s subsistent programs.
- Developed a contingency detection system that is able to detect the occurrence of an incident and to identify the most possible incident location that facilitates the mission of repairing team and provides up-to-date information to improve contingency analysis accuracy.
- The study eventually improves the distribution system reliability through its contribution to provide operators sufficiently fast, accurate and realistic prediction information to prevent further cascading outage failure.

6.3 Future Work

In the future, some topics should be taken up to reach better over all performance for the study, one of them concern on the new load components, another topics is about establishing Advanced Metering Infrastructure (AMI). Also once this study is applied in the real time monitoring system, any possible feed back may rise will deserve specifying part of future work to deal with it.

It is necessary to update and/or include new products that have emerged into the market after the development of the original load models. Future works should refine the load model for TV (Plasma, LCD, and LED) and include the load model for game consoles such as XBOX 360, PS3, and Wii.

In the competitive electricity structure, the data exchange between supplier and customers becomes more important for efficient and secure operation of power systems. Automated Meter Reading (AMR) technology has played an important role in helping utilities to overcome the meter reading challenges. However, it is not enough in today’s environment. The Federal administrations perceive the necessities of electricity demand response programs and have passed the Energy Policy Act (EPAct) 2005 to provide supporting infrastructures and technologies for demand response programs for all classes of consumers. Accordingly, Advanced Metering Infrastructure (AMI) deployments play a large part in today’s new strategies to develop a smart grid infrastructure. AMI is an emerging technology evolving from Automated Meter Reading (AMR). The main goal of AMR was to reduce the costs of electrical meter reading but AMI provides the promise of other capabilities based on bidirectional communications where data can be sent to a meter and/or customer as well as retrieved from it and in some cases, the ability to execute control actions (such as shutting off individual load). Similar to other utility systems, Consolidated Edison Company of New York, Inc. is implementing an AMI system to enable the company and consumers to gather and utilize metered data in a more intelligent and cost effective manner.

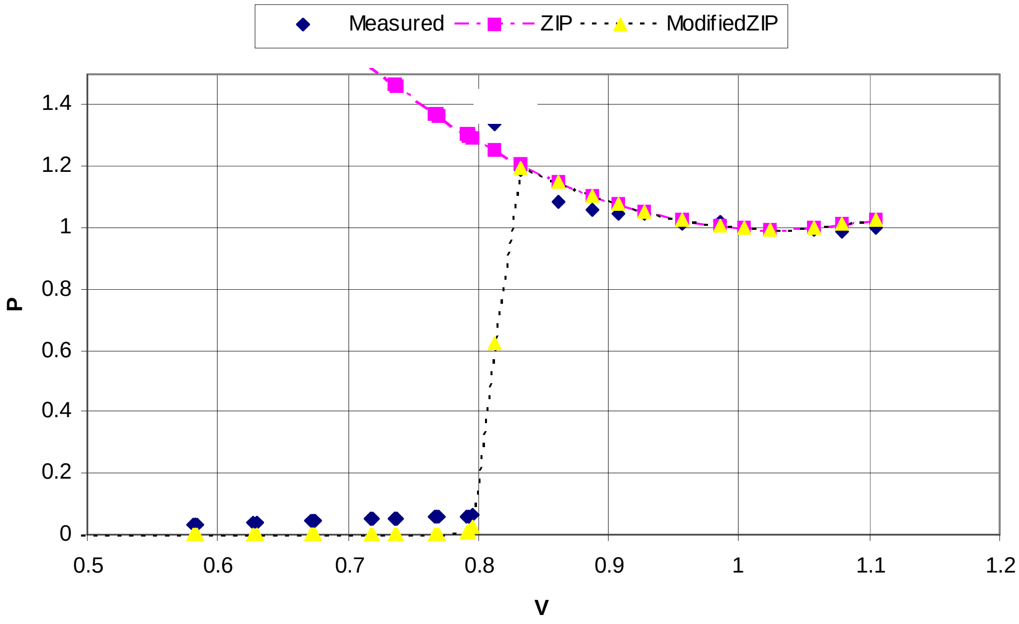
One of the most promising applications for the AMI data to improve the accuracy of its system analysis is using the information to enhance the capabilities of the PVL. Due to limitations on available information, current PVL is based upon peak demand (one snapshot only) to perform load conciliation. The program performs well based upon peak demand. However, no other operation conditions such as off-peak or different seasons are used in the model.

Future works should utilize data collected from AMI system to provide accurate customer daily load profiling for load estimation and network demand reconciliation to improve the efficiency and security of the underground network of Con Edison systems.

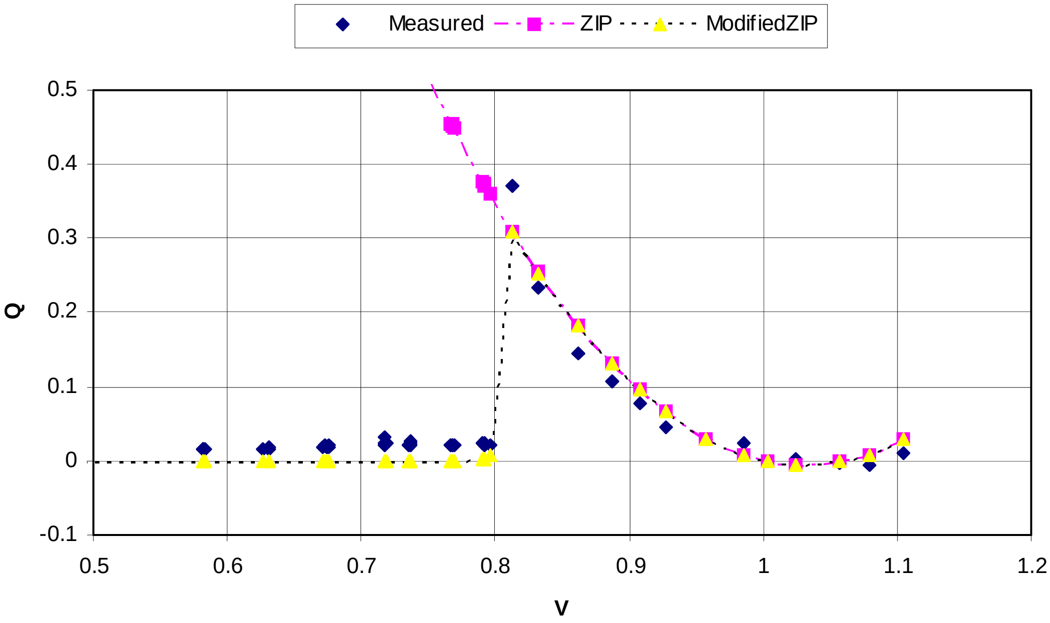
APPENDIX A

MEASUREMENTS OF PV AND QV CHARACTERISTICS AND COMPARISON WITH CURVE FITTED RESULTS

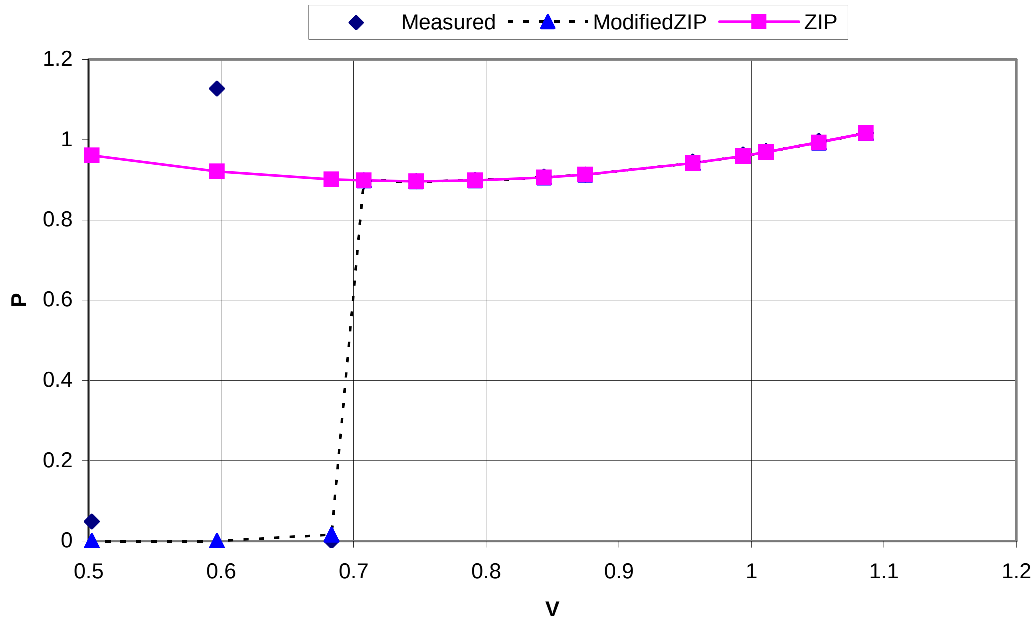
1.1 Device 1: P-V



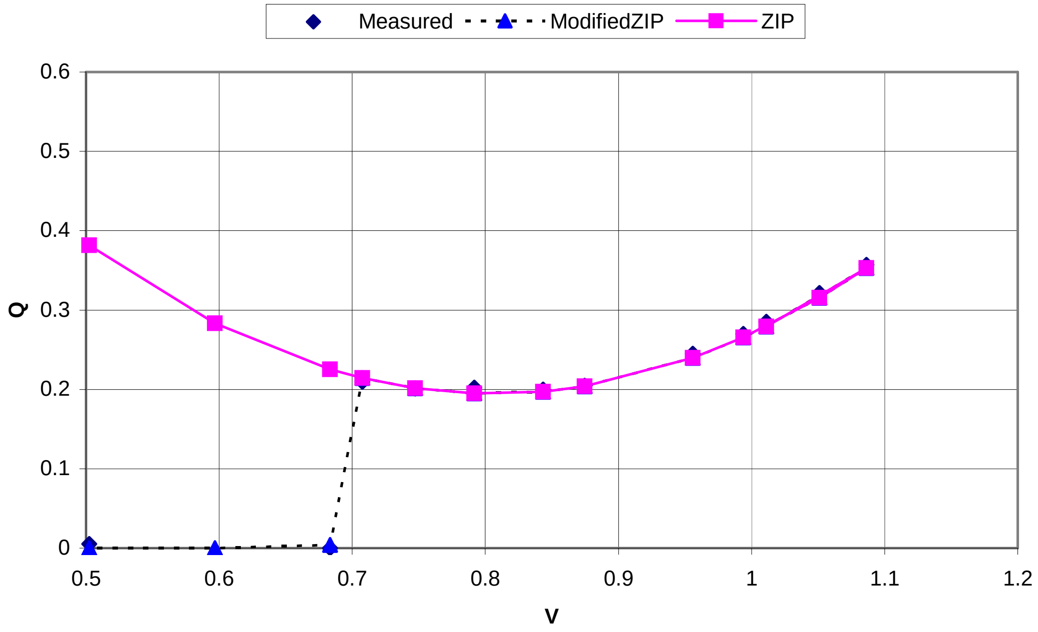
1.2 Device 1: Q-V



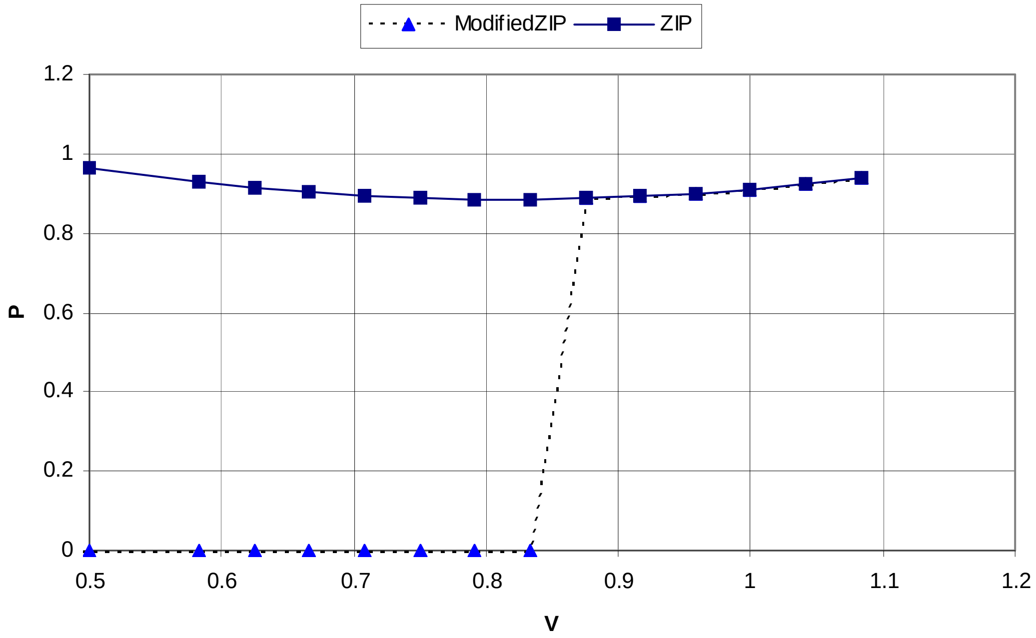
2.1 Device 2: P-V



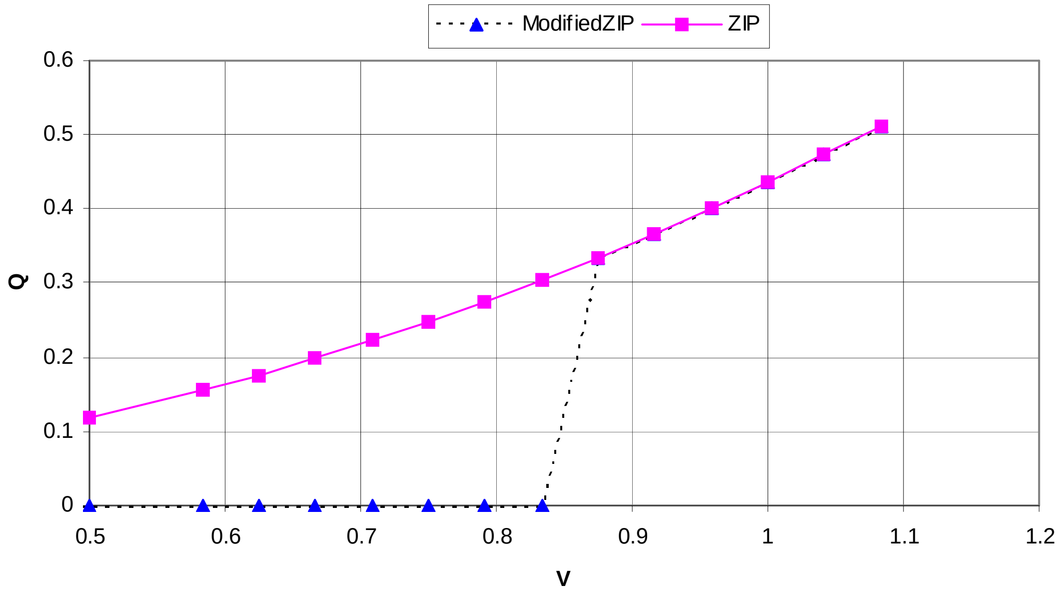
2.2 Device 2: Q-V



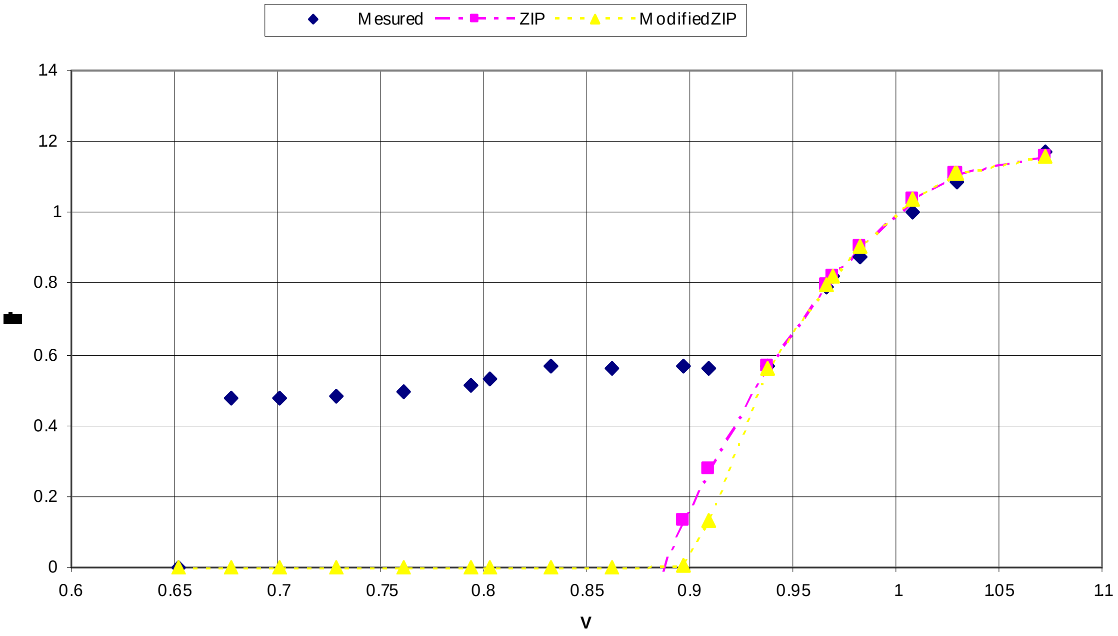
3.1 Device 3: P-V



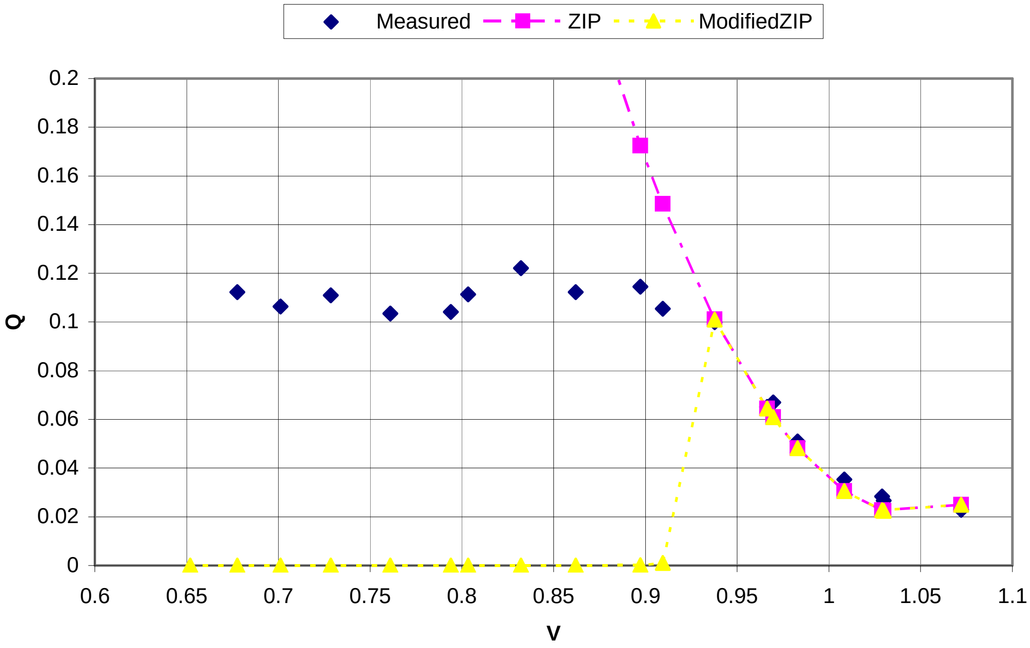
3.2 Device 3: Q-V



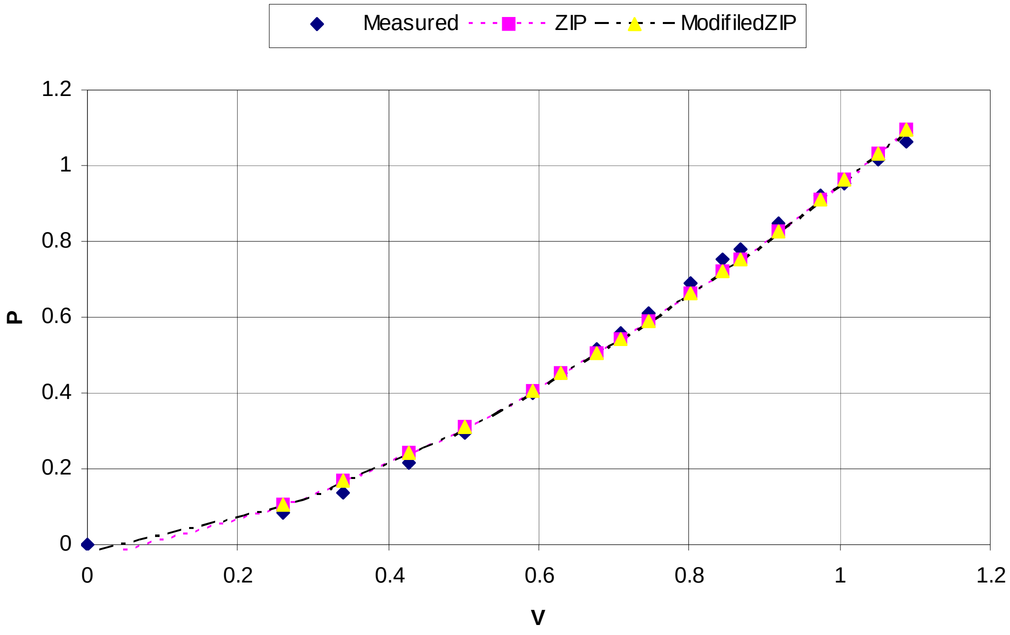
4.1 Device 4: P-V



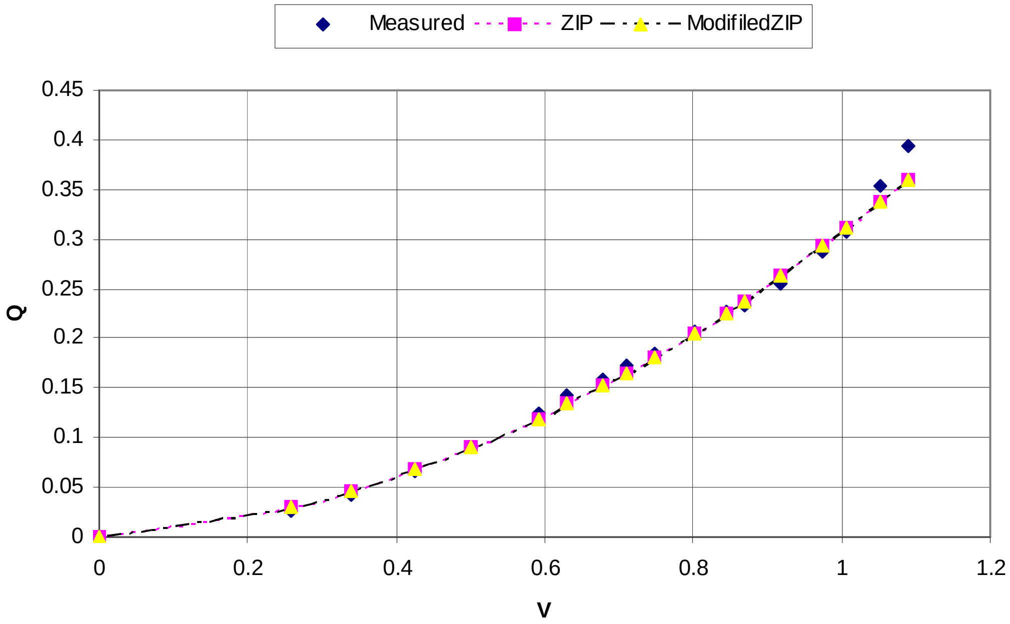
4.2 Device 4: Q-V



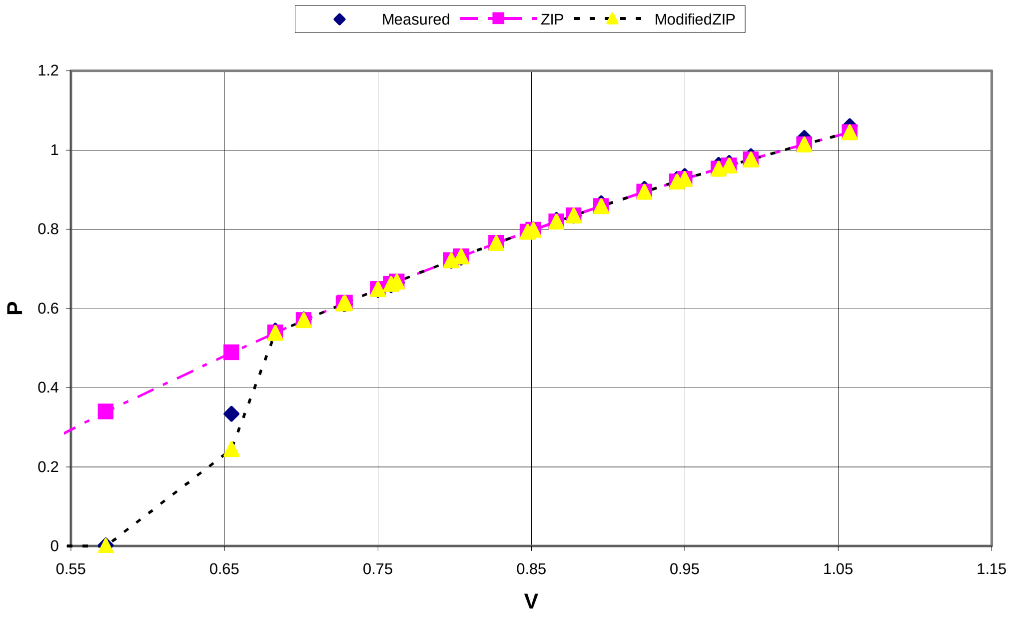
5.1 Device 5: P-V



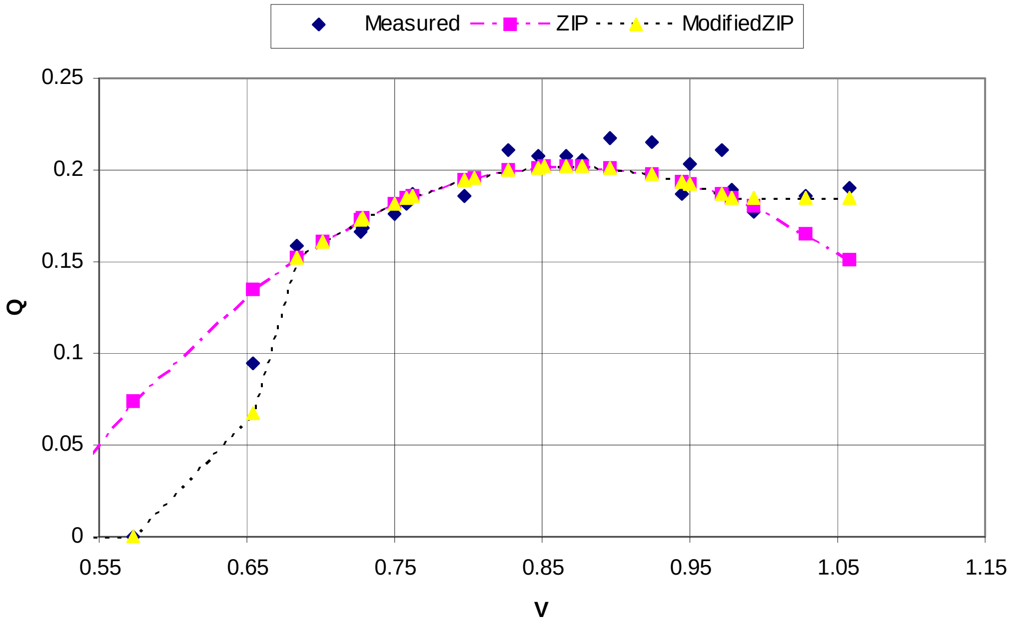
5.2 Device 5: Q-V



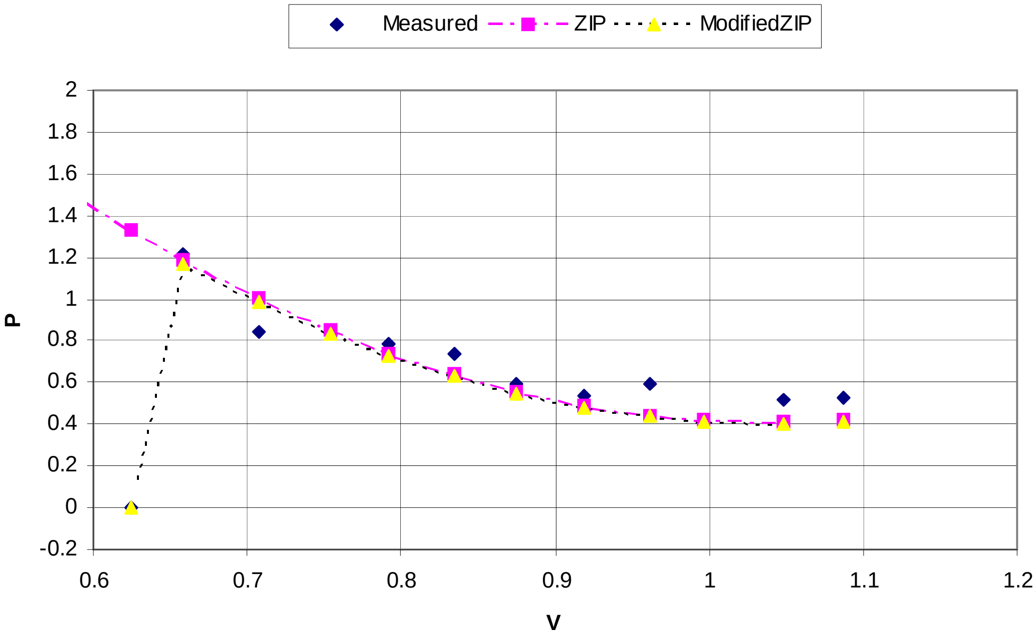
6.1 Device 6: P-V



6.2 Device 6: Q-V



7.1 Device 7: P-V



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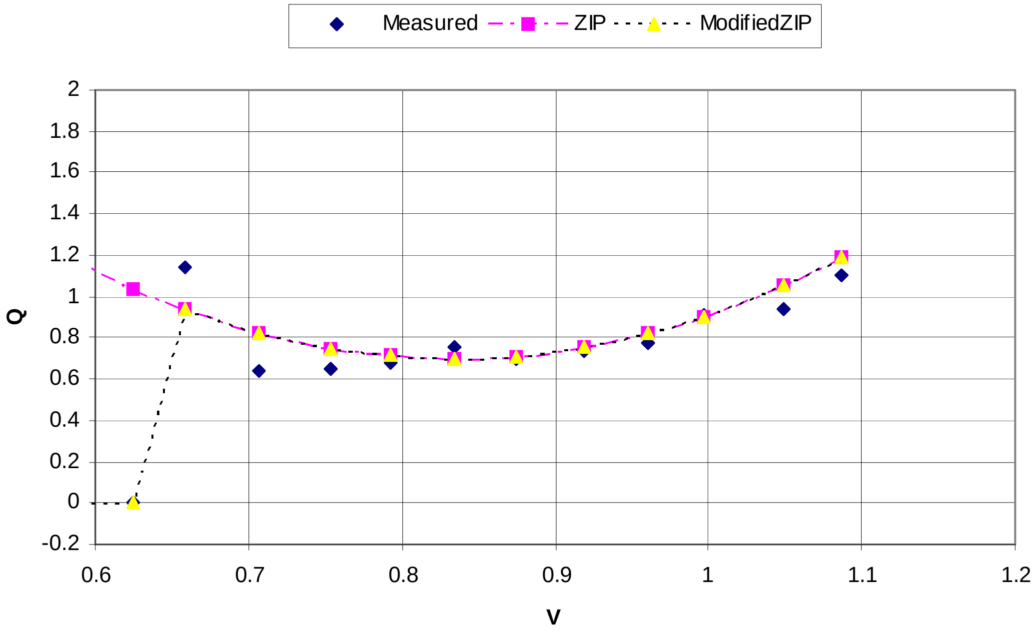

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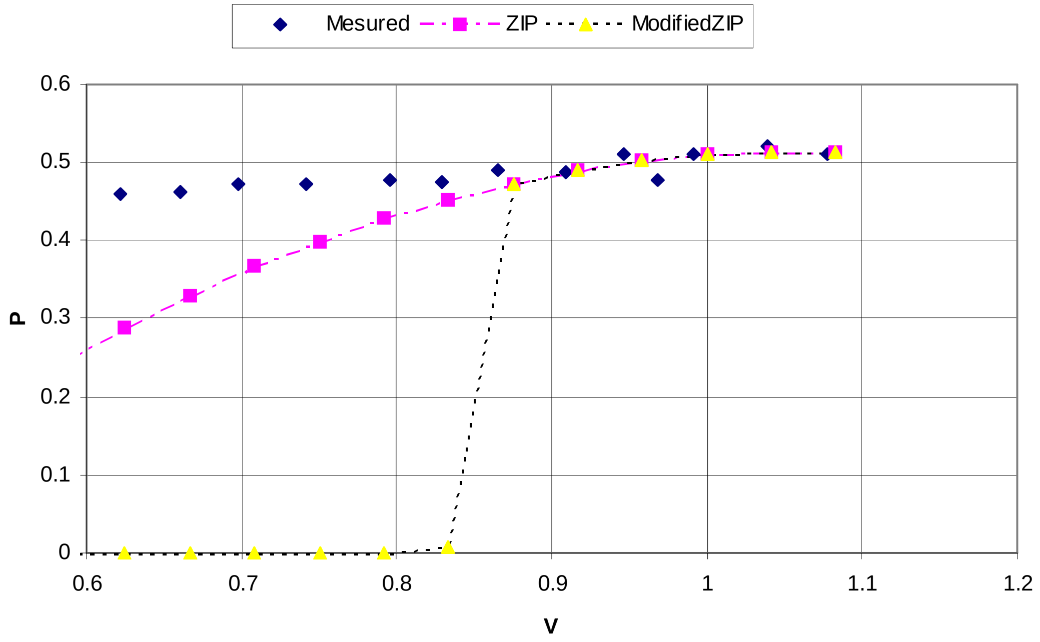

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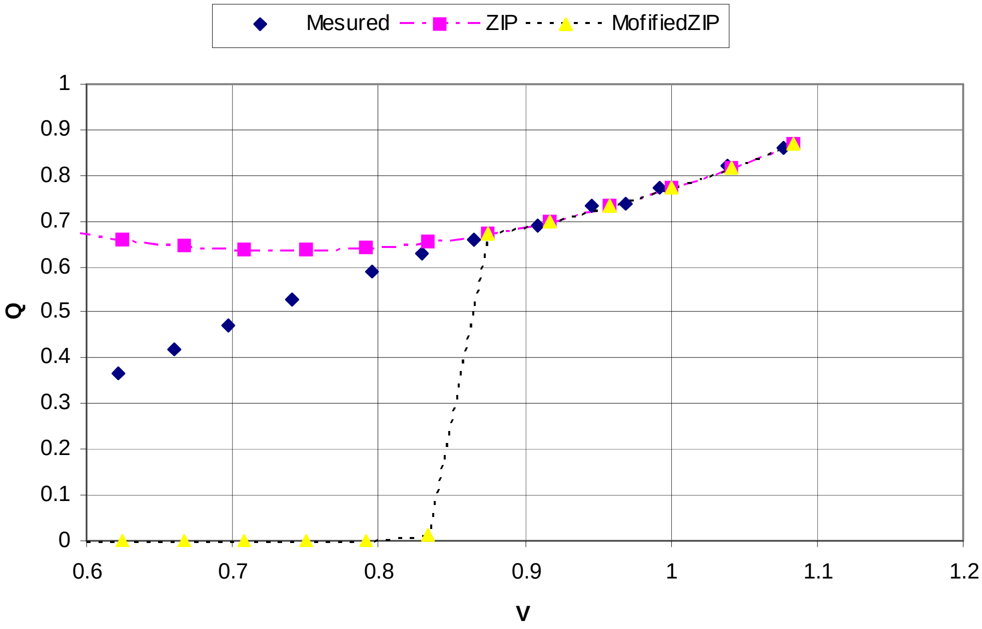

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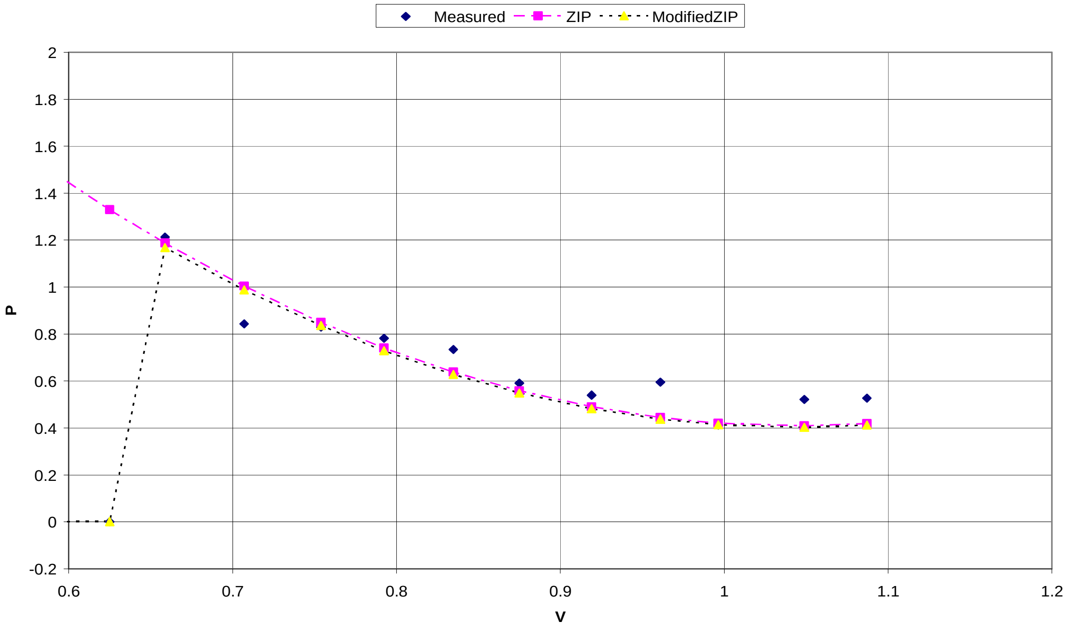

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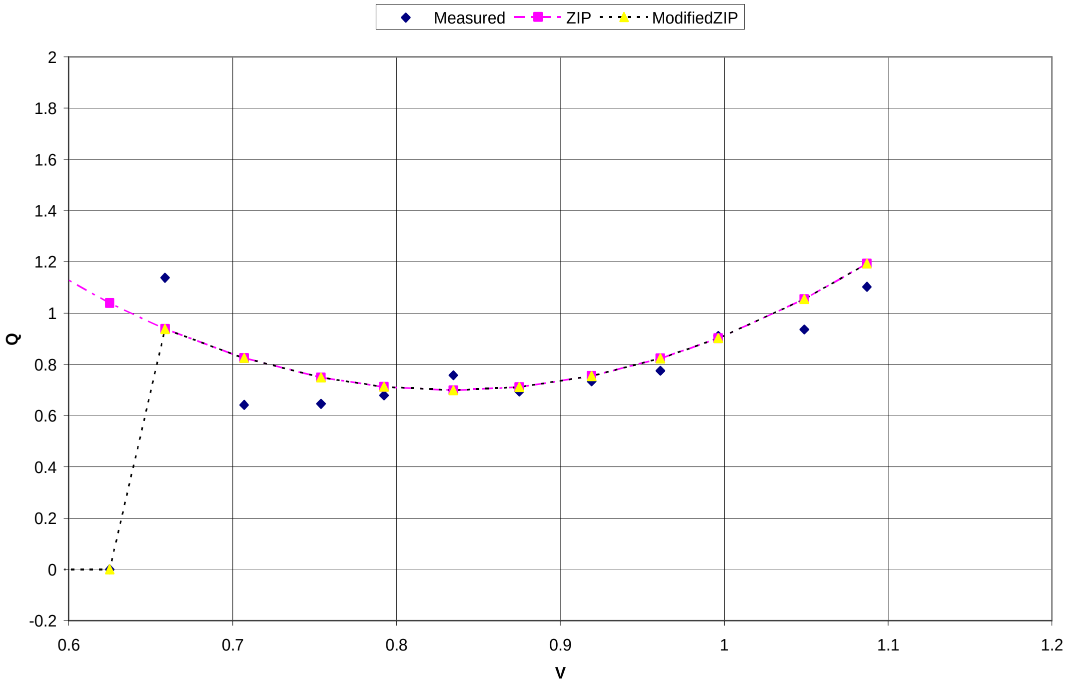

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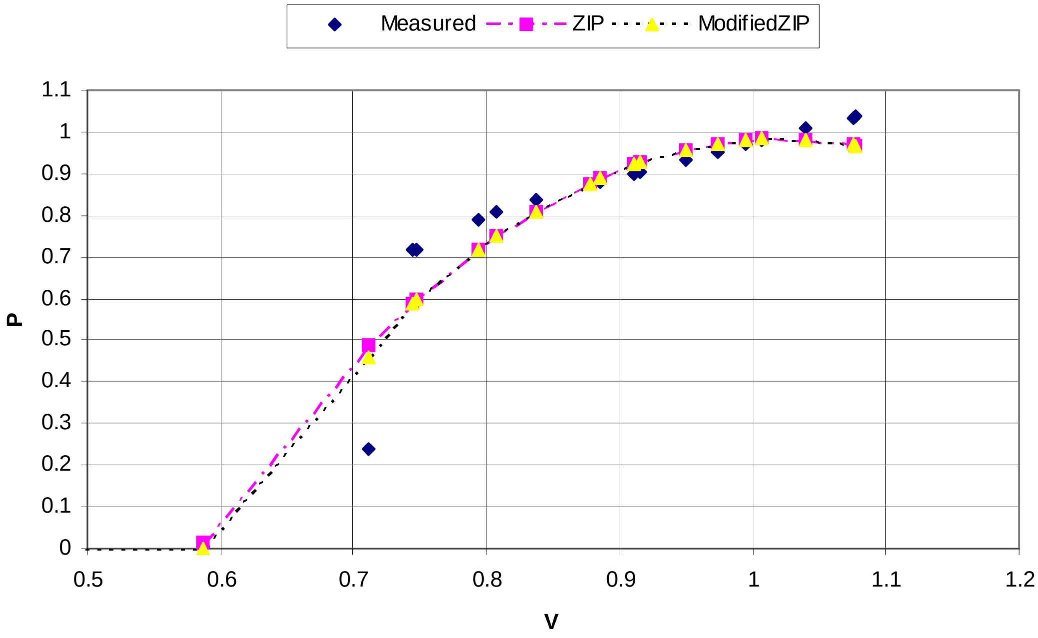
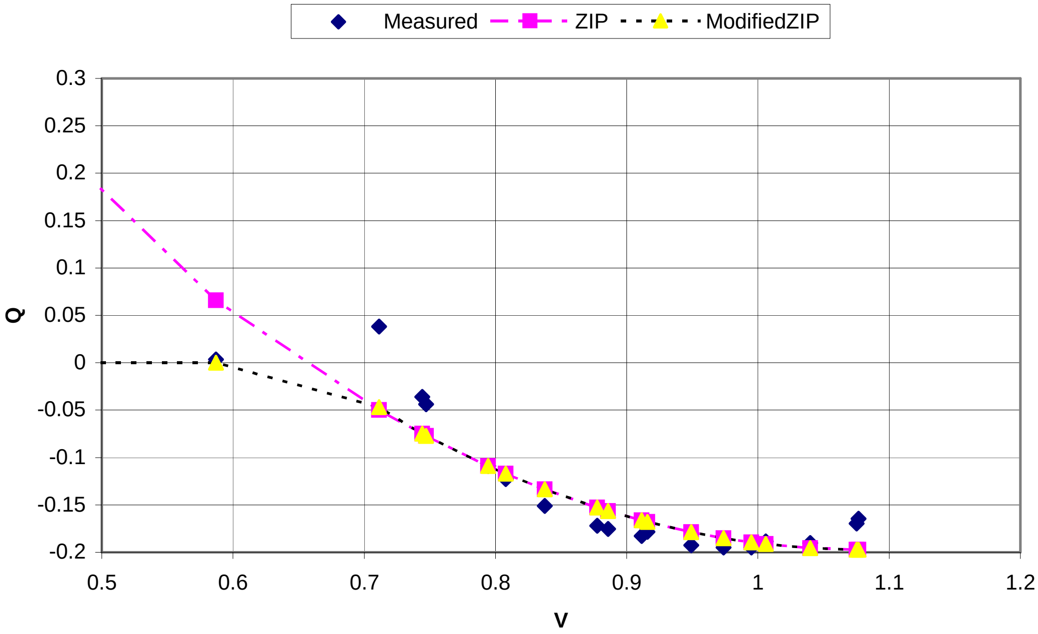
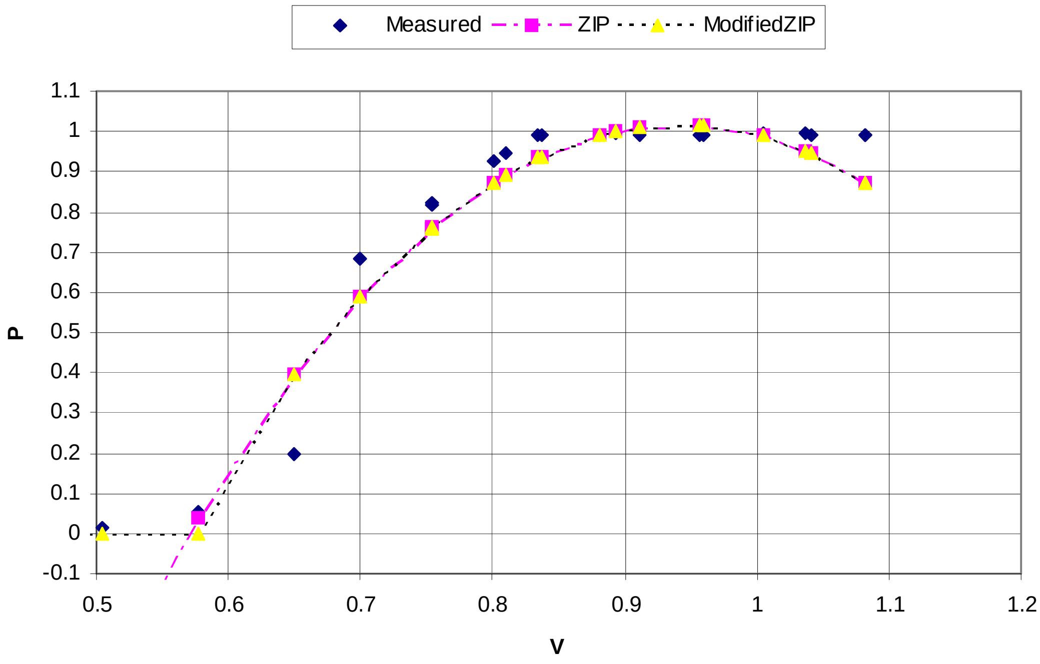


10.2 Device 10: Q-V



11.1 Device 11: P-V



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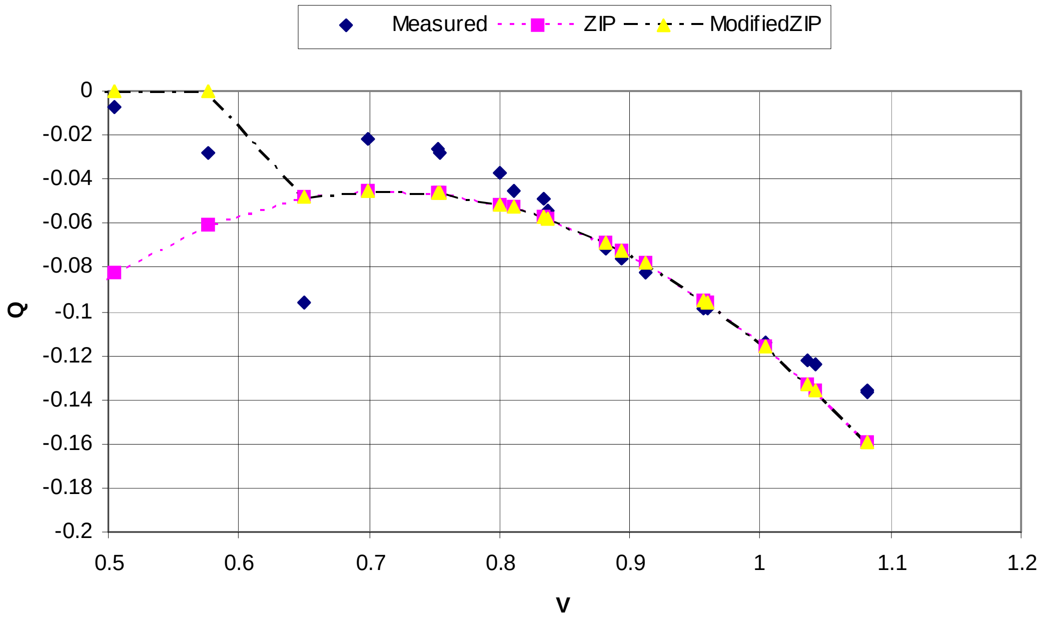
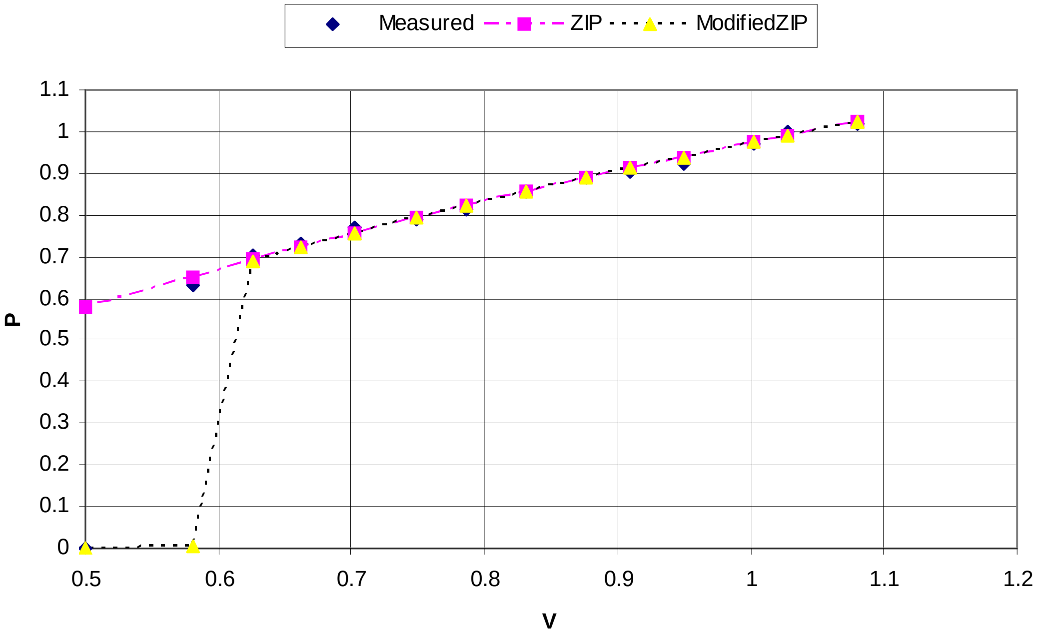
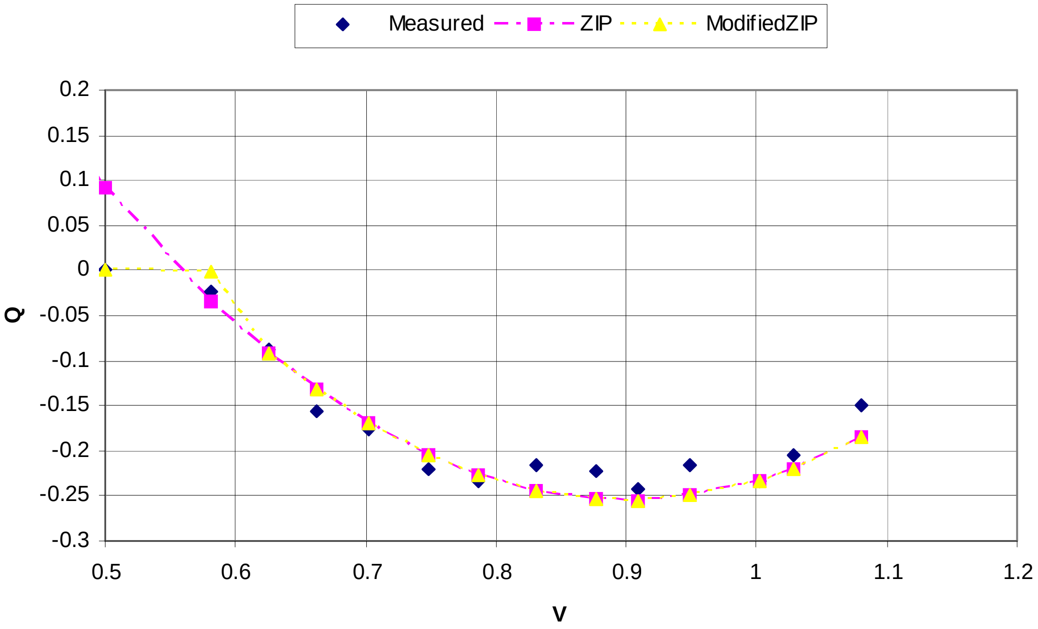


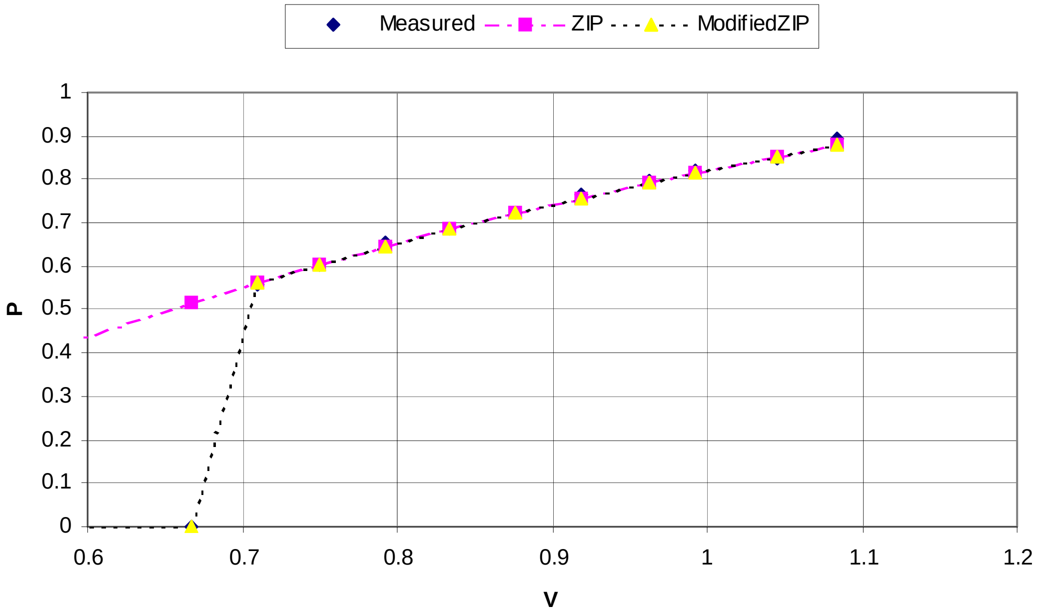
12.1 Device 12: P-V



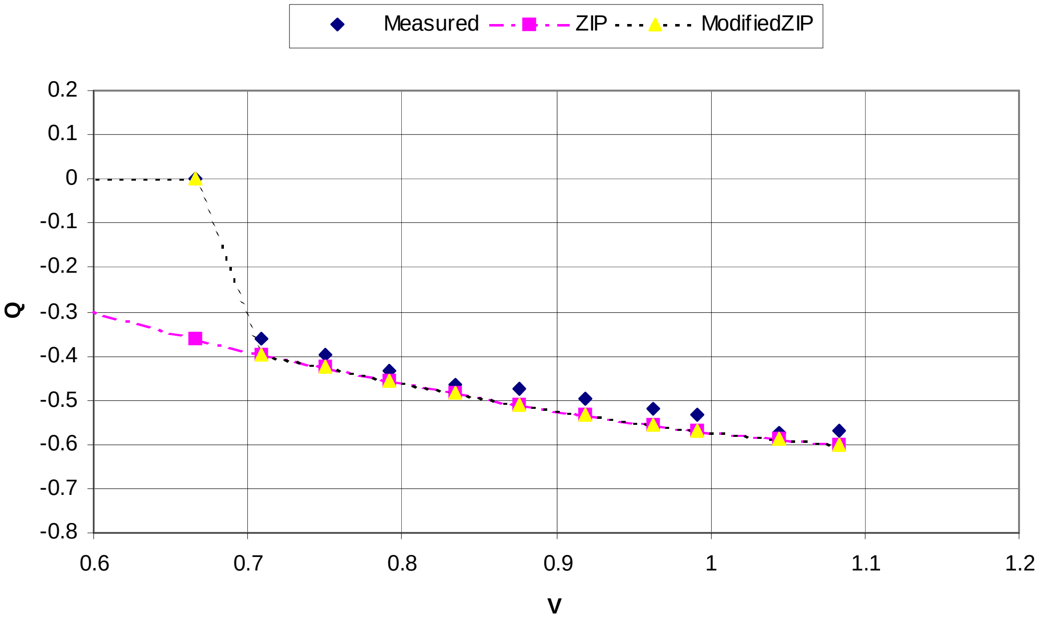
12.2 Device 12: Q-V



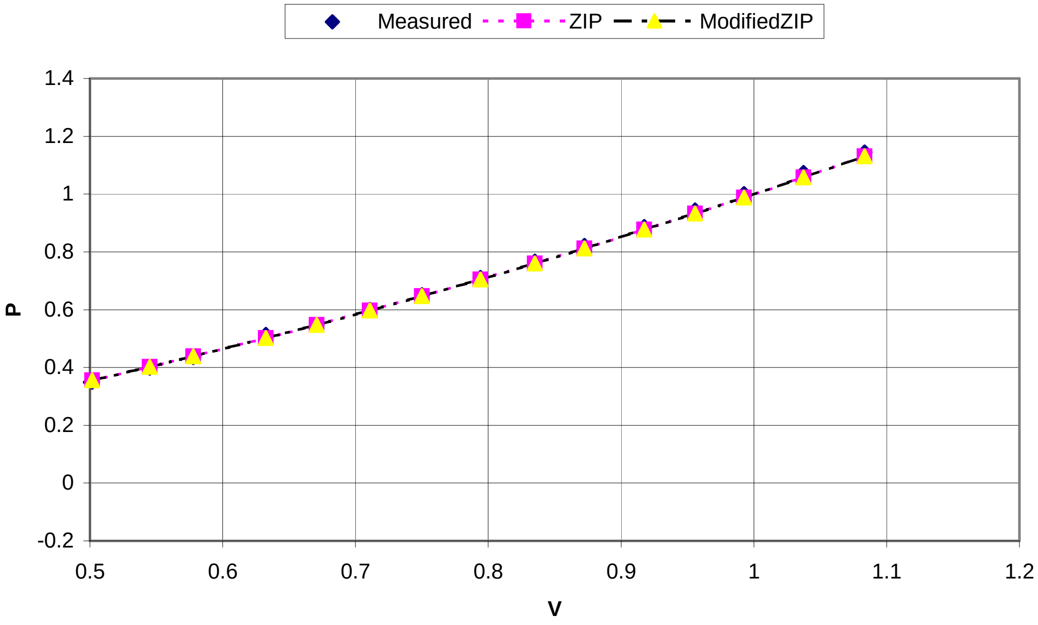
13.1 Device 13: P-V



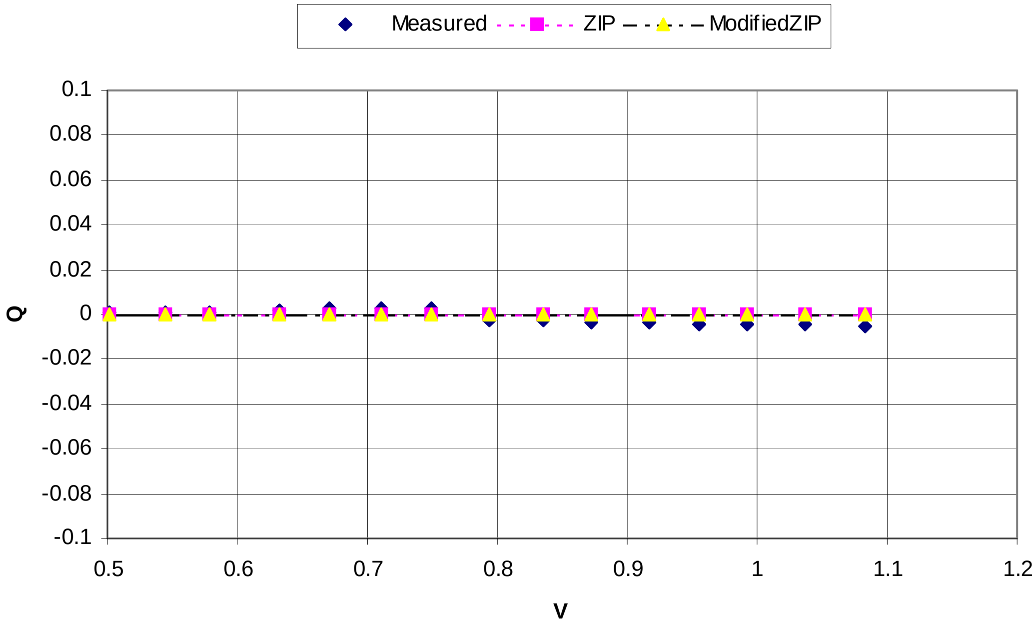
13.2 Device 13: Q-V



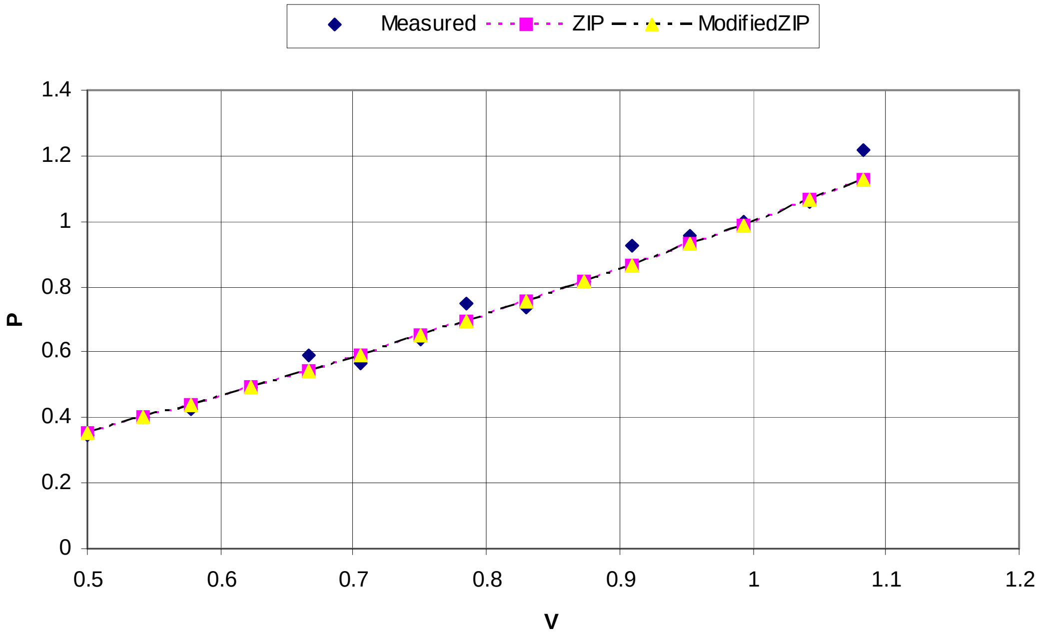
14.1 Device 14: P-V



14.2 Device 14: Q-V



15.1 Device 15: P-V



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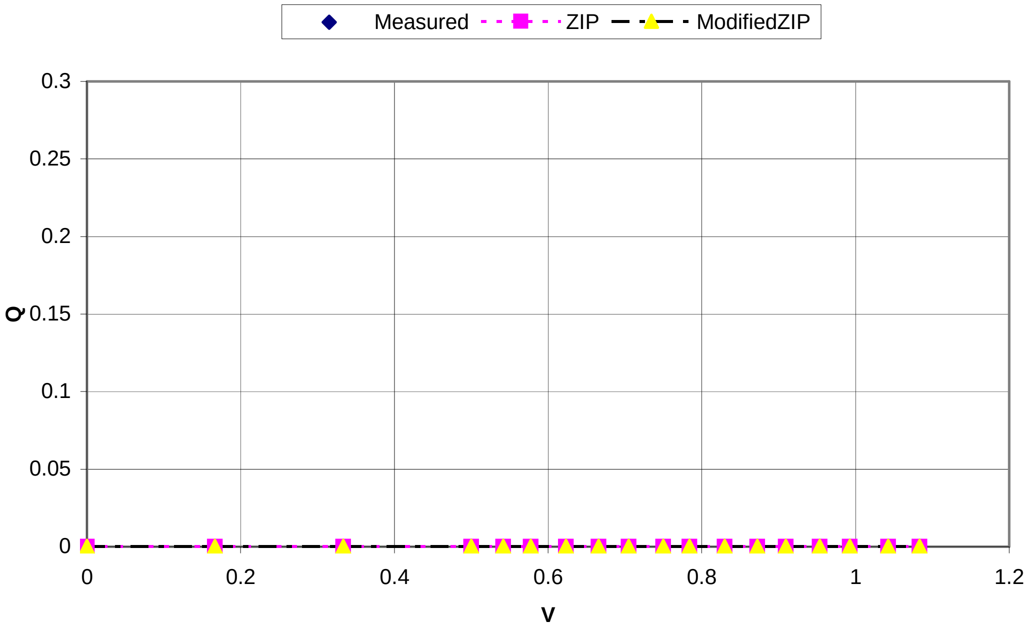
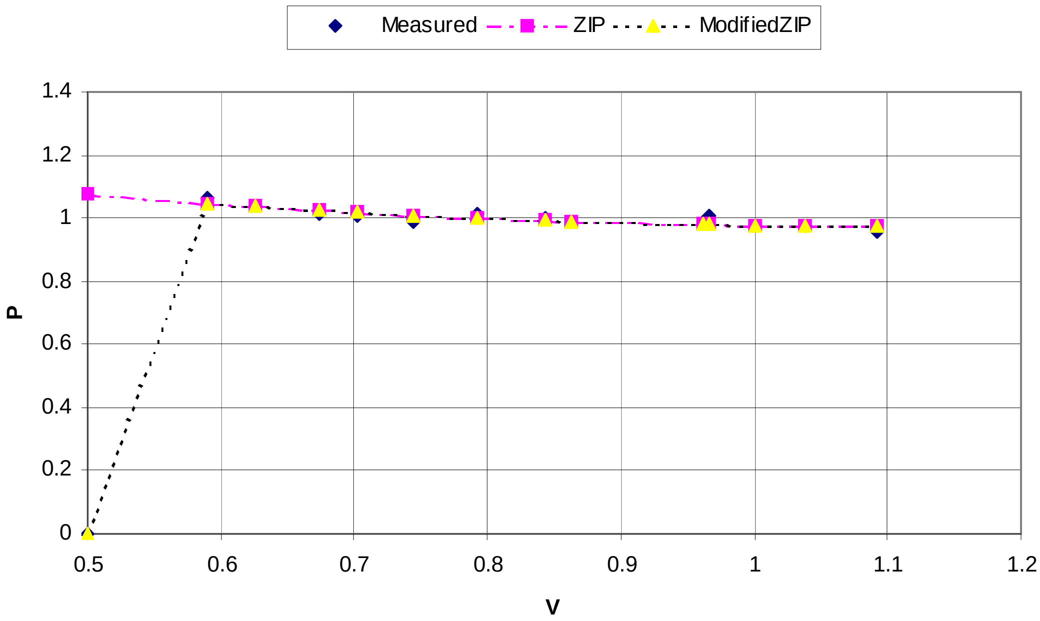
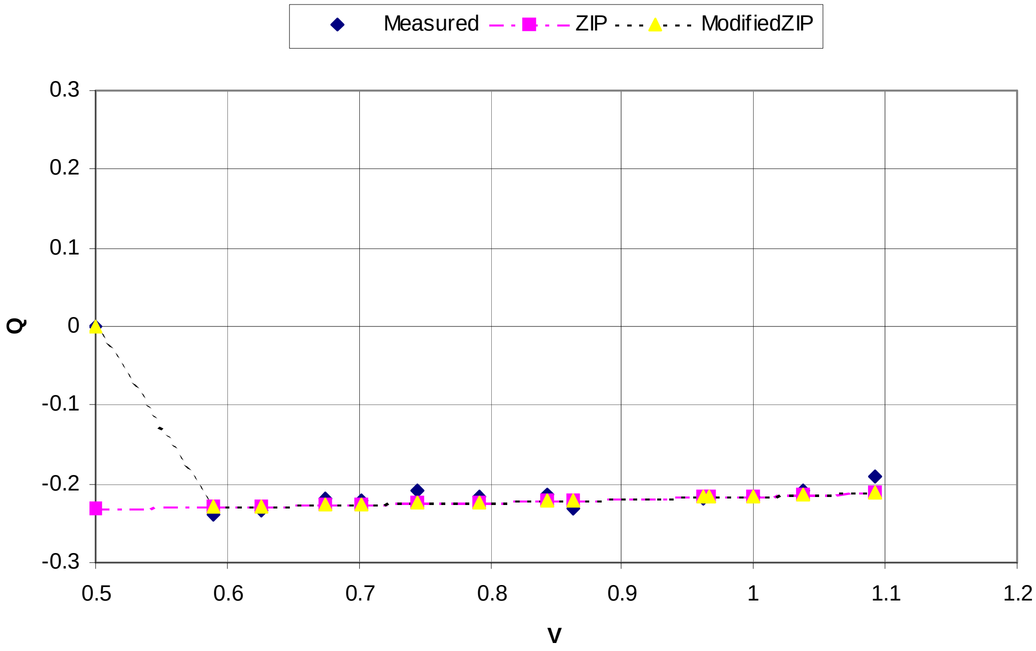


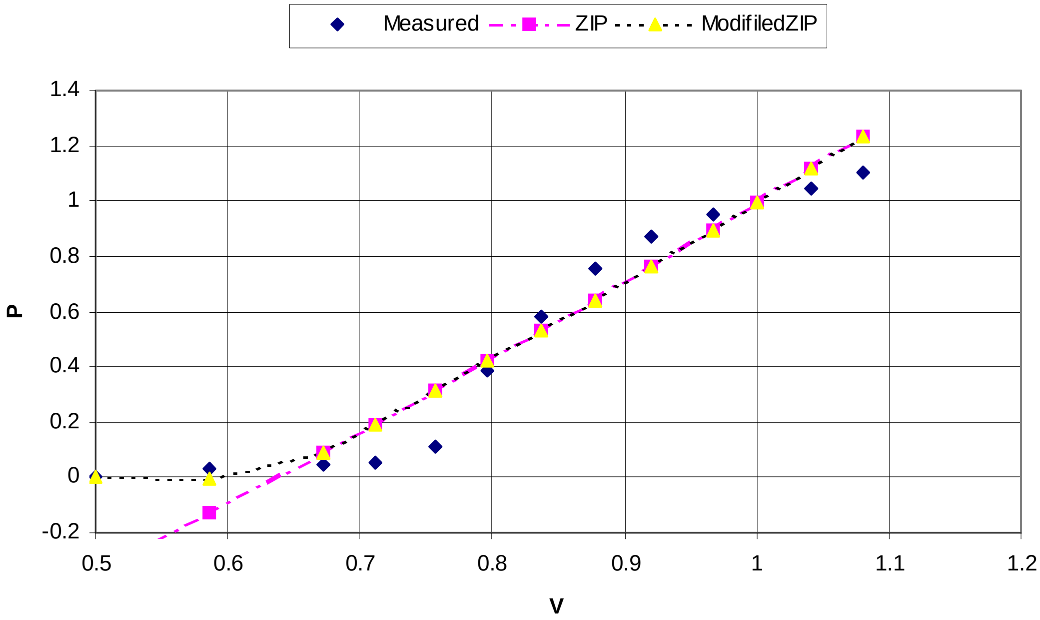
16.1 Device 16: P-V



16.2 Device 16: Q-V



17.1 Device 17: P-V



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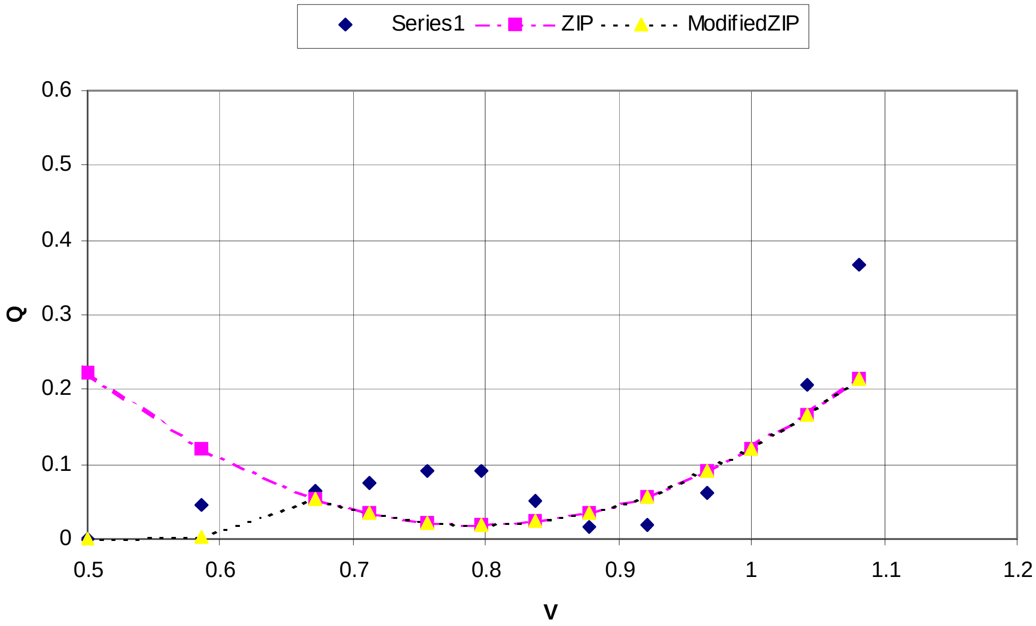
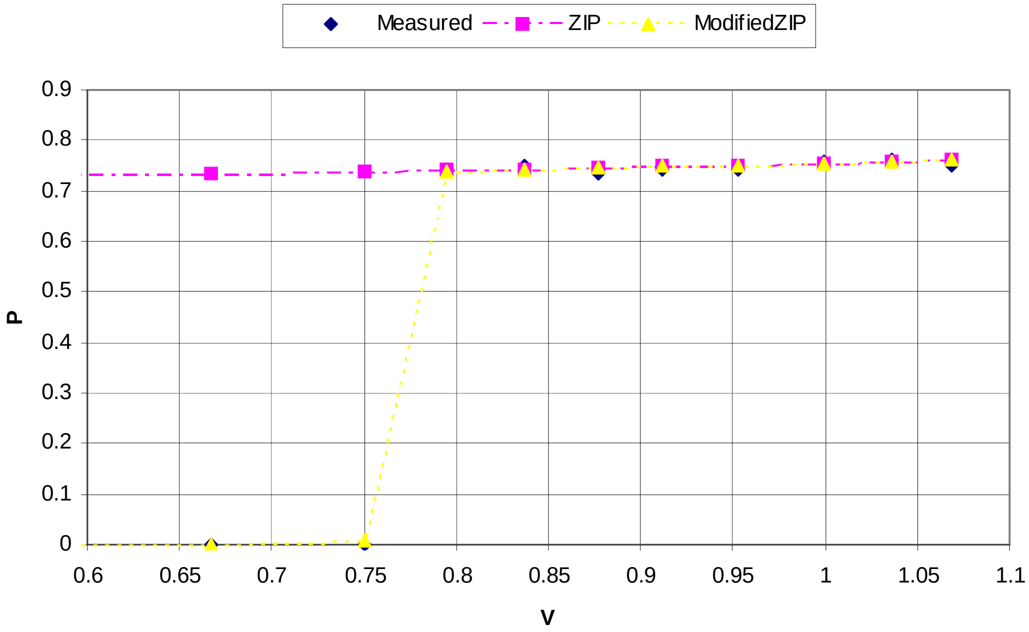
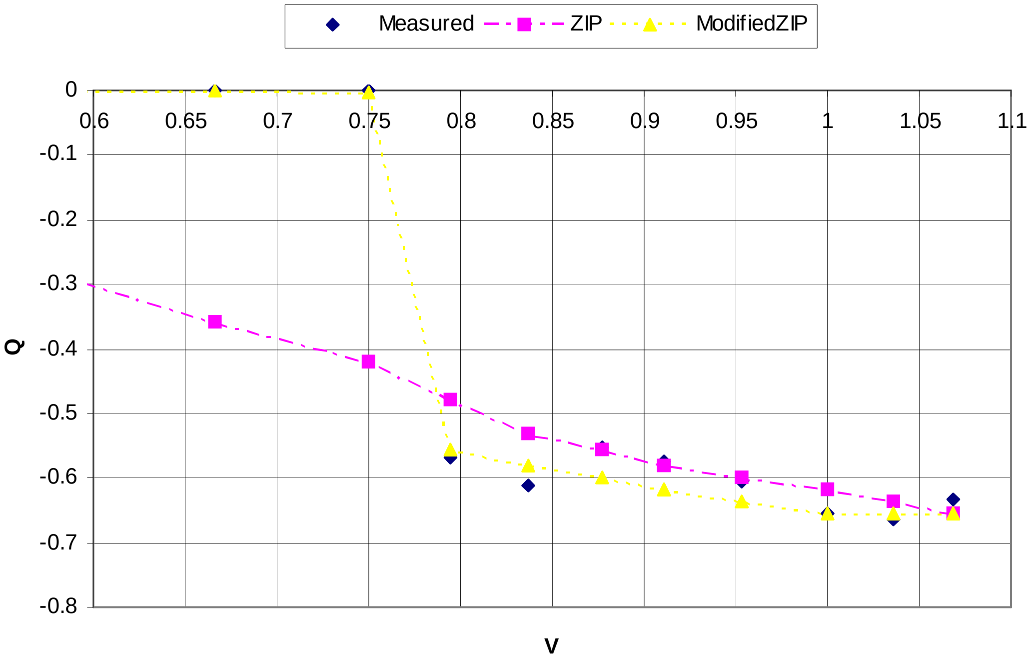


18.1 Device 18: P-V



18.2 Device 18: Q-V



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