# Feeder Performance Analysis with Distributed Algorithm

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## ABSTRACT

How to evaluate the performance of an electric power distribution system unambiguously and quantitatively is not easy. How to accurately measure the efficiency of it for a whole year, using real time hour-by-hour Locational Marginal Price data, is difficult. How to utilize distributed computing technology to accomplish these tasks with a timely fashion is challenging.

This thesis addresses the issues mentioned above, by investigating feeder performance analysis of electric power distribution systems with distributed algorithm.

Feeder performance analysis computes a modeled circuit's performance over an entire year, listing key circuit performance parameters such as efficiency, loading, losses, cost impact, power factor, three phase imbalance, capacity usage and others, providing detailed operating information for the system, and an overview of the performance of every circuit in the system.

A diakoptics tearing method and Graph Trace Analysis based distributed computing technology is utilized to speed up the calculation. A general distributed computing architecture is established and a distributed computing algorithm is described.

To the best of the author's knowledge, it is the first time that this detailed performance analysis is researched, developed and tested, using a diakoptics based tearing method and Graph Trace Analysis to split the system so that it can be analyzed with distributed computing technology.

***To my beloved parents***

***Guoqing Wang and Daogui She***

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# CHAPTER 1 Introduction

## 1.1 Overview

In 1882, the first electric power station, Pearl Street Electric Station in New York City, went into operation, symbolizing the birth of the electric utility industry [1]. Since then, this industry has expanded remarkably with generation stations and transmission and distribution networks spreading across the whole country as energy is expected to be increasingly converted to electricity [2].

Figure 1.1 illustrates the electric power system and its major systems, including generation system, transmission system and distribution system.

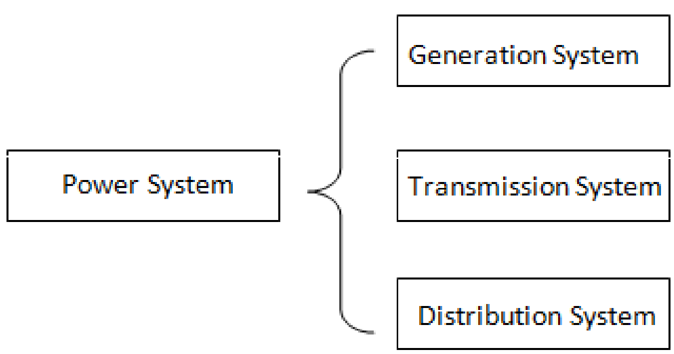


Figure 1.1 Electric Power System

In past years, the analysis of the high-voltage transmission systems drew the major attention of researchers and engineers in the electric power industry while little effort was put into the analysis of the distribution system [3], especially the detailed performance analysis of such systems.

It is reported in [4] that the electric power distribution system can account for up to 60 percent of the total capital budget and 20 percent of the operating cost, and the distribution system can be 80 percent larger than the transmission system [5]. So, it is critical for the electric utility industry to understand the overall performance of the electric power distribution system as the analysis of these systems has been a very important part of the overall planning of power systems. A viable and optimized plan can not only bring great social benefits by assuring that the growing demand for electricity of customers is satisfied, but also generate vast economic benefits by dramatically reducing the cost, with the most conservative estimate by 5 to 10 percent [4].

In [3], the author points out that distribution planners must accomplish the task of how to identify the goals for their system by clarifying what exactly constitutes "satisfactory performance" and how is that measured both unambiguously and quantitatively. What is more, a reasonable performance analysis can also help planners to target the best design from among the thousands or even tens of thousands of feasible designs that might work for their system and fully exploit every opportunity for savings or improvement as it can be a truly daunting task considering the increasing cost of additions and modifications and the limitation of resources.

Electric power distribution systems are complicated combinatorial entities, consisting of hundreds of thousands of individual circuit elements. By taking advantage of modern computational tools which have the ability to accurately model the operating characteristics of unbalanced three-phase distribution feeders, it is possible to conduct the analysis of electric power distribution system in a more detailed manner.

Various computer programs have been developed to assist engineers in electric power system analysis, including load estimation, power flow, capacitor design, phase balancing and reconfiguration analysis, etc. However, detailed performance analysis that takes into account hourly load variations of electrical power distribution systems has never been conducted. Thus, feeder performance analysis, which can analyze and evaluate the efficiency of electric power distribution systems over 8760 hours for non-leap years (8784 hours for leap years), using real time hour-by-hour Locational Marginal Prices data, is to be investigated here.

As extensive computation on the electric power distribution model is needed in order to accomplish feeder performance analysis, distributed computation technology could be utilized to speed up the computation, considering the fact that there exist points in the power distribution system which can decompose the whole system into several independent subsystems naturally. With distributed computation technology, multiple autonomous computers and storage devices as well as databases are organized together to interactively co-operate with each other to achieve a common goal.

## 1.2 Challenges in Feeder Performance Analysis with Distributed Computation

The challenges in feeder performance analysis with distributed computation are summarized as the following:

- Modeling

To have a proper model of an electric power distribution system is not an easy task. There are three aspects in terms of a proper model.

- ✓ The model reflects the real world, considering all the important attributions of the system. In electric power distribution systems, this means the system topology information, component configuration information, system load information [6], and power flow information.
- ✓ The model cannot be too complicated by considering every possible attribution of the system.
- ✓ The volume of data involved for modeling the electric power distribution system is huge, and how to prepare the correct data is an intimidating task. Garbage in, garbage out would be one of most unavoidable problems if the data itself is incorrect. Actually, as indicated in [7], there is very limited actual data about the system for modeling and analysis due to the fact that the distribution system is designed to operate without much monitoring and control. Fortunately, the smart grid technology arising recently brings hope [8].

This thesis is not dedicated to solving the modeling problem of electric power distribution systems. However, without a proper model, it is not even possible to conduct the detailed performance analysis of the electrical power distribution system.

- Computation Time

Modeling of an electrical power distribution system requires large amounts of computer memory, and it is typically time consuming to conduct computation on the entire model

- Generality

Different utilities usually have different system topology structures, component configurations and particularly, data information. For example, Locational Marginal Price is a very important data source in order to evaluate the cost of the operation of electric power distribution systems. However, the format for the LMP data varies among Independent System Operators (ISOs) [9] [10]. How to conduct performance analysis on electric power distribution systems operated by different utilities needs to be addressed.

## 1.3 Literature Review

A literature search has been performed in the areas listed below:

- Computer –Aided analysis of electric power distribution systems
- Distributed Computing

### 1.3.1 Computer-Aided Analysis of Electric Power Distribution Systems

Various innovative computer-aided analysis of electrical power distribution systems have been researched and implemented. Computer-aided tools can be categorized into three groups as follows:

- Modeling tools
- Analysis tools
- Design tools

Modeling tools provide the computer software framework for electric power distribution analysis. In papers [11]- [18], an Integrated System Model (ISM) which aims to tie the various utility data systems, including Geography Information System (GIS), Supervisory Control and Data Acquisition (SCADA) system, billing system, etc., are discussed. The concept of integrated modeling considers using results from multiple, fundamental analysis applications. The fundamental architecture, programming data structures and algorithms are addressed in [19]-[21], especially Graph Trace Analysis (GTA), a multidiscipline approach that uses generic algorithms and a common model-based analysis framework.

Basic analysis tools for electric power distribution systems are intended to predict or evaluate the key attributions of the system such as the load, impedance, voltage, currents, real and reactive power flows, efficiency, etc. Analysis tools are usually built on top of the modeling tool. The most fundamental analysis tools include load estimation, impedance analysis, and power flow analysis. Other analysis tools may include, but are not limited to, fault analysis, flicker analysis, reliability analysis, phase prediction, harmonic analysis and feeder performance analysis. In [22], load estimation analysis is conducted by using load research data to calculate the diversity factors and KWHR-to-peark-KW conversion factors, which aims to predict the time at which the daily peak KW demand, for a specific class of customer, will occur. It is suggested in this paper that one of the most efficient ways of estimating the peak load is by dividing the customers into classes based on their usage patterns. Cable impedance analysis is studied in [23] by comparing approximate impedance calculations used by utilizes in distribution networks with exact calculations. The ISM power flow analysis as described in [24] presents a sweep-based, multi-phase power flow method for solving general distribution networks that can be heavily meshed and include transformers in the loops. Furthermore more, it is demonstrated that it can solve both IEEE standard transmission and distribution problems, which are solved with different algorithms traditionally. Fault analysis and reliability analysis based on the framework proposed in [11]-[18] are described in [25], [26] and [27]. For the phase prediction analysis, a low cost, algorithmic approach for estimating the phasing of laterals is presented in [28].

The design tools are oriented to help utilities make decisions about how to build or upgrade the system. Common design analysis includes reconfiguration, phase balancing, capacitor design, and protection design, to name a few. Authors in [29] introduce and compare four algorithms by which the reconfiguration for restoration of an arbitrary number of interdependent critical infrastructure systems can be achieved. An object-oriented analysis of distribution system reconfiguration for power restoration is discussed in [30] and a heuristic, nonlinear constructive method is described in [31]. Phase balancing analysis, which can recommend how to connect single and double phase laterals to the three phase spine, is explained in [32]. Literatures related to the design issues of how to optimally locate and size capacitor banks is found in [33]-[35].

### 1.3.2 Distributed Computing

The literature review about the topic of distributed computing is organized as follows:

- Traditional theoretical foundations of distributed computing
- Distributed computing in analysis of electric power systems
- Diakoptics: the method of tearing

In terms of theoretical foundations of distributed computing, people usually talk about distributed algorithms [36]. A distributed algorithm is an algorithm designed to run on distributed systems. Since 1960s, researchers have conducted research on different topics concerning distributed computing algorithms.

✓ Mutual exclusion

Paper [37] presented the first solution to the mutual exclusion problem, which is considered as the start of the field of concurrent and distributed algorithms [38]. M. Crummey and M.L.Scotty proposed a practical mutual exclusion algorithm in [39], which generates O(1) remote references per lock acquisition, independent of the number of processors attempting to acquire the lock. This algorithm is recognized as one of the most influential and practical mutual exclusion algorithms [40].

✓ Consensus

In [41] and [42] the authors introduced and studied the Byzantine fault tolerance model, pointing out that agreement between computers cannot be made if at least 1/3 of the nodes are faulty. It is shown in [43] that it is impossible to achieve distributed consensus when one faulty node exists in an asynchronous system. Paper [44] introduced the concept of partial synchrony in a distributed system and further studied the consensus problem in the partial synchronous system.

Distributed computing technology has also been applied in the analysis of electric power distribution systems, especially for the power flow calculation, which usually requires extensive computation. In [45], distributed algorithms for both radial and looped load flows for unbalanced, muti-phase electric power distribution systems are proposed, implemented and tested. An optimized contingency analysis program running in a distributed computation environment is presented in [46].

The Diakoptics method was presented by Gabriel Kron in the book entitled ‘Diakoptics: The Piecewise Solution of Large-Scale Systems’ in 1963 [47]. The terminology diakoptics originated from the Greek words “kopto” which means to tear and “dia” which means systems. Hence diakoptics can be interpreted as system-tearing .

The main idea of diakoptics is to decompose physical systems, typically electrical circuits, into subsystems with the particular property that the subsystems overlap on their boundaries. Each subsystem can be analyzed and solved separately as if the other subsystems were non-existent. Then the solution to each subsystem is recombined to give an exact overall solution [48].

The original purpose of diakoptics was not to distribute computing, but to facilitate the solution of complex problems that cannot be solved in one piece .When there were no digital computers with the capability to handle the calculation of large and complicated electrical circuits in one piece, Diakoptics was an effective way to approach the overwhelmingly difficult task. However, with the development of computer technology, especially computer network technology, Diakoptics, the method of tearing provides a natural way to make good use of distributed computing for systems with natural points of separation [49]. In particular, this technique divides the computation into relatively independent local parts, which may be done without any interprocessor communication, and thus the mutual exclusion and consensus problems are solved naturally at the same time.

## 1.4 Thesis Outline

The remainder of this thesis consists of three chapters.

Chapter two explains in detail the feeder performance analysis of electric power distribution systems, which computes a circuit's performance parameters over an entire year, listing key circuit performance parameters for all hours of the year. Power flow, the foundation of feeder performance analysis, is introduced briefly. Locational Marginal Prices analysis is also explained. A case study of a real word electric power distribution system is presented.

Chapter three discusses feeder performance analysis with distributed computation. The disturbed computation architecture is illustrated and a Graph Trace Analysis based description of the operation of the distributed computing algorithm is presented. A case study of a real world electric power distribution system is then conducted.

Chapter four presents conclusions and outlines possible further research.

# CHAPTER 2 Feeder Performance Analysis

## 2.1 Introduction

Electric power distribution systems comprise the parts of an electrical power system between the subtransmission system and the consumers' service. The goal is to transport the power from the transmission system to the customer efficiently, effectively, economically, as well as reliability.

By taking advantage of modern computing technology, it is possible to establish a detailed model for the electric power distribution system. Based on the model, feeder performance analysis of an electric power distribution system calculates feeder energy losses and their cost, three phase imbalance, as well as capacity usage, etc. It can measure the efficiency of feeders over 8760 hours for non-loop years (8784 hours for leap years), using real time hour-by-hour Locational Marginal Pricing (LMP).

Incorporated with phase balancing analysis and other design tools, it can evaluate system improvement projects with concrete cost data. It is also possible to use feeder performance analysis to select the most economical designs.

This chapter first introduces the Distributed Engineering Workstation, the platform in which feeder performance analysis is developed, and the overall architecture of feeder performance analysis. Then, Locational Marginal Pricing (LMP) analysis is discussed, followed by a brief introduction of power flow analysis. After that, the feeder performance analysis is explained in detail and using feeder performance to evaluate alternative feasible designs is illustrated. A case study of feeder performance analysis using a real world electrical power distribution system is conducted. Finally, the challenges of feeder performance analysis are summarized.

## 2.2 Feeder Performance Analysis Implementation

Feeder Performance analysis is built inside the Distributed Engineering Workstation (DEW). DEW is a multidiscipline, open-architecture environment, providing researchers the ability to conduct distribution systems engineering studies. The open architecture framework of DEW supports future expansion, which allows for applications to utilize the results from other applications [12]. An Application Programmer Interface (API) [17] is supplied for integrating application modules into the framework without affecting the operation of the other parts of DEW via the use of dynamic link libraries (DLLs).

The Feeder Performance DEW analysis is built upon Power Flow analysis by requesting results from the power flow. Figure 2.1 provides an overview of the software architecture of the Feeder Performance application.

In Figure 2.1, Locational Marginal Pricing data is obtained from the internet first. This data is then converted to the standard DEW Locational Marginal Price data format through an LMP data analysis program. Using hourly Locational Marginal Price information, the Feeder Performance analysis can measure the efficiency of feeders over 8760 hours per year.

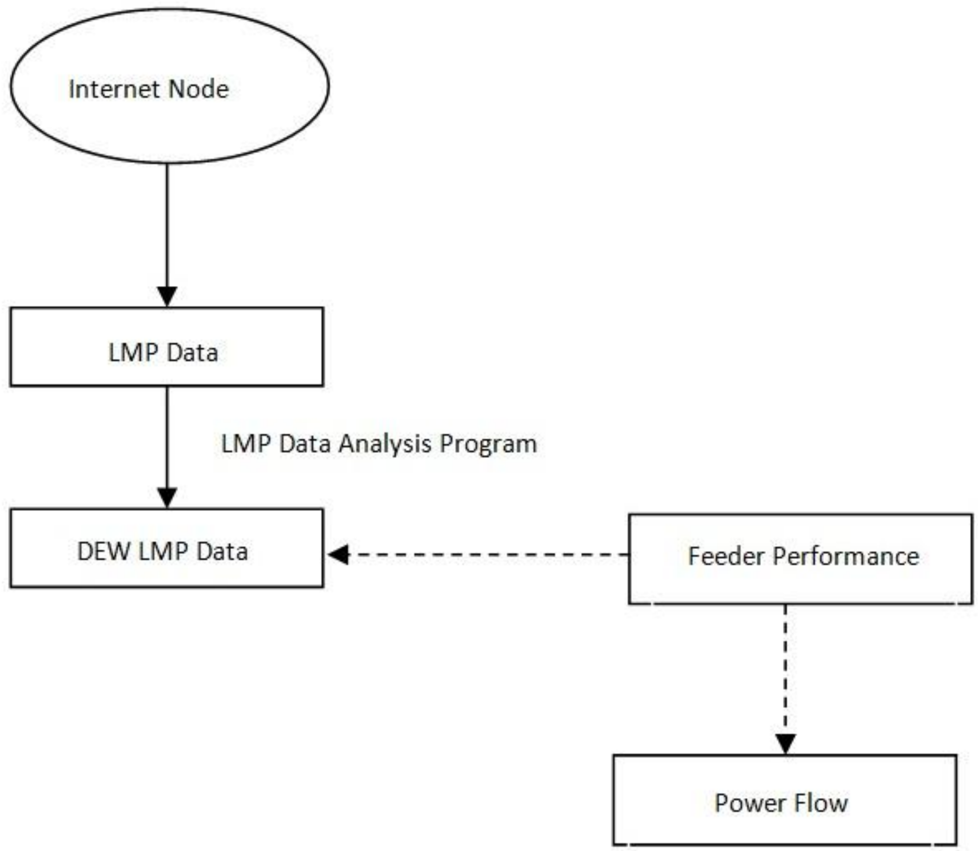


**Figure 2.1 Feeder Performance Analysis Overview**

For the performance evaluation of the electric power distribution system, the equipment load, power supply, power factor, losses, voltage values, costs and others are of interest to distribution engineers. Although the power flow analysis can supply the basic information of these attributes, the power flow analysis results are not enough to obtain a complete view of the performance of the whole system. By incorporating the power flow analysis together with the Locational Marginal Price data, feeder performance analysis of the power distribution system calculates feeder energy losses and their associated loss cost along with summary results concerning three-phase imbalance and equipment capacities. Engineers using feeder performance analysis with actual energy cost data generated by power flow analysis can evaluate system improvement projects with concrete cost benefits that derive from the time varying load pattern and costs and not just peak load values.

### 2.2.1 Locational Marginal Pricing (LMP) Data Analysis

LMP, the abbreviation of Locational Marginal Price, is the theoretical price of electricity at each node on the network, in other words, the price of energy at a location. As described in [50], a more formal definition of LMP is: "the marginal cost of supplying, at least cost, the next increment of electric demand at a specific location (node) on the electric power network, taking into account both supply (generation/import) bids and demand (load/export) offers and the physical aspects of the transmission system including transmission and other operational constraints."

It has the following characteristics [51]:

- LMP is the cost of supplying an increment of load at a particular location.
- LMPs are usually produced as a result of economic dispatch, which is the "*operation of generation facilities to produce energy at the lowest cost to reliabily serve consumers, recognizing any operational limits of generation and transmission facilities*" [52].
- Bid-based : In general, by matching offers from generators to bids from consumers at each node, a supply and demand equilibrium price is established, and the LMP in the day-ahead market is determined [53]
- Security constrained: the LMP calculation is subject to the constraints that exist on the transmission network, which may be caused when a potential overload occur due to a contingent event

The LMP data is accessible from websites maintained by the Independent System Operators (ISO). The format for the LMP data varies by different ISOs. For example, the format of LMP data supplied by New York ISO (NYISO) [9] is different from the one released by the Midwest ISO (MISO) [10]. The NYISO records LMP data at intervals varying from one to ten minutes, while the LMP data provided by MISO is on a constant hourly interval.

It is observed that the LMP data format maintained by MISO is relatively clear, well organized and easy to understand. Thus, it is suitable to be the prototype of a standard LMP data format.

The MISO LMP data format is shown in Table 2.1

**Table 2.1 MISO LMP Data Format**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MARKET_DAY | NODE | TYPE | VALUE | HE1 | HE2 | … | HE23 | HE24 |

- MARKET_DAY : the date
- NODE: the location
- TYPE: the type of the node
- VALUE: HE1 – HE24 represent the LMP value
- HE(X): the LMP value between hour (X-1) and hour X for the given date

For nonstandard LMP data (such as the NYISO data), formula 2.1 is utilized to convert it to the standard format with the price specified at hourly intervals.

$$L_r = \frac{1}{N}\sum_{i=1}^{i=N} L_{r_i} \qquad (2.1)$$

where $L_r$ is the LMP value for node $r$, $N$ denotes the number of LMP records in the hour under consideration for node $r$, and $L_{r_i}$ represents the LMP value for node $r$ between time point $i-1$ and $i$.

The LMP Data Analysis Program flow chart is shown in Figure 2.2.

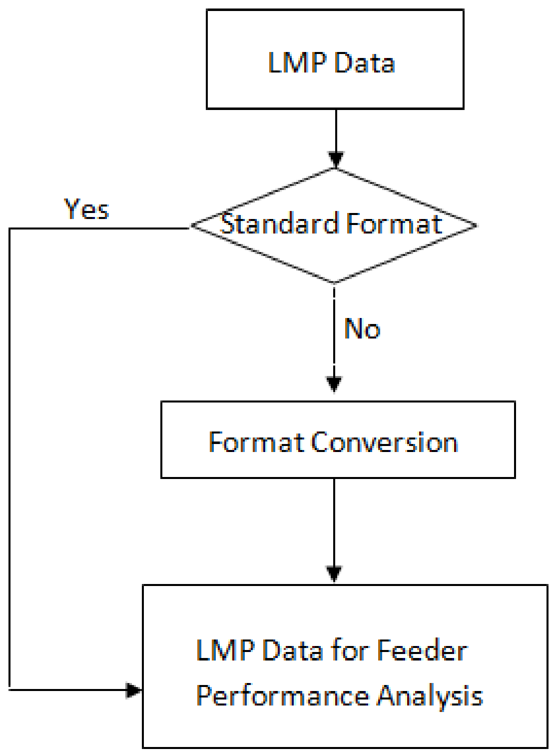


**Figure 2.2 LMP Data Analysis**

Table 2.2 shows a sample of the nonstandard LMP data and Table 2.3 shows a sample of the selected standard format for the LMP data.

**Table 2.2 Sample Nonstandard LMP Data**

| Time Stamp | Name | PTID | LBMP ($/MWHr) | Marginal Cost Losses ($/MWHr) | Marginal Cost Congestion ($/MWHr) |
|---|---|---|---|---|---|
| 01/01/2009 00:05:00 | CAPITL | 61757 | 81.04 | 4.66 | 0 |
| 01/01/2009 00:05:00 | CENTRL | 61754 | 76 | -0.38 | 0 |
| 01/01/2009 00:05:00 | DUNWOD | 61760 | 82.34 | 5.96 | 0 |
| 01/01/2009 00:05:00 | GENESE | 61753 | 71.49 | -4.89 | 0 |
| 01/01/2009 00:05:00 | H Q | 61844 | 75.85 | -0.53 | 0 |
| 01/01/2009 00:05:00 | HUD VL | 61758 | 82.11 | 5.73 | 0 |
| 01/01/2009 00:05:00 | LONGIL | 61762 | 84.25 | 7.87 | 0 |
| 01/01/2009 00:05:00 | MHK VL | 61756 | 79.51 | 3.13 | 0 |
| 01/01/2009 00:05:00 | MILLWD | 61759 | 82.41 | 6.03 | 0 |
| 01/01/2009 00:05:00 | N.Y.C. | 61761 | 82.49 | 6.11 | 0 |
| 01/01/2009 00:05:00 | NORTH | 61755 | 75.92 | -0.46 | 0 |
| 01/01/2009 00:05:00 | NPX | 61845 | 81.19 | 4.81 | 0 |
| 01/01/2009 00:05:00 | O H | 61846 | 65.08 | -11.3 | 0 |
| 01/01/2009 00:05:00 | PJM | 61847 | 71.65 | -4.74 | 0 |
| 01/01/2009 00:05:00 | WEST | 61752 | 67.22 | -9.17 | 0 |

**Table 2.3 Sample of Standard LMP Data Format**

| MARKET_DAY | NODE | TYPE | VALUE | HE01 | ... | HE23 | HE24 |
|---|---|---|---|---|---|---|---|
| 01/01/2009 | CAPITL | Gennode | LMP | 64.1042 | ... | 53.0508 | 46.1825 |
| 01/01/2009 | CENTRL | Gennode | LMP | 60.2042 | ... | 49.4817 | 43.2108 |
| 01/01/2009 | DUNWOD | Gennode | LMP | 65.1625 | ... | 54.5292 | 47.4067 |
| 01/01/2009 | GENESE | Gennode | LMP | 57.1575 | ... | 48.28 | 41.0917 |
| 01/01/2009 | H Q | Gennode | LMP | 60.0267 | ... | 49.7292 | 53.64 |
| 01/01/2009 | HUD VL | Gennode | LMP | 64.9658 | ... | 54.3842 | 47.275 |
| 01/01/2009 | LONGIL | Gennode | LMP | 66.9475 | ... | 64.5958 | 60.9917 |
| 01/01/2009 | MHK VL | Gennode | LMP | 63.0283 | ... | 52.1817 | 45.2758 |
| 01/01/2009 | MILLWD | Gennode | LMP | 65.2217 | ... | 54.5992 | 47.4467 |
| 01/01/2009 | N.Y.C. | Gennode | LMP | 65.3 | ... | 54.84 | 47.6608 |
| 01/01/2009 | NORTH | Gennode | LMP | 59.9842 | ... | 49.9225 | 43.3092 |
| 01/01/2009 | NPX | Gennode | LMP | 64.2733 | ... | 53.3692 | 58.16 |
| 01/01/2009 | O H | Gennode | LMP | 52.6083 | ... | 29.7858 | 24.6 |
| 01/01/2009 | PJM | Gennode | LMP | 56.6192 | ... | 44.4358 | 52.13 |
| 01/01/2009 | WEST | Gennode | LMP | 54.1017 | ... | 32.2983 | 33.9483 |

### 2.2.2 Power Flow Analysis

Power flow analysis (also called load flow analysis) is applied to a power system model to compute the voltage magnitude and angle at each bus under steady-state conditions. Real and reactive power flows for all the equipment interconnecting the buses, as well as equipment losses, are computed [1].

As the characteristics of transmission networks, which are typically three-phase and mostly operate balanced, are different from the characteristics of distribution networks, which can have any number of phases and are usually radial and unbalanced, the power flow of transmission networks is usually distinct from that of distribution networks.

The power flow algorithm described in [24], solves both IEEE standard transmission and distribution systems. Building on the analysis results of the power flow, the feeder performance analysis is developed.

The power flow analysis results which are used in feeder performance analysis are as follows:

- Voltage magnitude at the end of component, in kV
- Voltage phase angle, in degrees
- Current magnitude at the start of component, in A
- Current phase angle, in degrees
- Power flow through a component, in kW
- Reactive power flow through a component, in kVar
- Power Factor associated with complex power flow through a component, in percent

- Phase imbalance calculated in terms of power flow imbalance
- Customer level voltage, in volts
- Calculated load for line/cable section, in kW
- Percentage of Available Capacity, in percent

### 2.2.3 Performance Analysis

The Feeder Performance application computes a modeled circuit's performance parameters over an entire year, listing key circuit performance parameters for all hours of the year. To the best of our knowledge, it is the first time that this detailed performance analysis is investigated.

Figure 2.3 illustrates the flow chart of feeder performance analysis.

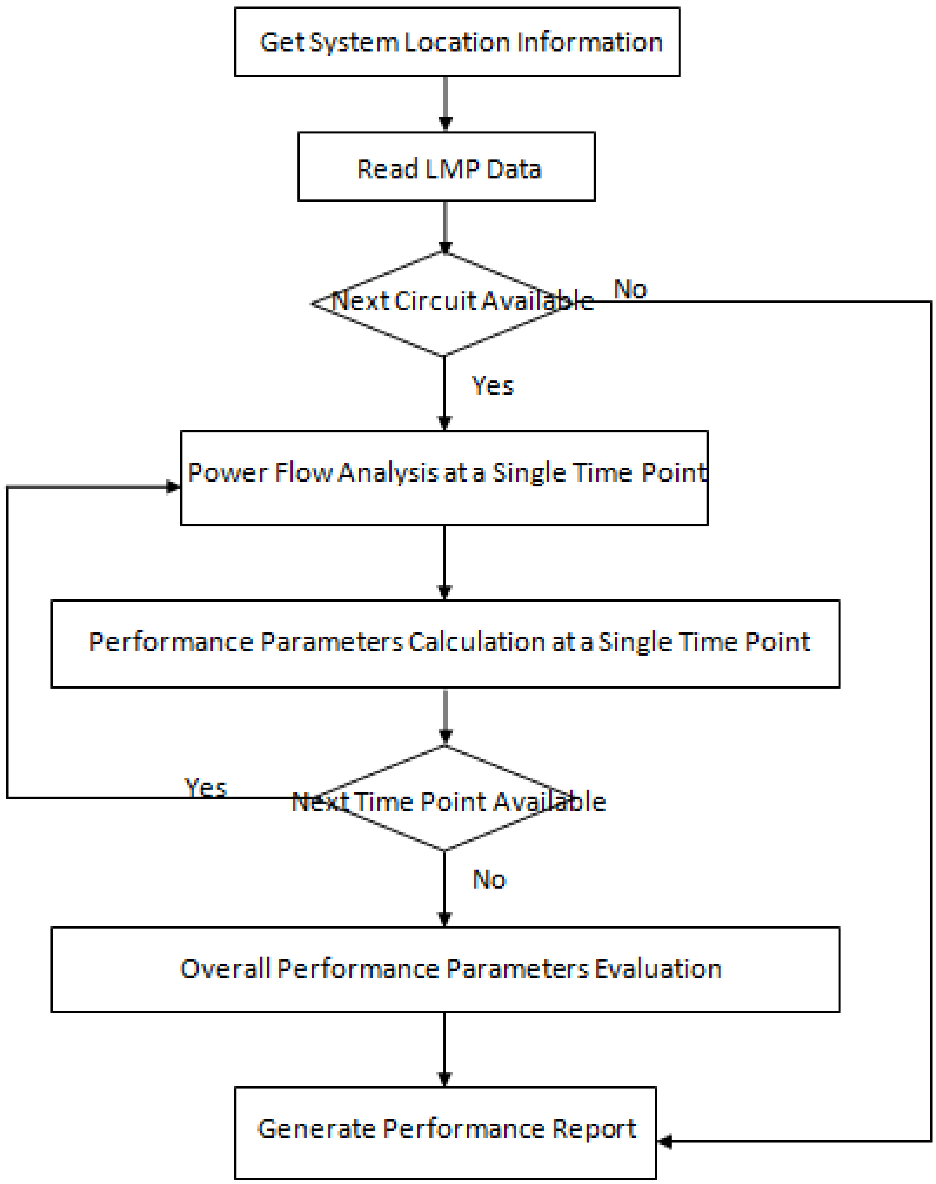


**Figure 2.3 Feeder Performance Analysis Flow Chart**

The performance analysis results include an hourly based report for every circuit and a summary report for all circuits in the system.

The hourly based feeder performance analysis results are:

- The time for the analysis results

- The total circuit loading, in kWh
- The total circuit losses, in kWh
- The applicable LMP for the associated circuit and time point, in dollars/mWh
- The cost impact of circuit losses, in dollars
- The efficiency for the circuit, in percent
- Circuit losses of phase A, in kWh
- Circuit losses of phase B, in kWh
- Circuit losses of phase C, in kWh
- The cost impact of circuit losses of phase A, in dollars
- The cost impact of circuit losses of phase B, in dollars
- The cost impact of circuit losses of phase C, in dollars
- Power factor of phase A, in percent
- Power factor of phase B, in percent
- Power factor of phase C, in percent
- Maximum power factor deviation, which represents the worst performing phase's power factor deviation from unity, in percent
- Phase imbalance calculated in terms of power flow imbalance, in percent
- Phase A current at start of circuit, in Amps
- Phase B current at start of circuit, in Amps
- Phase C current at start of circuit, in Amps
- Maximum phase imbalance, which represents the maximum imbalance for the three-phase portion of circuit only, in Amps

- Smallest single phase capacity, which represents the minimum available capacity over all single (and two) phase primary lines and cables, in percent
- Unique Identifier (UID)  of the component with the smallest single phase capacity, which can be used to locate the component in the model
- Smallest three phase capacity, which represents the minimum capacity over all three phase primary lines and cables, in percent
- UID of  the component having the smallest three phase capacity, which can be used to locate the component in the model
- Smallest customer level  voltage of phase A, in volts
- UID of the component with the smallest customer level voltage of phase A, providing the location of that component.
- Smallest customer level  voltage of phase B, in volts
- UID of the component with smallest customer level voltage of phase B, which can be used to locate the component in the model
- Smallest customer level  voltage of phase C, in volts
- UID of the component with smallest customer level voltage of phase C, which can be used to locate the component in the model.

The loading for circuit $\mathrm{k}$ at time t is represented by $\mathrm{CL_{kt}}$ and is calculated by formula 2.2

$$\mathrm{CL_{kt}} = \sum_{\mathrm{i}}(\mathrm{PF_{kti}} - \mathrm{CLoss_{kti}}) \tag{2.2}$$

,where $\mathrm{PF_{kti}}$ is the phase i power flow and $\mathrm{CLoss_{kti}}$ is the phase i circuit losses for circuit $\mathrm{k}$ at time point t, $\mathrm{i} \in \{\mathrm{A, B, C}\}$.

The total losses for circuit $\mathrm{k}$ at time t is represented by $\mathrm{CLoss_{kt}}$ and is calculated by formula 2.3.

$$\mathrm{CLoss_{kt}} = \sum_{\mathrm{i}}(\mathrm{CLoss_{kti}}) \qquad (2.3)$$

The cost impact of losses occurred in circuit $\mathrm{k}$ for the associated time point t, $\mathrm{Cost_{kt}}$ ,is given by formula 2.4.

$$\mathrm{Cost_{kt}} = \mathrm{L_r} * \mathrm{CLoss_{kt}} \qquad (2.4)$$

, where $\mathrm{L_r}$ is the LMP price for circuit $\mathrm{k}$ as calculated in formula 2.1. Circuit $\mathrm{k}$ needs to be in the area of node $\mathrm{r}$.

The efficiency of the circuit $\mathrm{k}$ at time point ,$\mathrm{Eff_{kt}}$ ,is given by formula 2.5.

$$\mathrm{Eff_{kt}} = \frac{\mathrm{CL_{kt}}}{\mathrm{CLoss_{kt}} + \mathrm{CL_{kt}}} \qquad (2.5)$$

The maximum Power Factor deviation of circuit $\mathrm{k}$ at time point t, $\mathrm{MPfD_{kt}}$ ,which gives the worst performing phase's power factor deviation from unity, is determined by formula 2.6.

$$\mathrm{MPfD_{kt}} = \mathrm{Max}(100 - |\mathrm{PFactor_{kti}}|) \qquad (2.6)$$

,where $\mathrm{PFactor_{kti}}$ is the phase i power factor of circuit $\mathrm{k}$ at time point t, $\mathrm{i} \epsilon \{\mathrm{A, B, C}\}$.

The Maximum Phase Imbalance of circuit $\mathrm{k}$ at time point t, $\mathrm{MPI_{kt}}$ , showing the maximum current imbalance, is calculated from formula 2.7.

$$\mathrm{MPI_{kt}} = \mathrm{Max}(|\mathrm{Current_{kti}} - \mathrm{Current_{ktj}}|) \qquad (2.7)$$

, where $\mathrm{Current}_{\mathrm{kti}}$ and $\mathrm{Current}_{\mathrm{ktj}}$ is the phase, j current for circuit $\mathrm{k}$ at time point t, $\mathrm{i}, \mathrm{j} \in \{\mathrm{A}, \mathrm{B}, \mathrm{C}\}$ and $\mathrm{i} \neq \mathrm{j}$.

The smallest single phase capacity of circuit $\mathrm{k}$ at time point $\mathrm{t}$, $\mathrm{SSPC}_{\mathrm{kt}}$, which demonstrates the minimum available capacity from all single (and two) phase primary lines and cables is evaluated by formula 2.8.

$$\mathrm{SSPC}_{\mathrm{kt}} = \mathrm{Min}(\mathrm{SPC}_{\mathrm{kti}}) \tag{2.8}$$

, where $\mathrm{SPC}_{\mathrm{kti}}$ is the available capacity for the single phase (or two phase) component $\mathrm{i}$ in circuit $\mathrm{k}$ at time point t and

$$\mathrm{i} \in \{\text{all primary lines, cables and components with nominal primary voltage magnitude greater than 600 volts}\},$$

The smallest three phase capacity of circuit $\mathrm{k}$ at time point t, $\mathrm{STPC}_{\mathrm{kt}}$, which demonstrates the minimum available capacity from all three phase primary lines and cables in the circuit is evaluated by formula 2.9.

$$\mathrm{STPC}_{\mathrm{kt}} = \mathrm{Min}(\mathrm{STC}_{\mathrm{kti}}) \tag{2.9}$$

,where $\mathrm{STC}_{\mathrm{kti}}$ is the available capacity for the three component $\mathrm{i}$ in circuit $\mathrm{k}$ at time point t,

$$\mathrm{i} \in \{\text{all primary lines, cables and components with nominal primary voltage magnitude greater than 600 volts}\}$$

The smallest customer level phase i voltage of circuit $k$ at time point t, $\mathrm{SCustV_{kti}}$, is represented by formula 2.10.

$$\mathrm{SCustV_{kti}} = \mathrm{Min}(\mathrm{CustV_{ktij}}) \tag{2.10}$$

, where $\mathrm{CustV_{ktij}}$ is the customer level phase i voltage for the component j in circuit $k$ at time point t,

$\mathrm{i}\epsilon\{\mathrm{A, B, C}\}$, $\mathrm{j}\epsilon\{$all components with customer level voltage$\}$

The summary report results for all the circuits provide the following information for each circuit:

- Feeder name
- Annual energy loss, in kWh
- Annual loss cost, in dollars
- Annual energy supplied, in kWh
- Annual efficiency factor, in percent
- Annual phase A energy loss, in kWh
- Annual phase B energy loss, in kWh
- Annual phase C energy loss, in kWh
- Annual phase A cost, in dollars
- Annual phase B cost, in dollars
- Annual phase C cost, in dollars
- Average max phase imbalance of the circuit for the start of the circuit, in amps

- Average max power factor deviation of the circuit for the start of the circuit, in percent

The annual energy loss, annual loss cost, and annual energy supplied by circuit k for year y $AEloss_{ky}$ , $ACost_{ky}$ , $AEnergy_{ky}$ are formulated as 2.11, 2.12, 2.13 show below, respectively.

$$AEloss_{ky} = \sum_t (CLoss_{kt}) \tag{2.11}$$

$$ACost_{ky} = \sum_t (Cost_{kt}) \tag{2.12}$$

$$AEnergy_{ky} = \sum_t (CL_{kt} + CLoss_{kt}) \tag{2.13}$$

,where

$t \epsilon$ {all time points in year y (8760 hours for non leap years or 8784 hours for leap years)}

The annual phase i energy loss, annual phase i loss cost of circuit k for year y $AEloss_{kyi}$ , $ACost_{kyi}$ are given in 2.14, 2.15 shown below, respectively.

$$AEloss_{kyi} = \sum_t (CLoss_{kti}) \tag{2.14}$$

$$ACost_{kyi} = \sum_t (L_r * CLoss_{kti}) \tag{2.15}$$

,where $i \epsilon \{A, B, C\}$ ,

$t \epsilon$ {all time points in year y (8760 hours for non leap years or 8784 hours for leap years)},

$L_r$ is the LMP price for circuit k from LMP node r.

The annual efficiency factor of the circuit k at year y, $AEff_{ky}$, is given by formula 2.16

$$\mathrm{AEff_{ky}} = \frac{\mathrm{AEloss_{ky}}}{\mathrm{AEnergy_{ky}}} \tag{2.16}$$

The average max phase imbalance and the average max power factor deviation for circuit k, calculated at the start of the circuit for year y, $\mathrm{AMPI_{ky}}$ , $\mathrm{AMPfD_{ky}}$ , are evaluated in formula 2.17 and 2.18, respectively.

$$\mathrm{AMPI_{ky}} = \frac{\sum_t(\mathrm{MPI_{kt}})}{\mathrm{T}} \tag{2.17}$$

$$\mathrm{AMPfD_{ky}} = \frac{\sum_t(\mathrm{MPfD_{kt}})}{\mathrm{T}} \tag{2.18}$$

, where

$t \epsilon$ {all time points in year y (8760 hours for non leap years or 8784 hours for leap years)} ,

$\mathrm{T} = 8760$ for non leap years or $\mathrm{T} = 8784$ for leap years

## 2.3 Alternative Design Evaluation through Feeder Performance Analysis

Figure 2.4 illustrates using feeder performance to evaluate alternative feasible designs.

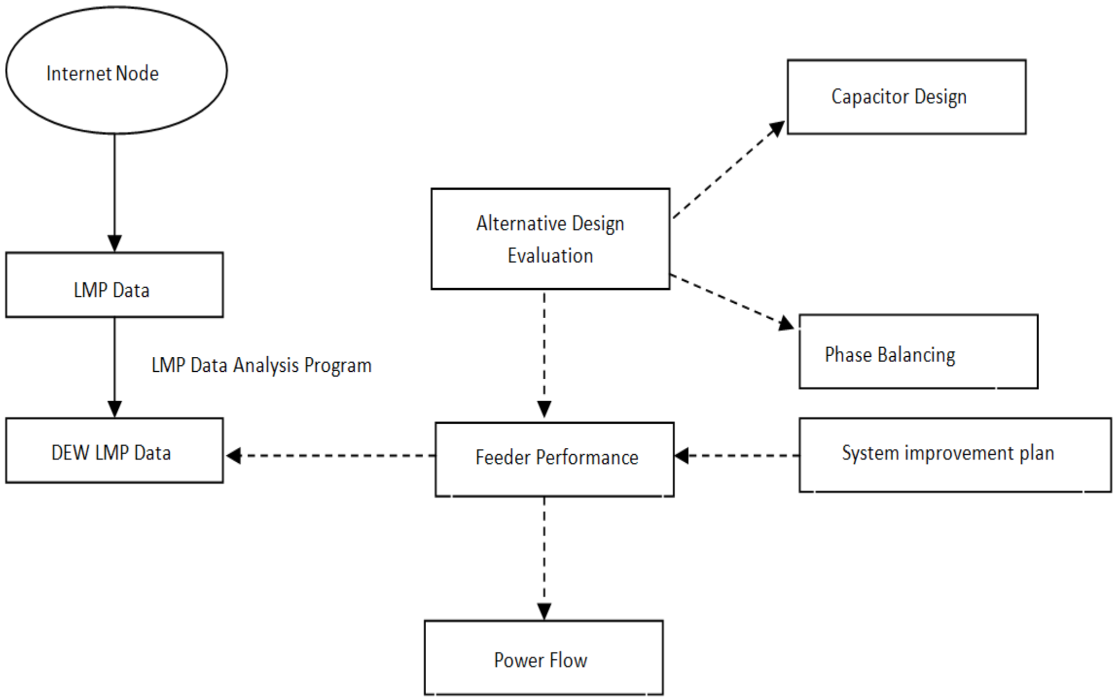


**Figure 2.4 Using Feeder Performance to Evaluate Alternative Feasible Designs**

By using feeder performance analysis on the whole electrical power distribution system model, it is possible to target the most inefficient circuit (phase), the circuit (phase) with the most loss cost, the most unbalanced circuit, the circuit with the most significant power factor derivation, and others in the electrical power distribution system. Thus it gives designers important quantified criteria to consider. The case study conducted in Section 2.4 will illustrate this in detail.

What is more, there may be many feasible designs available for designers to consider, and it is impractical to implement all the feasible designs considering the increasing cost of additions and modifications and limitation of resources. Feeder performance can help the designers choose the most economical designs via comparing the key circuit performance parameters. For example, if a circuit needing improvement has significant phase unbalancing issue while the power factor remains in an acceptable range, it is wise to do phase balancing instead of capacitor design. Regarding how to choose the most suitable design, the case study conducted as follows will provide further demonstration.

## 2.4 Feeder Performance Analysis Case studies

Figure 2.5 shows a real-world electrical power distribution system model built in DEW and Figure 2.6 shows the Feeder Performance Analysis Interface in DEW. The LMP data in Figure 2.6 is downloaded from ISO websites and the location (node) information is indicated by the user.

Feeder Performance Analysis is then utilized on the system shown in Figure 2.5.

Figure 2.7 to Figure 2.21 illustrate the hourly based feeder performance analysis for a sample circuit in the electrical power distribution system as shown in Figure 2.5.

It is demonstrated in Figure 2.7 that the load demand reaches the peak value in summer at 5500 kWh to 6200 kWh, causing the maximum loss of the whole year at the same period as shown in Figure 2.8 at around 160kWh to 210kWh. It also can be concluded that the load demand is always 20 to 40 percent higher, depending on the season, during the weekends than during the weekdays of the same month from Figure 2.7.

The annual LMP value as shown in Figure 2.9 is very uneven. It may rise sharply from tens of dollars/mWh to around 700 dollars/mWh in July and it is also possible to fall dramatically from 100 dollars/mWh to -300 dollars/mWh at the end of June, which means serving an additional MW of load at that time will reduce the operating cost.

By multiplying the loss of the sample circuit and LMP value of it, the sample circuit annual cost is plotted in Figure 2.10. By comparing Figures 2.9 and 2.10, it is concluded that the cost is largely dependent on the LMP value itself.

The annual efficiency of the circuit as plotted in Figure 2.11 remains relatively constantly at around 97% to 98%, meaning that the operation of the sample circuit is pretty efficient.

It is not so surprising to find in Figure 2.14 that the power factor of phase A of the sample circuit in summer is lower than that in other seasons in the year by 2 to 8 percent and in Figure 2.15 that the maximum power factor deviation in summer is greater than that in other seasons in the year by 5 to 9 percent.

Figure 2.18 makes it clear that the smallest single phase capacity in September is negative, around -8 percent, implying that some of the single phase laterals in the sample circuit are overloaded during that time and may need special attention. In Figure 2.20, the phase A current goes as high as 350A in the summer and the smallest phase A customer level voltage is drop down to around 105V in the summer as shown in Figure 2.21, verifying the fact that the summer demand load is large.

Figures 2.22 to 2.29 show the summary report results for the sample system shown in Figure 2.5. These plots provide circuit ID in the sample system to the various key performance parameters such as circuit annual efficiency, annual energy loss, annual loss cost, annual average maximum phase imbalance, and annual average maximum power factor deviation.

There are wild fluctuations in the annual efficiency factor as shown in Figure 2.22, with the lowest efficiency at ID 250. By comparing Figure 2.22 with Figures 2.23 and 2.24, it is concluded that the higher the annual efficiency of the circuit, the lower its annual energy loss and cost are.

Similarly, the system annual maximum phase imbalance as shown in Figure 2.28 and the system annual maximum power factor deviation as shown in Figure 2.29 are erratic, but the circuit with the worst performance, in terms of either worst phase balance or power factor deviation, can be easily located.

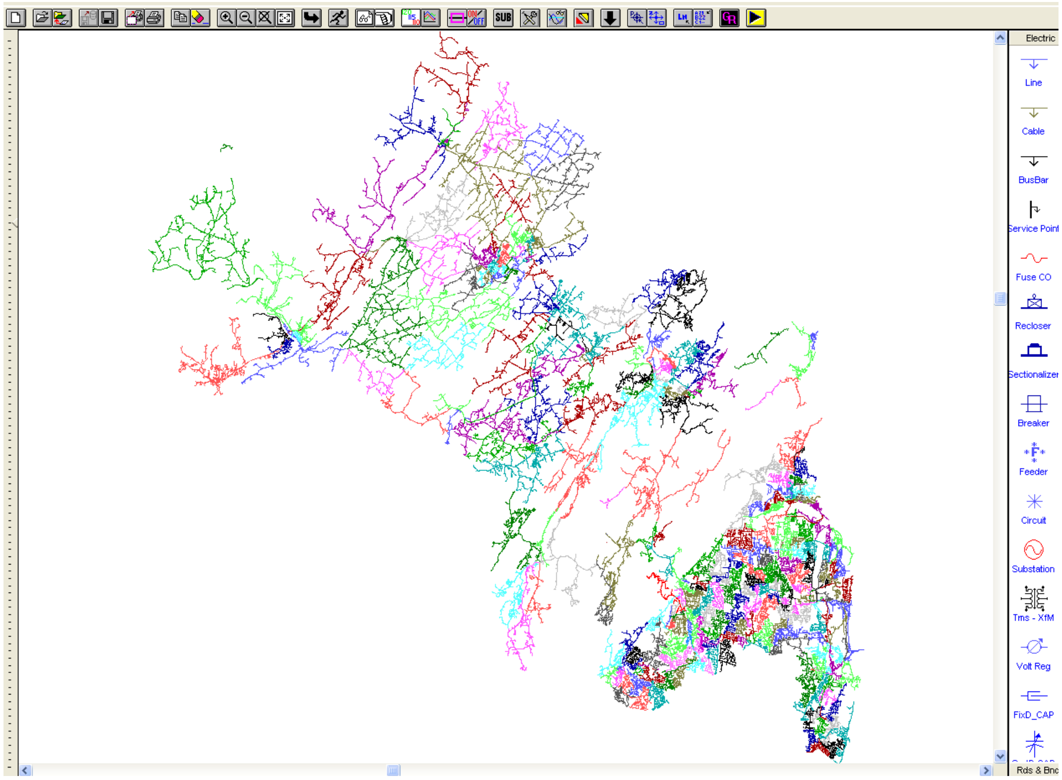


Figure 2.5 Example power distribution system

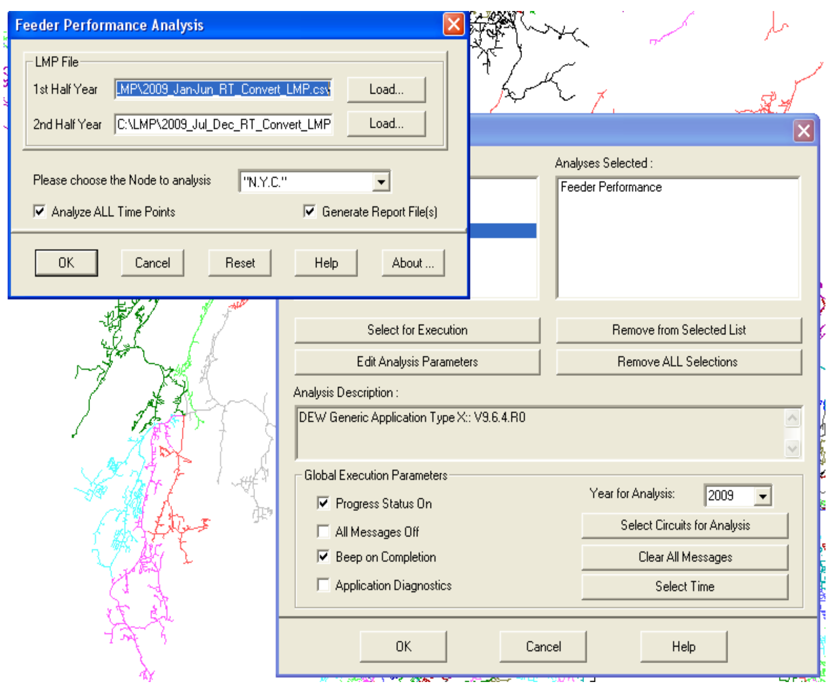


Figure 2.6 Feeder Performance Analysis Interface

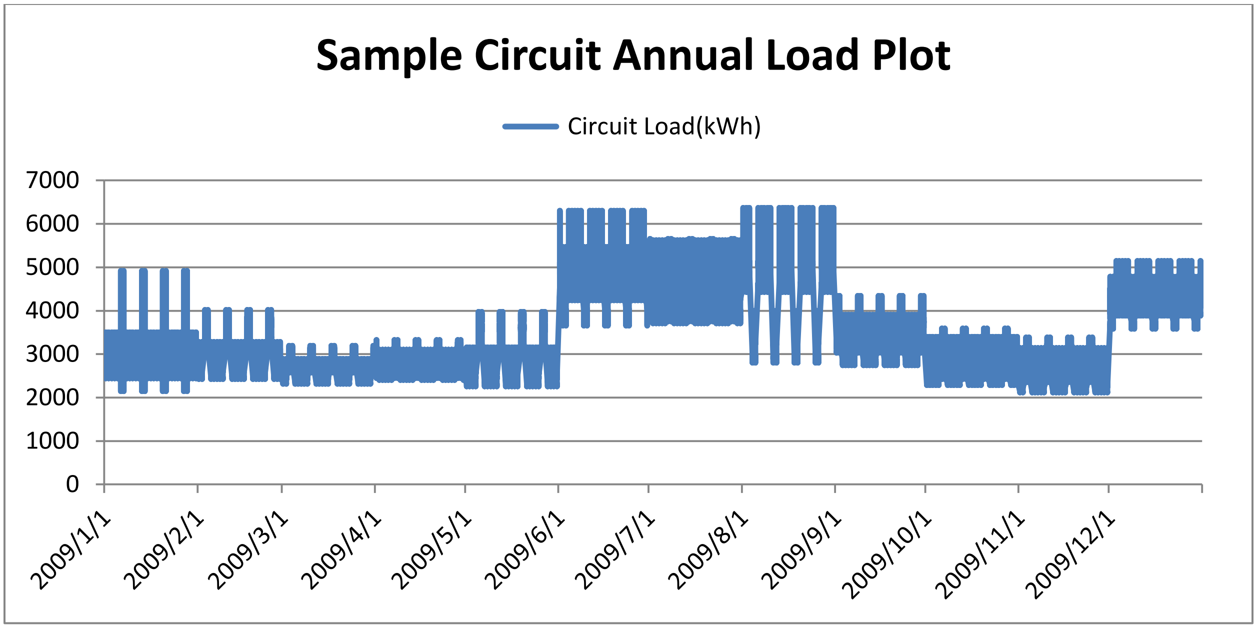


Figure 2.7 Sample Circuit Annual Load Plot

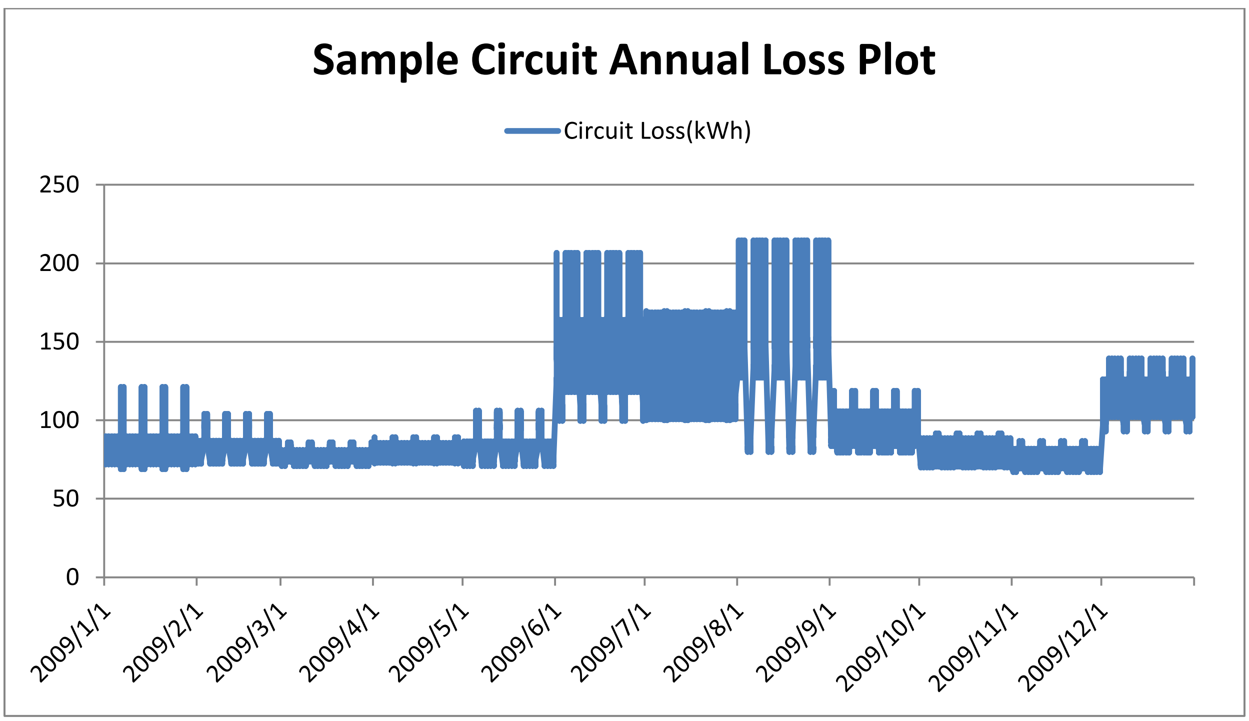


Figure 2.8 Sample Circuit Annual Loss Plot

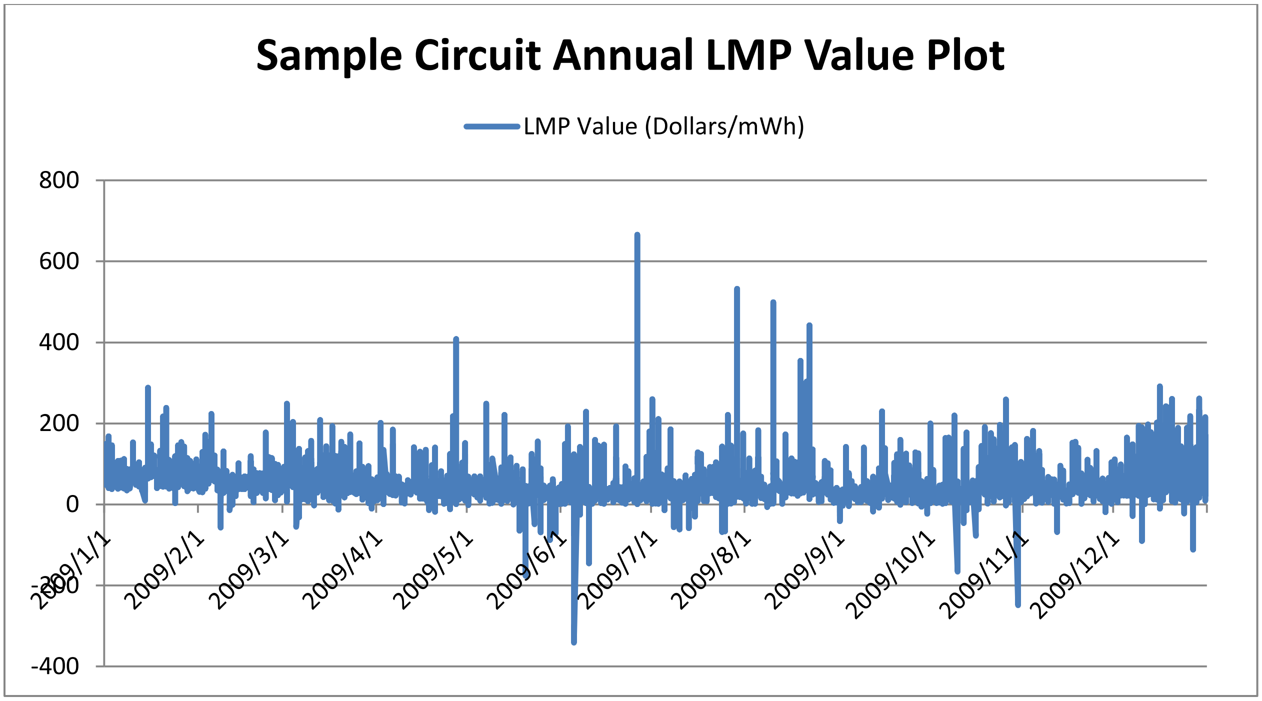


Figure 2.9 Sample Circuit Annual LMP Value Plot

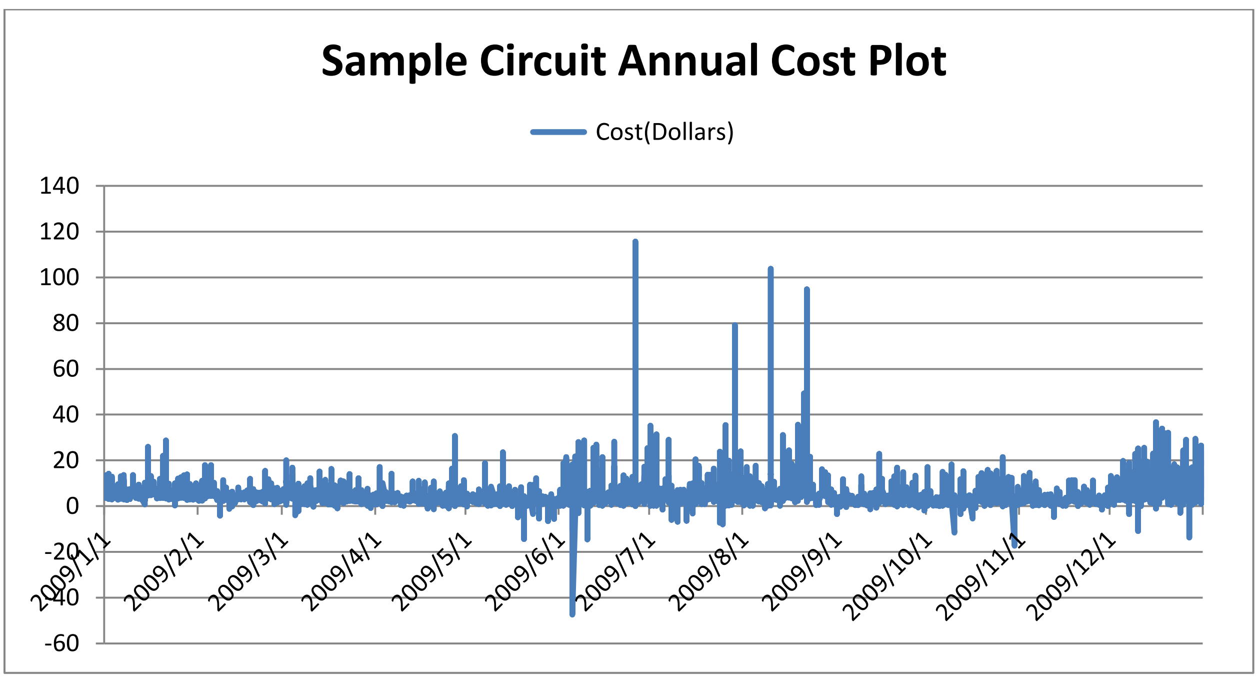


Figure 2.10 Sample Circuit Annual Cost Plot

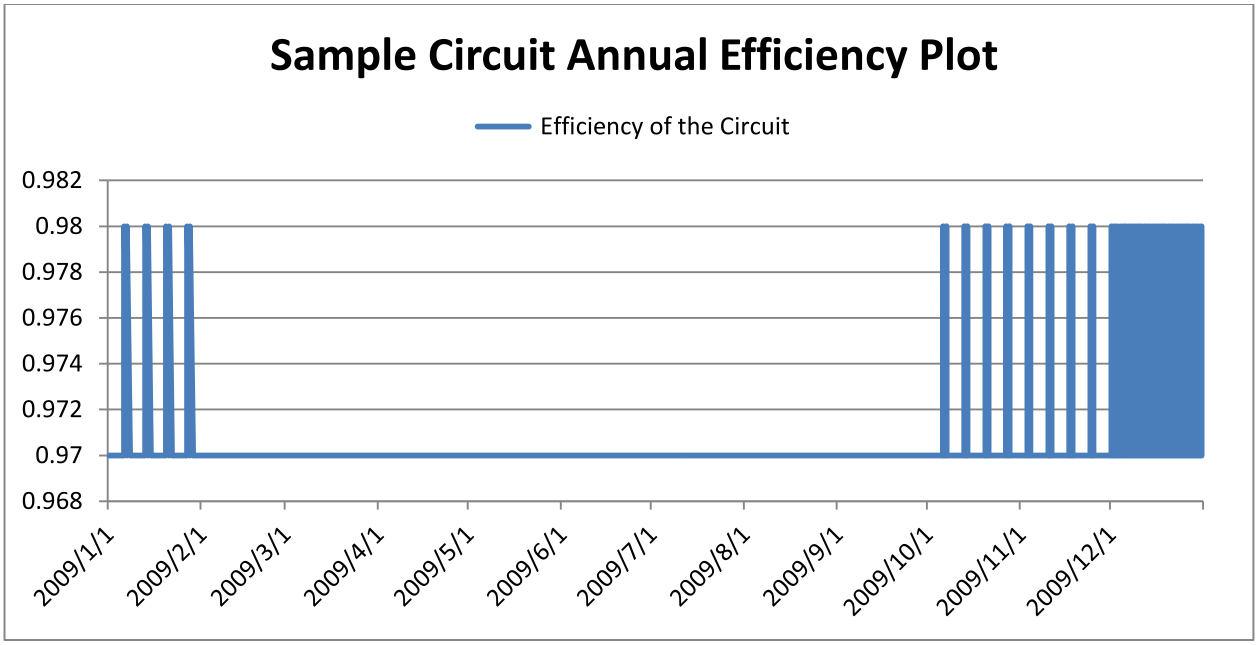


**Figure 2.11 Sample Circuit Annual Efficiency Plot**

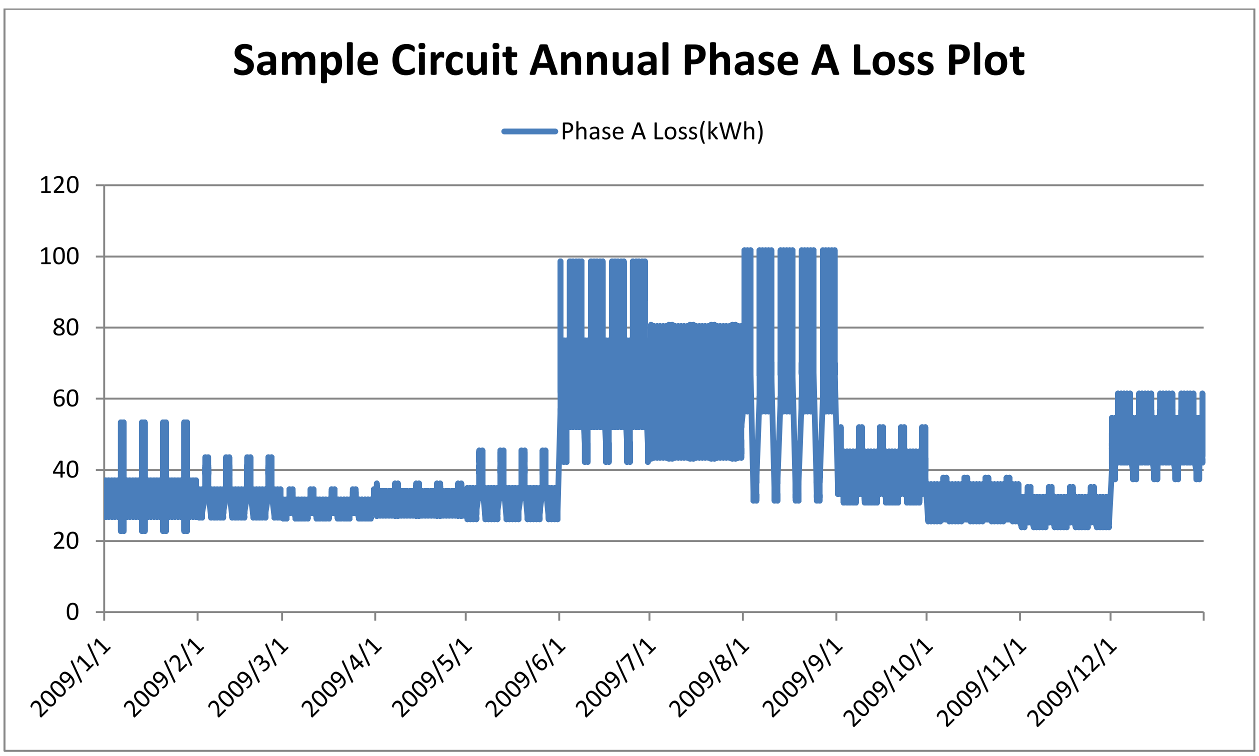


**Figure 2.12 Sample Circuit Annual Phase A Loss Plot**

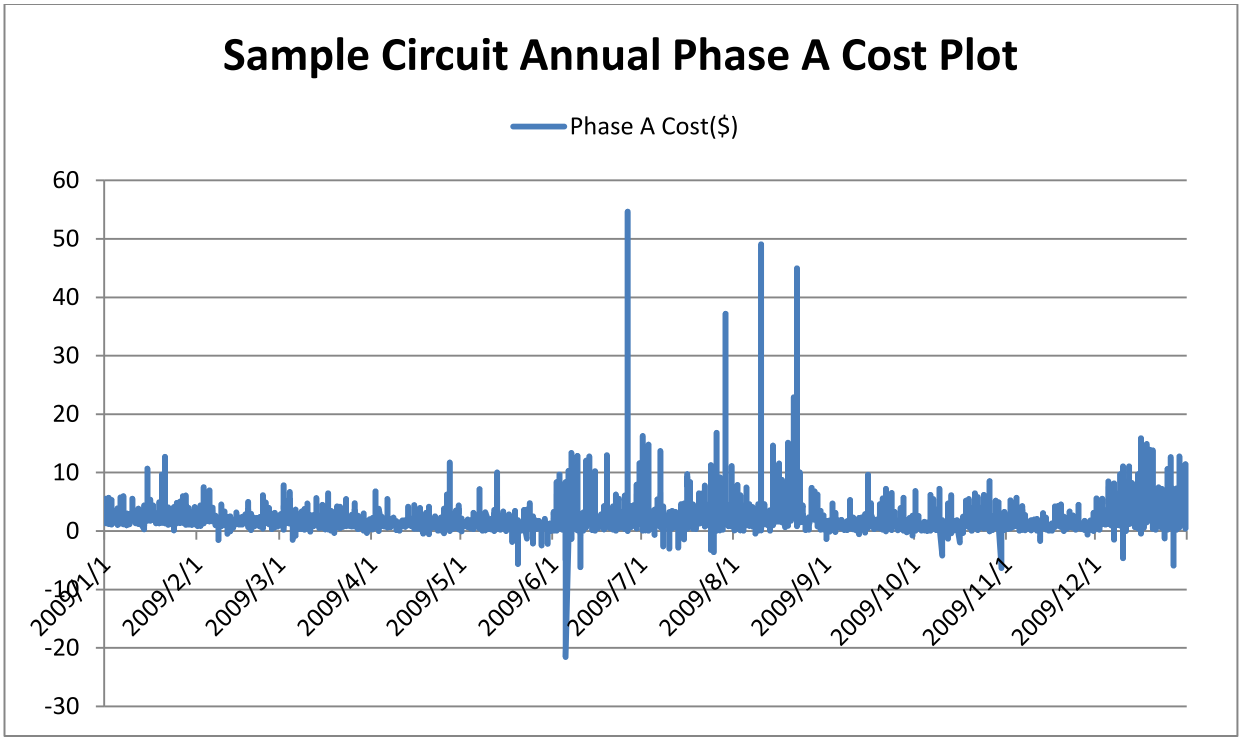


**Figure 2.13 Sample Circuit Annual Phase A Cost Plot**

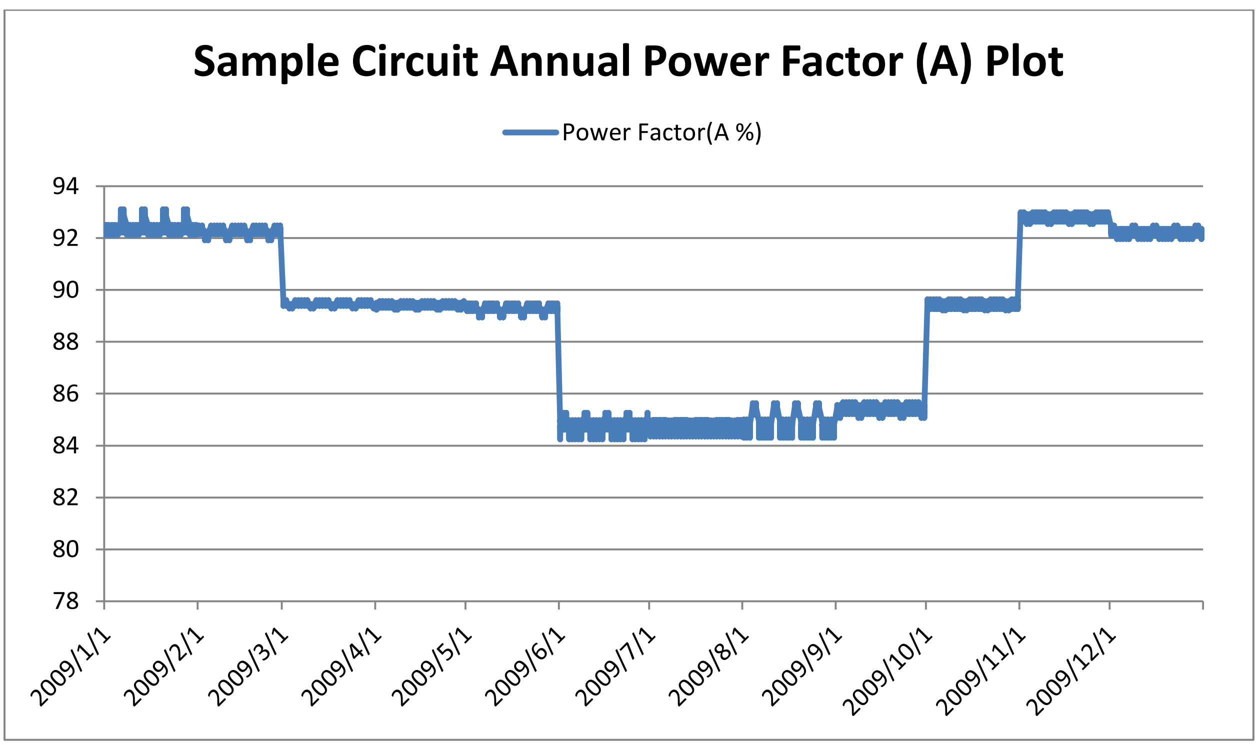


**Figure 2.14 Sample Circuit Annual Power Factor (A) Plot**

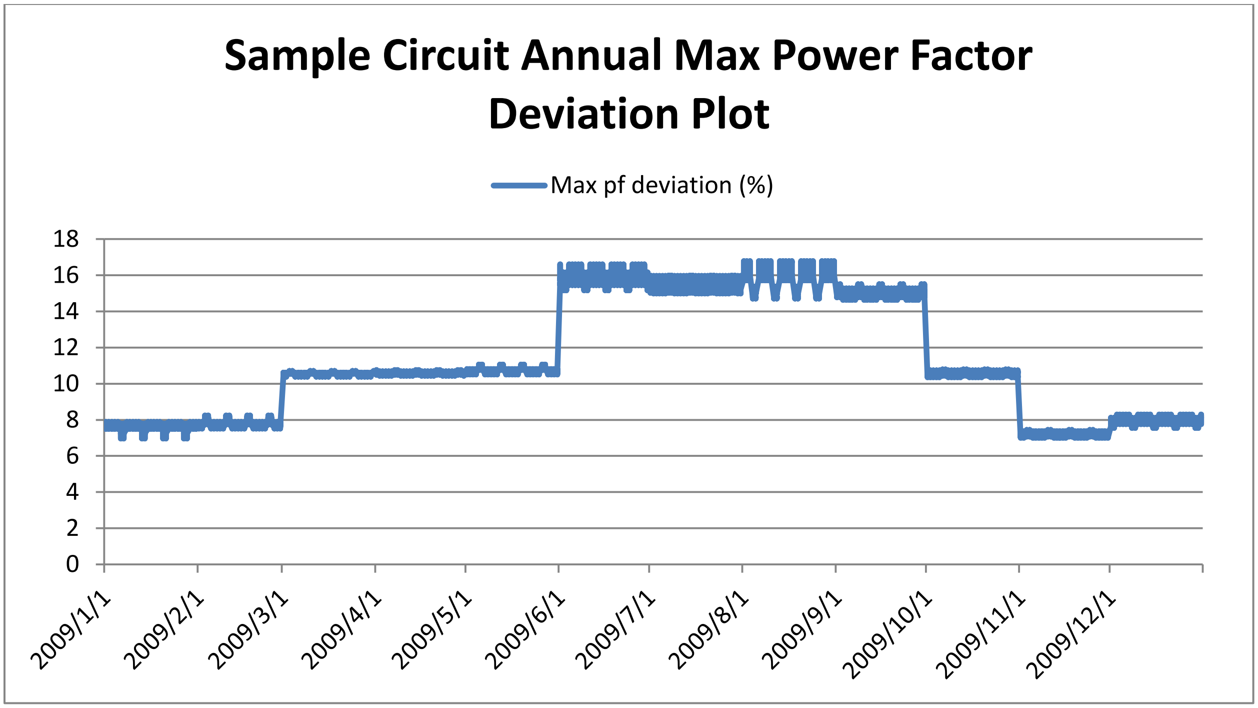


**Figure 2.15 Sample Circuit Annual Maximum Power Factor Deviation Plot**

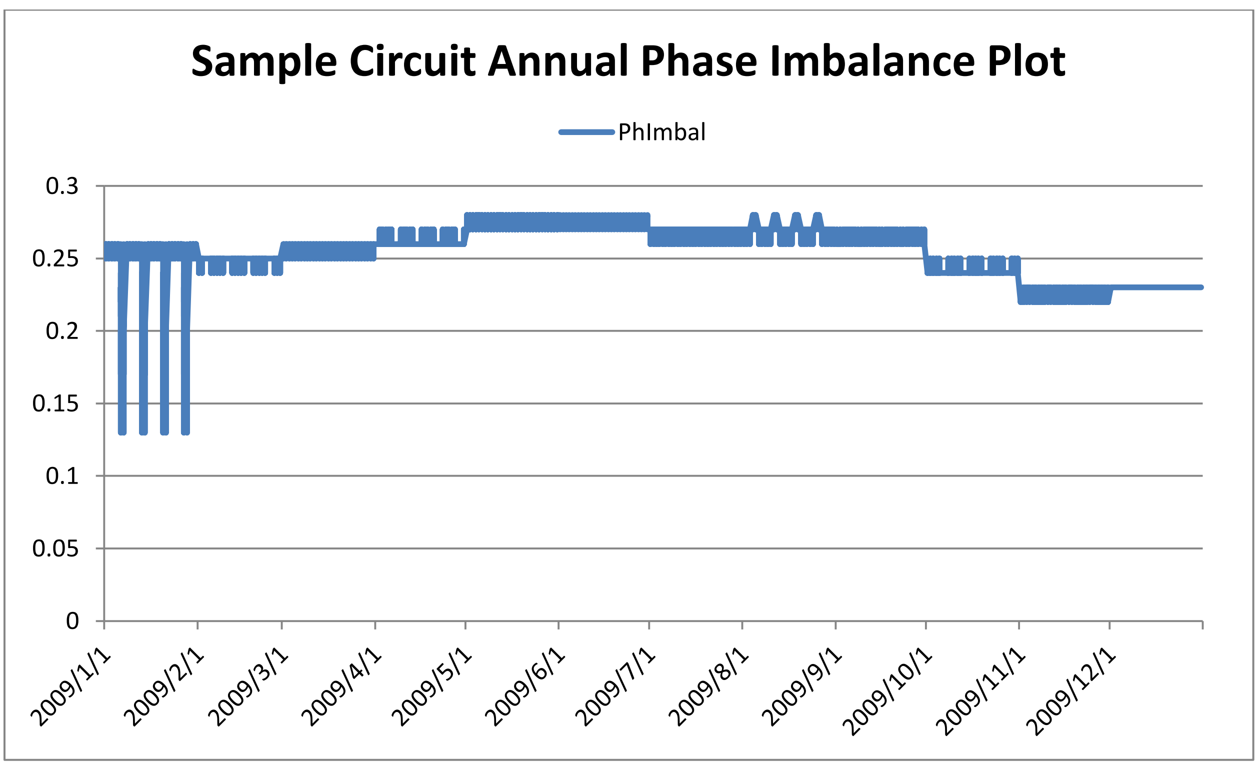


**Figure 2.16 Sample Circuit Annual Phase Imbalance Plot**

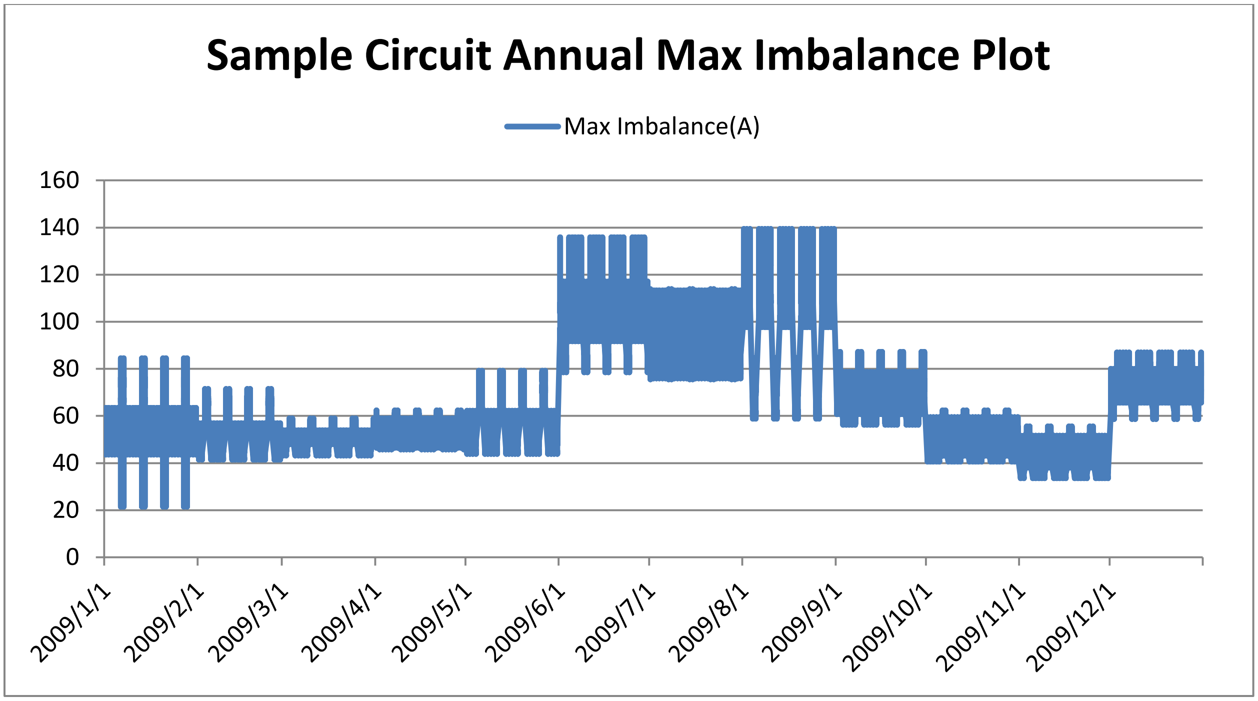


Figure 2.17 Sample Circuit Annual Maximum Imbalance Plot

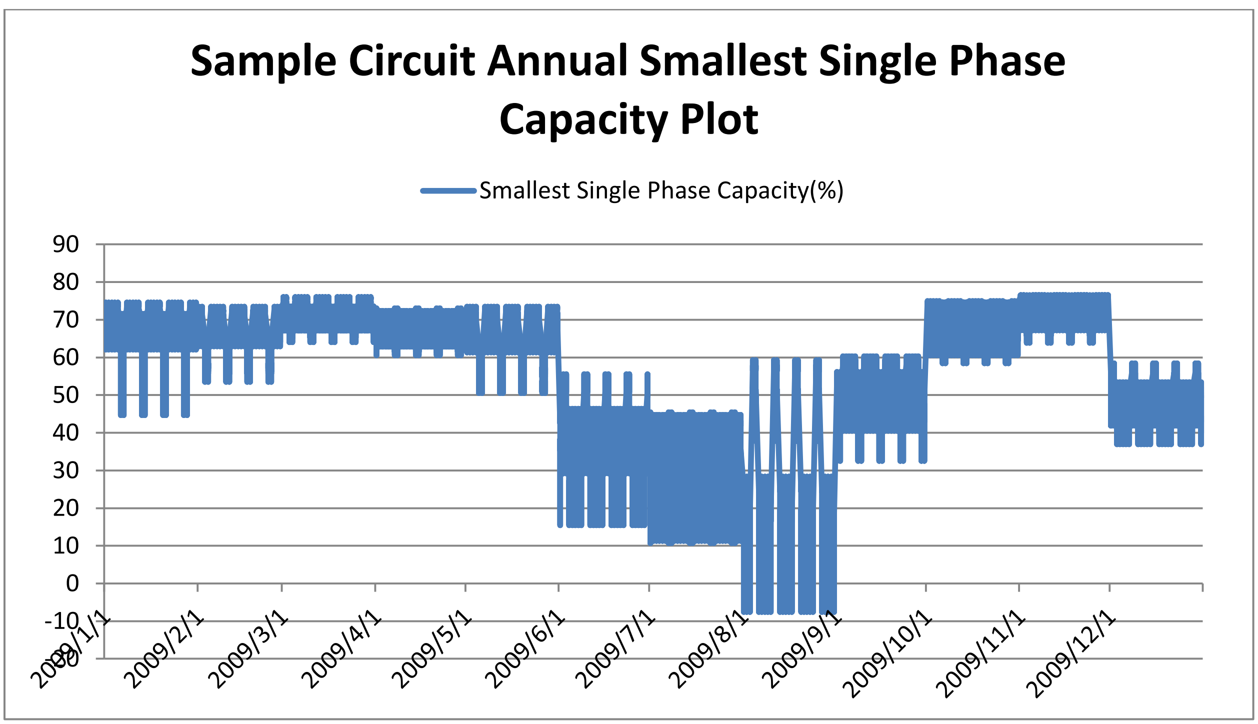


Figure 2.18 Sample Circuit Annual Smallest Single Phase Capacity Plot

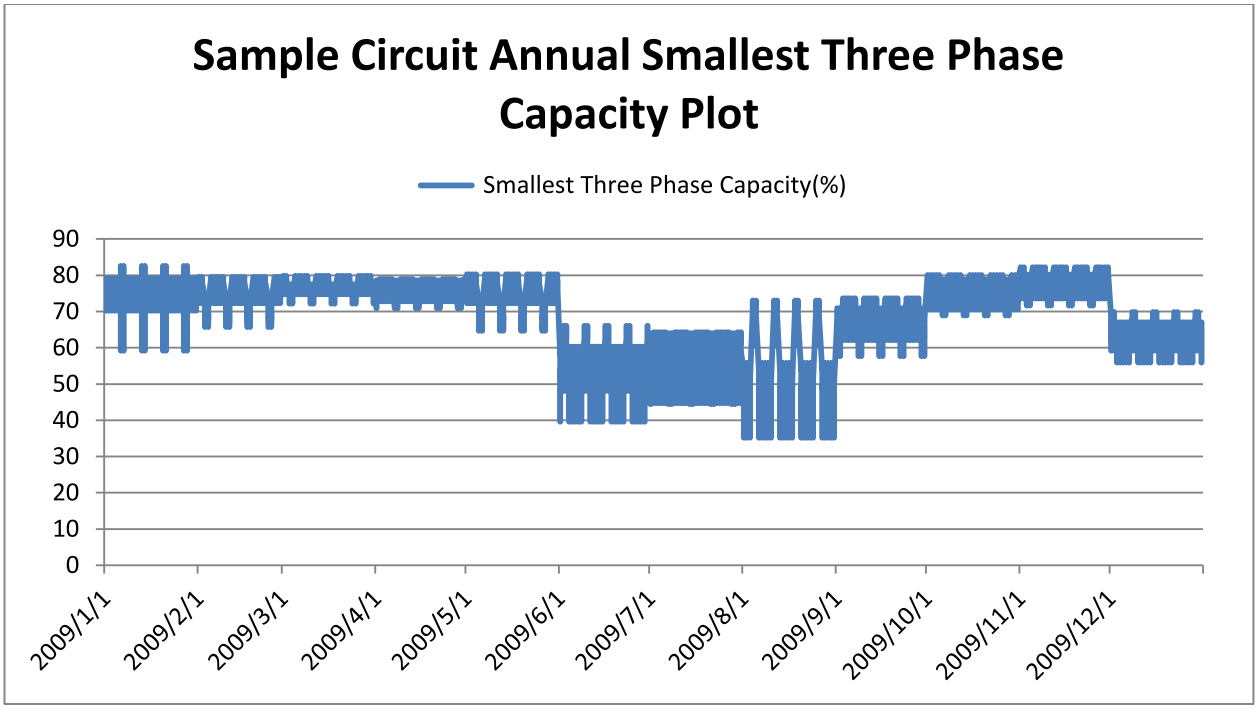


**Figure 2.19 Sample Circuit Annual Smallest Three Phase Capacity Plot**

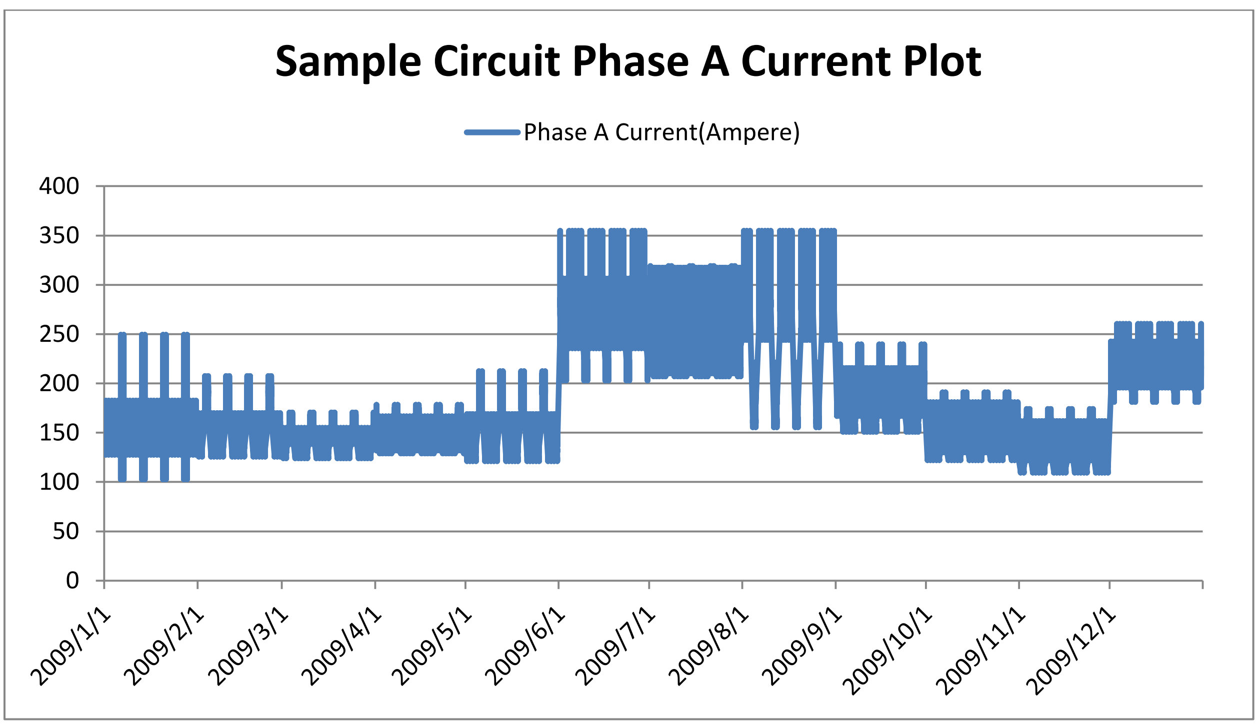


**Figure 2.20 Sample Circuit Phase A Current Plot**

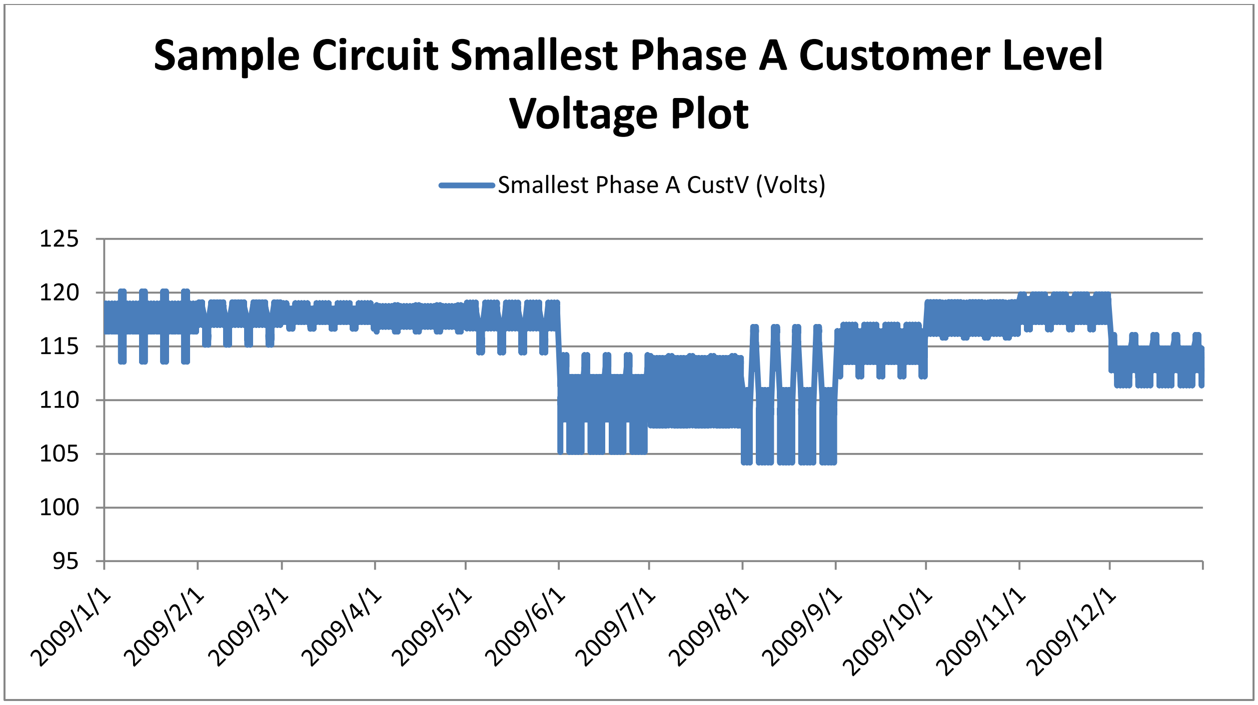


**Figure 2.21 Sample Circuit Smallest Phase A Customer Level Voltage Plot**

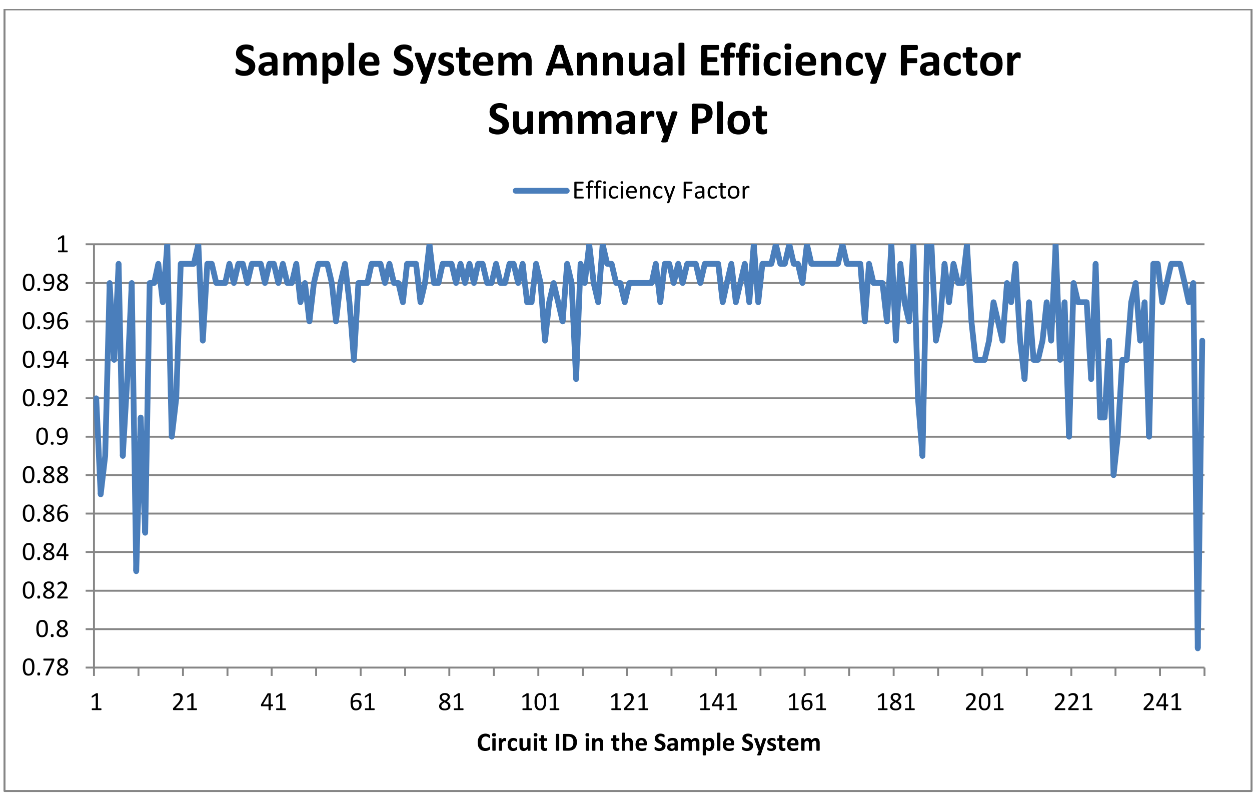


**Figure 2.22 Sample System Annual Efficiency Factor Summary Plot**

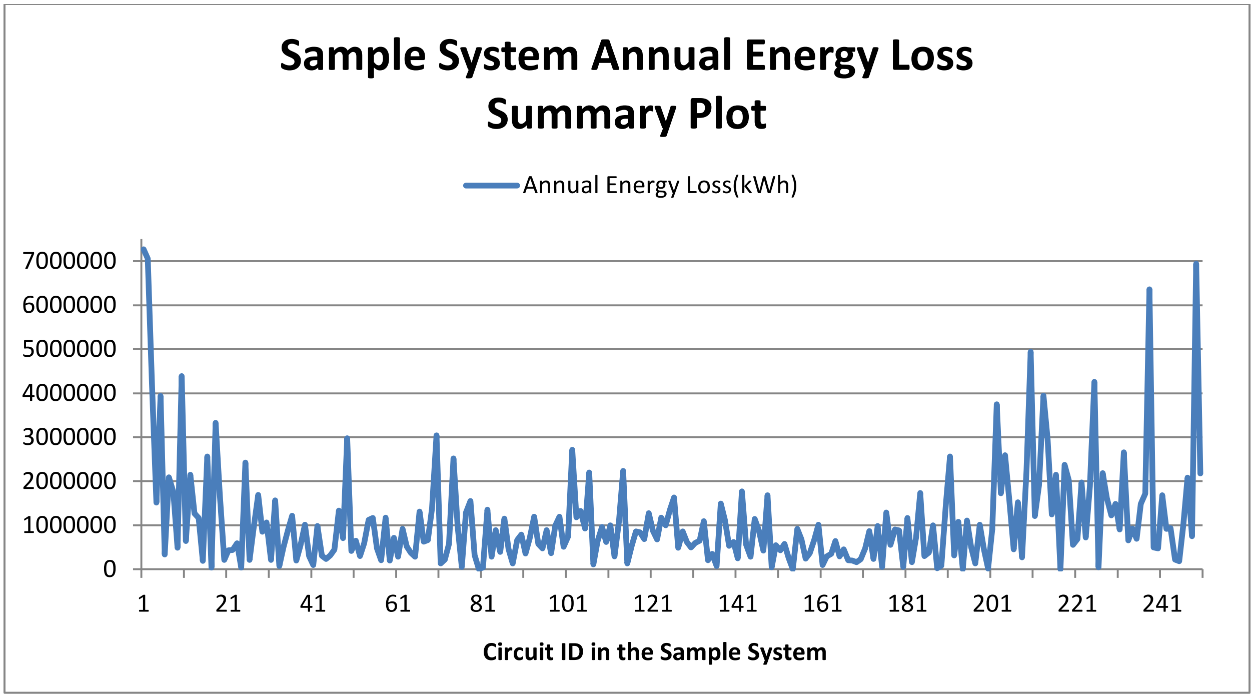


Figure 2.23 Sample System Annual Energy Loss Summary Plot

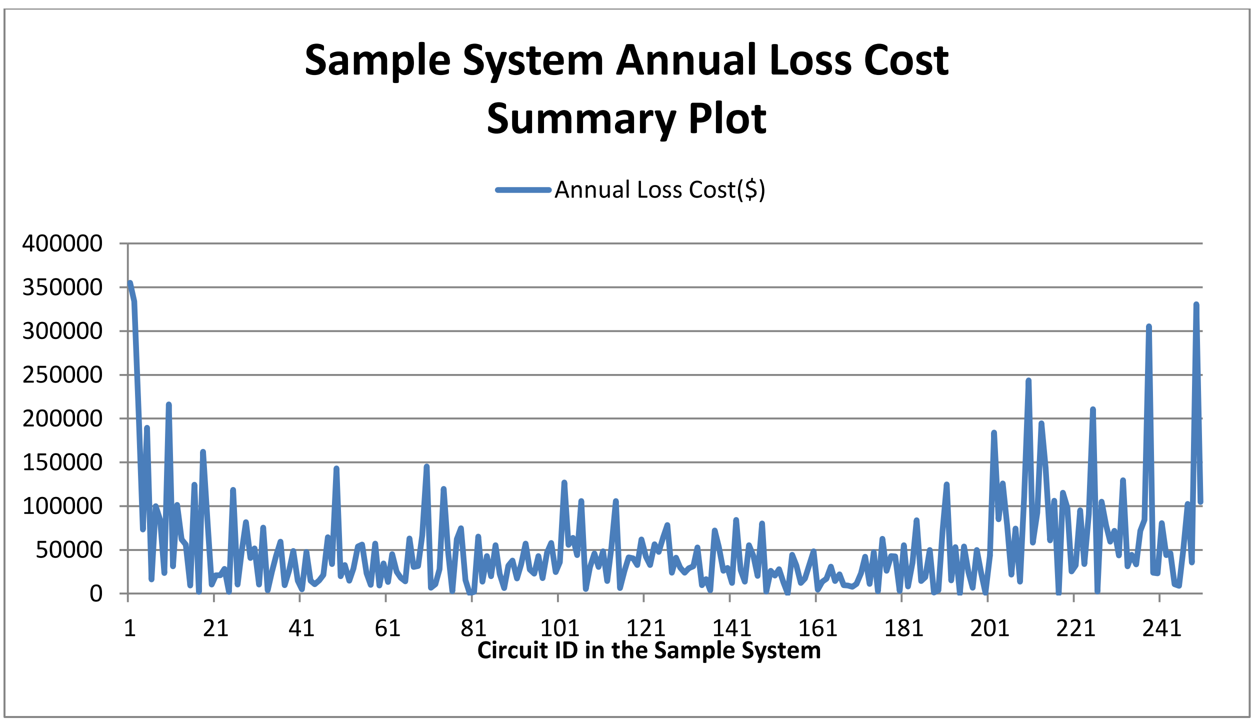


Figure 2.24 Sample System Annual Loss Cost Summary Plot

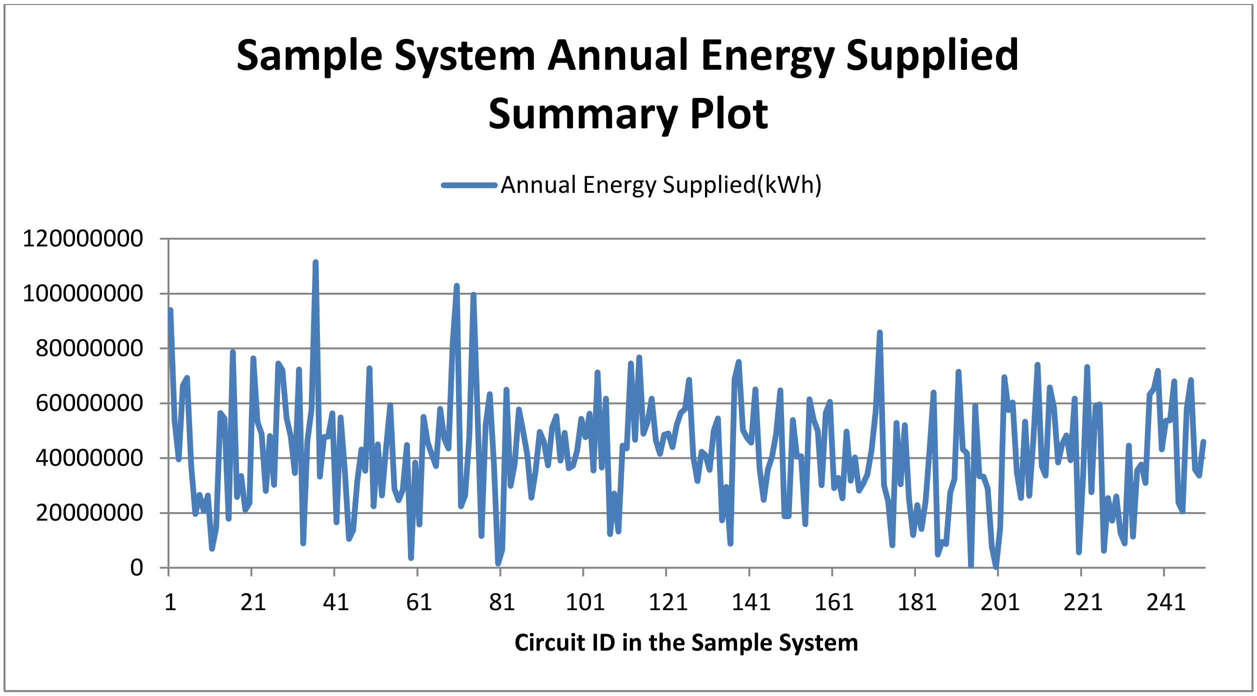


Figure 2.25 Sample System Annual Energy Supplied Summary Plot

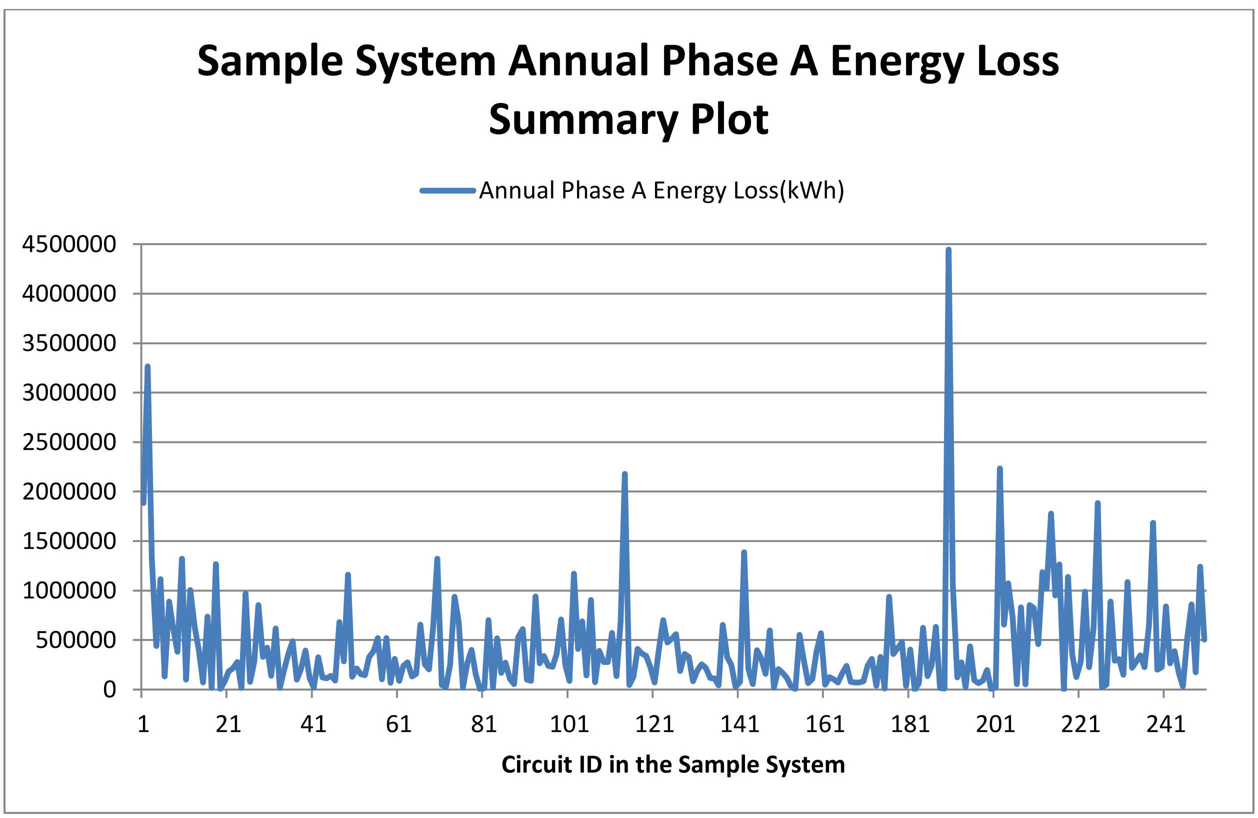


Figure 2.26 Sample System Annual Phase A Energy Loss Summary Plot

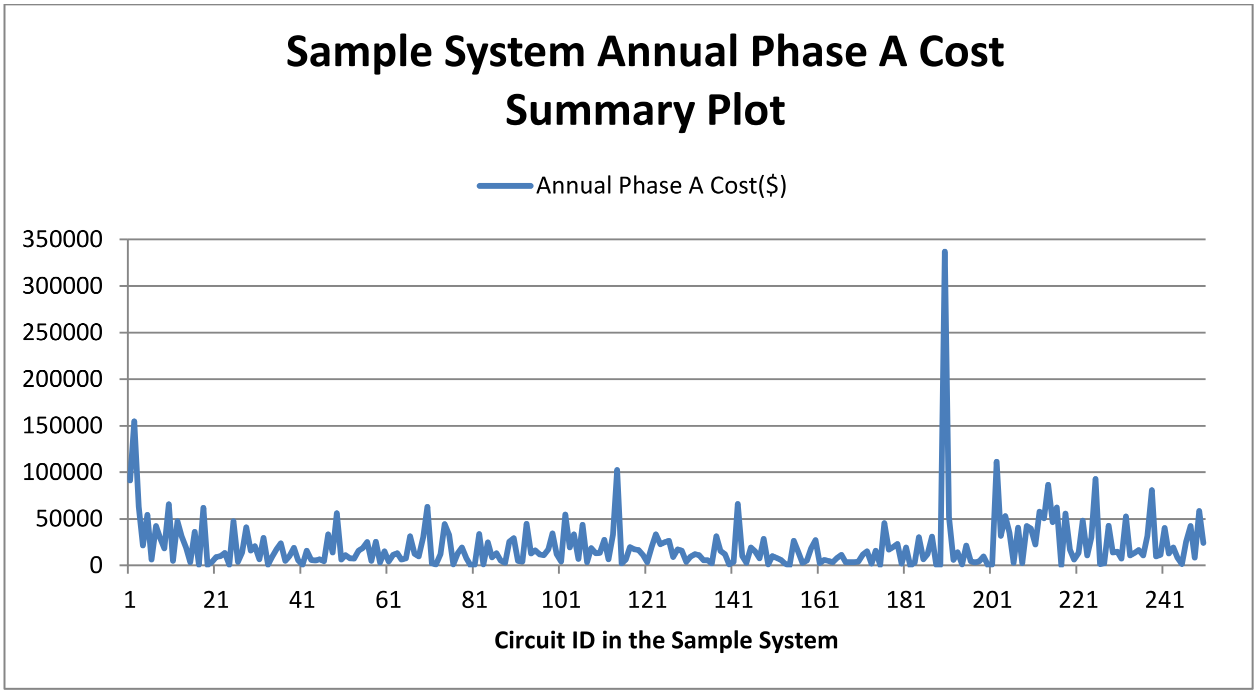


Figure 2.27 Sample System Annual Phase A Cost Summary Plot

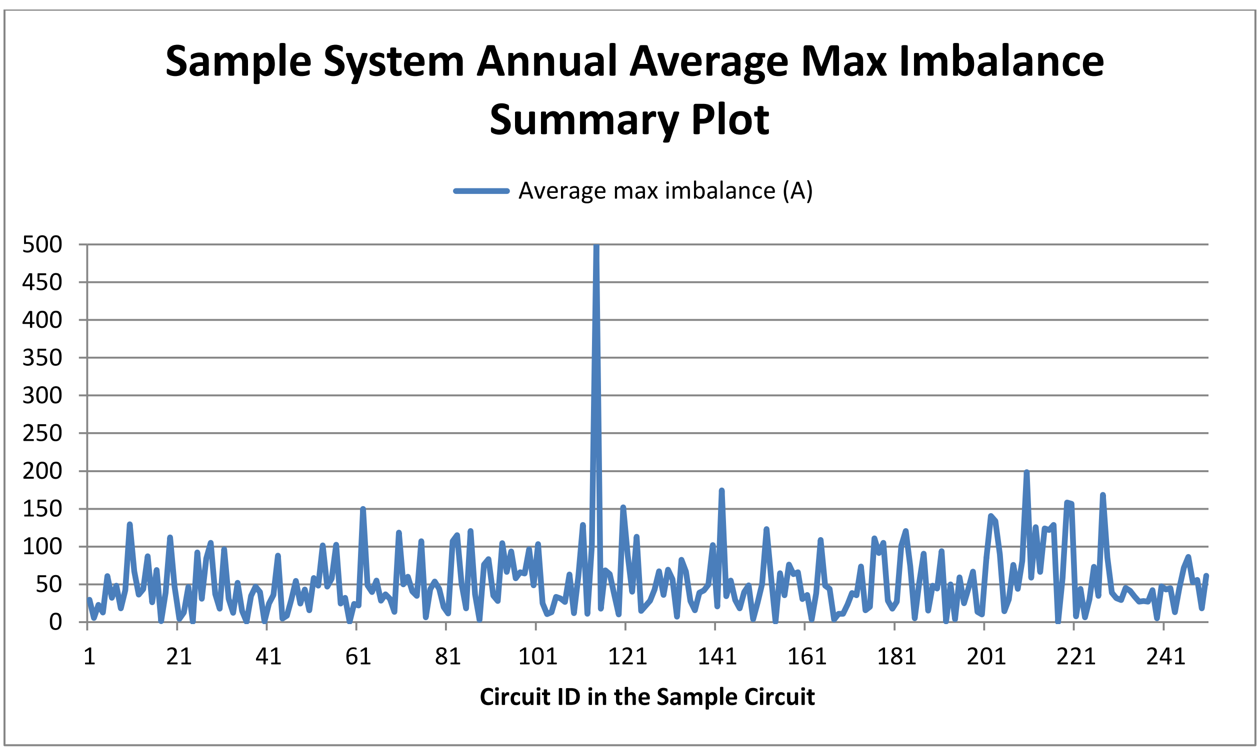


Figure 2.28 Sample System Annual Average Maximum Imbalance Summary Plot

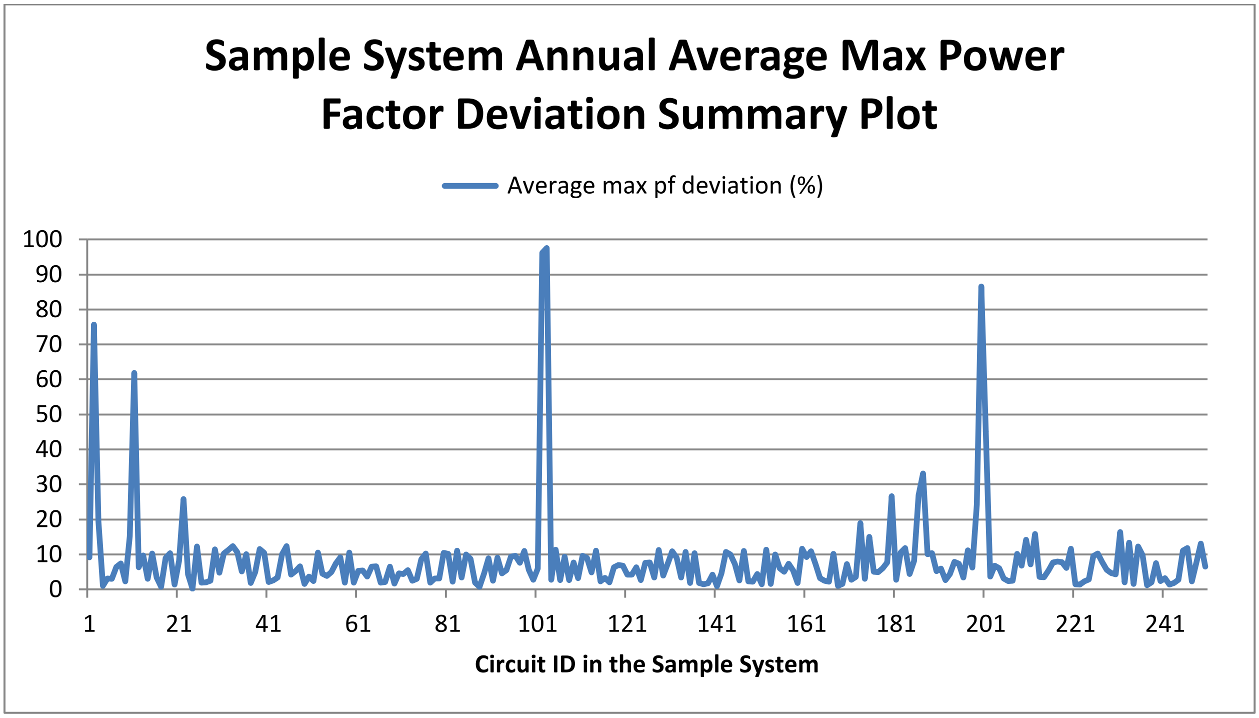


**Figure 2.29 Sample System Annual Average Maximum Power Factor Deviation Summary Plot**

As resources are limited, it is not possible to improve every circuit in the system. By locating the most inefficient circuit, a possible criterion is supplied to the designers .Tables 2.4 to 2.8 illustrate the system improvement after phase balancing is conducted on the most inefficiency circuit with Circuit ID 260.

**Table 2.4 System Improvement by Phase Balancing (1)**

| | Annual Energy Loss(kWh) | Annual Loss Cost($) | Annual Energy Supplied(kWh) |
|---|---|---|---|
| Circuit ID 260 (Orginal) | 7269724.71 | 355144.02 | 94032876.14 |
| Circuit ID 260 (Phase Balanced) | 5277339.48 | 253828.75 | 76251953.4 |
| Improvement | -1992385.23 | -101315.27 | -17780922.74 |

**Table 2.5 System Improvement by Phase Balancing (2)**

| | Annual Phase A Energy Loss(kWh) | Annual Phase B Energy Loss(kWh) | Annual Phase C Energy Loss(kWh) |
|---|---|---|---|
| Circuit ID 260 (Orginal) | 1885309.93 | 2982200.34 | 2402214.44 |
| Circuit ID 260 (Phase Balanced) | 2003144.85 | 1434355.33 | 1839839.31 |
| Improvement | 117834.92 | -1547845.01 | -562375.13 |

**Table 2.6 System Improvement by Phase Balancing (3)**

| | Annual Phase A Cost($) | Annual Phase B Cost($) | Annual Phase C Cost($) |
|---|---|---|---|
| Circuit ID 260 (Orginal) | 91167.49 | 147206.52 | 116770.01 |
| Circuit ID 260 (Phase Balanced) | 95813.26 | 69377.71 | 88637.79 |
| Improvement | 4645.77 | -77828.81 | -28132.22 |

**Table 2.7 System Improvement by Phase Balancing (4)**

| | Average max imbalance (A) | Average max pf deviation (%) | Efficiency Factor |
|---|---|---|---|
| Circuit ID 260 (Orginal) | 29.25 | 9.19 | 0.92 |
| Circuit ID 260 (Phase Balanced) | 5.67 | 8.19 | 0.93 |
| Improvement | -23.58 | -1 | 0.01 |

## 2.5 Challenges of Feeder Performance Analysis

The challenges of feeder performance analysis are as follows:

- Computation time

It is very time consuming to conduct feeder performance analysis on a single computer as the electrical power distribution system is usually extremely large, typically containing hundreds of thousands of components. For the example system shown in Figure 2.5, it will take around 12 hours and 20 minutes to finish the feeder performance analysis on the machine configured as Intel Xeon E5405@2,4GHz and 3.5G RAM.

- Memory usage

It takes around 2G RAM to run the feeder performance analysis on the machine above and thus significantly reduce the run speed. Another potential issue is that if the system analyzed is sufficiently big, then the main memory can not hold the analysis calculations for even a single time point, and the feeder performance analysis can not be conducted.

# CHAPTER 3 Feeder Performance Analysis with Distributed Algorithm

## 3.1 Introduction

As discussed in Chapter 2, it is very time and memory consuming to conduct feeder performance analysis on a single computer as the electrical power distribution system is usually extremely large.

Motivated by speeding up the calculations and reducing the memory usage so that the performance analysis can run in a more timely fashion, distributed computing is considered.

This chapter first reviews the background of distributed computing. Diakoptics, is then considered and briefly introduced. Finally, the architecture of distributed computing for feeder performance analysis is discussed with a case study using a real world electrical power distribution system, for which the performance improvement is illustrated.

### 3.1.1 Introduction to distributed systems and distributed computing

The advent of the computer network in the 1970s made communication among computers possible. More and more computing tasks, such as SETI@home[54], a project dedicated to the search for Extraterrestrial Intelligence (SETI), require huge computing capability. Although there are a variety of ways to greet this challenge, distributed computing using ordinary computers is perhaps the most economical approach, especially when compared to supercomputers.

A distributed system consists of multiple autonomous computers, storage devices and databases which interactively co-operate, aiming for a common goal. There are various definitions of a distributed system. Basically, there are loosely coupled distributed systems, in which users are aware of a multiplicity of machines. There are also tightly coupled distributed systems, in which the differences between the various computes and the ways they communicate with each other are hidden from users [55]. The distributed system should have the following basic characteristics:

- It has multiple computers to cooperate with each other
- It is connected by the network
- It can be expanded or scaled.

Figure 3.1 presents an example of a distributed system.

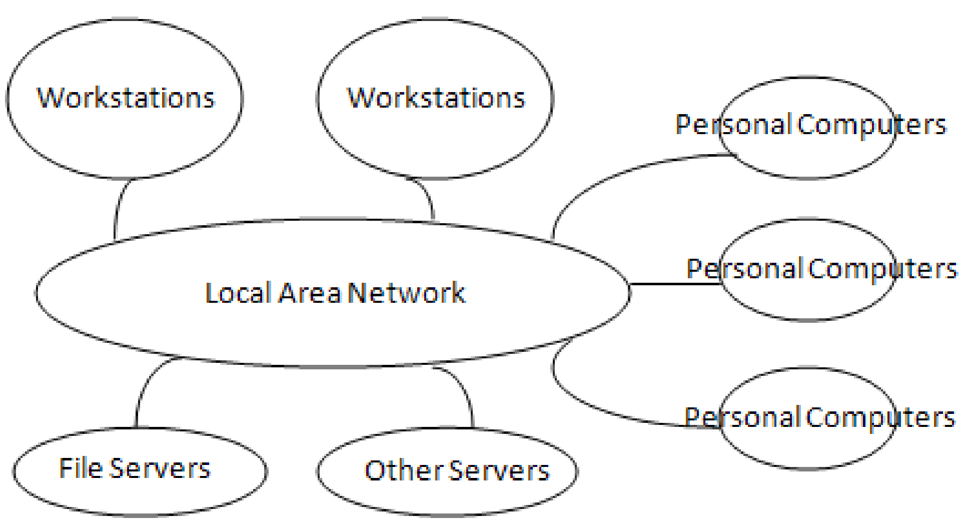


**Figure 3.1 Distributed Systems**

Based on the nature of distributed computing, the main motivation to explore distributing computing technology can be summarized as the two following key points:

- The application itself is inherently distributed. This kind of application will require the use of a communication network which connects several computers. Although there are many cases in which we can us a single computer in principle, the introduction of a distributed system provides practical benefits.
    - A distributed system may have higher performance/cost ratio to obtain the desired level of performance.
    - A distributed system may be expanded based on the performance requirement.
    - A distributed system may be more reliable than a non-distributed system as a result of redundancy.

### 3.1.2 Diakoptics, the method of system tearing

Diakoptics is the method of system tearing. The main idea is to split up physical systems, typically electrical circuits, into subsystems with the particular property that the subsystems overlap on their boundaries. Each subsystem can be analyzed and solved separately as if the other subsystems were non-existent. Then the solution to each subsystem is then joined back together to give a solution to the whole problem.

Figure 3.2 illustrates the diakoptics concept used for distributed computing.

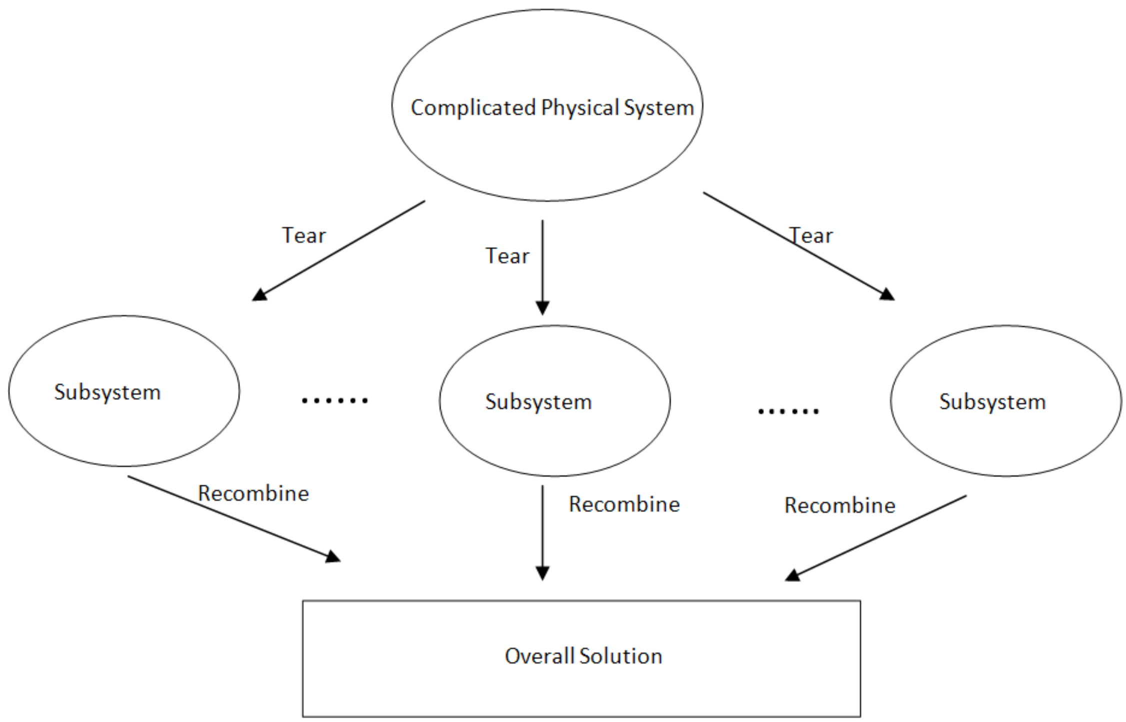


**Figure 3.2 Diakoptics for Distributed Computing**

## 3.2 Distributed computing architecture in DEW

Contrasted to the transmission and sub transmission lines which are in a meshed network, the distribution feeders are usually radial to simplify overcurrent protection [31]. With the radial configuration of electrical power distribution systems in mind, the DEW system model is designed to have natural points at which the tearing can occur. These natural points are usually circuits, voltage sources as well as feeders and cotrees. By taking advantage of Graph Trace Analysis (GTA) on the model, which will be discussed further in Section 3.2.1, the system can be separated into independent subsystems naturally, and thus the analysis for the system in distributed computing can be conducted based on the diakoptics approach.

Figure 3.3 shows the distributed computing architecture in DEW. A circuit sever is responsible for breaking the system into independent circuits and then placing them into a circuit queue. Feeder performance workers are independent processors which grab independent circuits in the circuit queue and conduct feeder performance analysis, generating the independent output reports. Finally, the circuit server collects all of the independent output reports and combines them into one summary report.

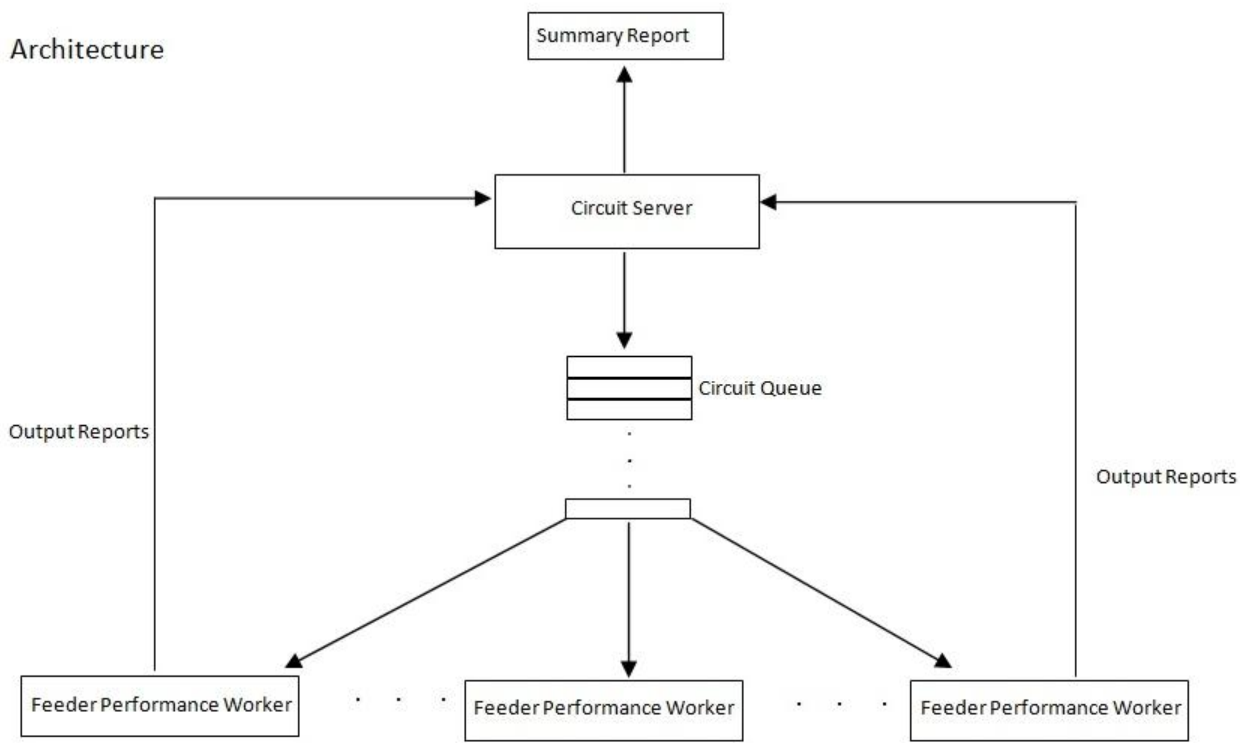


**Figure 3.3 Distributed Computing Architecture in DEW**

### 3.2.1 Graph Trace Analysis

Graph Trace Analysis (GTA) is a multidiscipline method originally developed at Virginia Tech for addressing generic analysis with topology iterators, especially electric power systems, but which has been extended now to other system types [19], [21] and [56].

Power distribution systems can be modeled as an edge-edge graph. In GTA, each edge corresponds to one-and-only-one component in the power distribution system. For every component in the GTA model, there is one-and-only-one reference source for it. Connectivity between components is maintained by iterators based on the reference source. Table 3.1 illustrates the four basic iterators for radial power distribution system, which implement traces in GTA.

**Table 3.1 Basic Iterators Used in GTA**

| | |
|---|---|
| forward iterator $f$ | points to the first downstream component fed by the same reference source as the component owning $f$ |
| backward iterator $b$ | the reverse iterator of the corresponding forward iterator |
| feeder path iterator $fp$ | points to the upstream component which feeds the given component |
| brother iterator $br$ | points to the first component in the forward trace that is not fed by the given component |

Forward and Backward traces are not related to the actual physical circuit connections but represent where the components are stored in memory, while the feeder path trace is based on the physical connections of the circuit. As the feeder path trace is functionally complete, all other traces can be derived from it [21]. Instead of being used to perform circuit traces, brother iterators may be used to detect dead ends or physical jumps in connectivity [19].

Figure3.4 gives an example circuit and Table 3.2 illustrates the four basic iterators for every component in the example circuit.

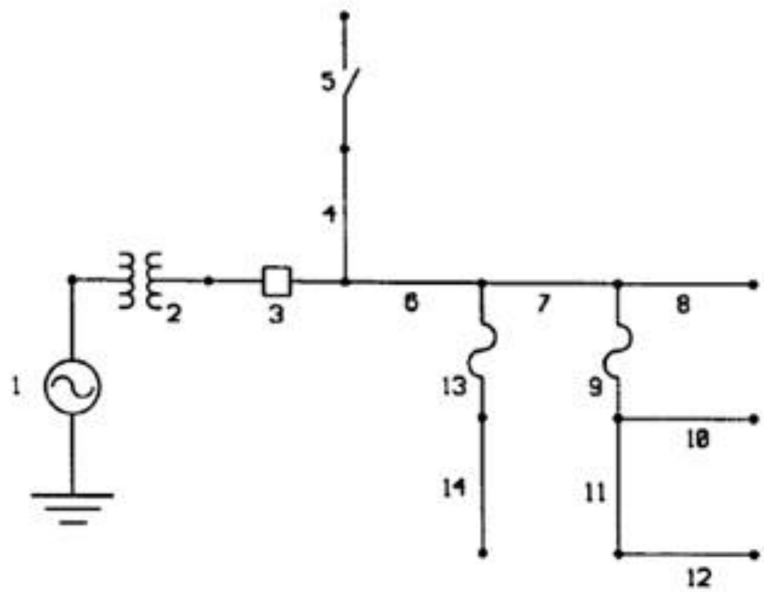


**Figure 3.4 Sample Circuit for Illustrating GTA [19], [used with permission]**

**Table 3.2 Iterators for Sample Circuit [19], [used with permission]**

| Component | $f$ | $b$ | $fp$ | $br$ |
|---|---|---|---|---|
| 1 | 2 | NULL | NULL | NULL |
| 2 | 3 | 1 | 1 | NULL |
| 3 | 4 | 2 | 2 | NULL |
| 4 | 5 | 3 | 3 | 6 |
| 5 | 6 | 4 | 4 | 6 |
| 6 | 7 | 5 | 3 | NULL |
| 7 | 8 | 6 | 6 | 13 |
| 8 | 9 | 7 | 7 | 9 |
| 9 | 10 | 8 | 7 | 13 |
| 10 | 11 | 9 | 9 | 11 |
| 11 | 12 | 10 | 9 | 13 |
| 12 | 13 | 11 | 11 | 13 |
| 13 | 14 | 12 | 6 | NULL |
| 14 | NULL | 13 | 13 | NULL |

The four iterators described above are sufficient for the trace algorithms for radial circuits. For non-radial circuits, adjacent iterators are used to manage and track cotree elements, which mark an independent loop [17], [19]. This work only discusses the distributed algorithm for radial power distribution systems. More information on the distributed algorithm for looped power distribution systems can be found in [45].

The iterator based trace analysis described above enables the “tearing” of independent circuits from the integrated system model, and thus naturally structures the distributed computing.

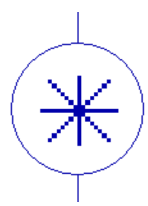

**Figure 3.5 Start Componet in DEW**

In DEW, for every circuit, there is one component called start-of-circuit which identifies the start of a separate circuit run, as shown in Figure 3.5. It is the reference for all the remaining components in that circuit. This provides  a natural point to “tear” or separate the system as shown in Figure 3.6.

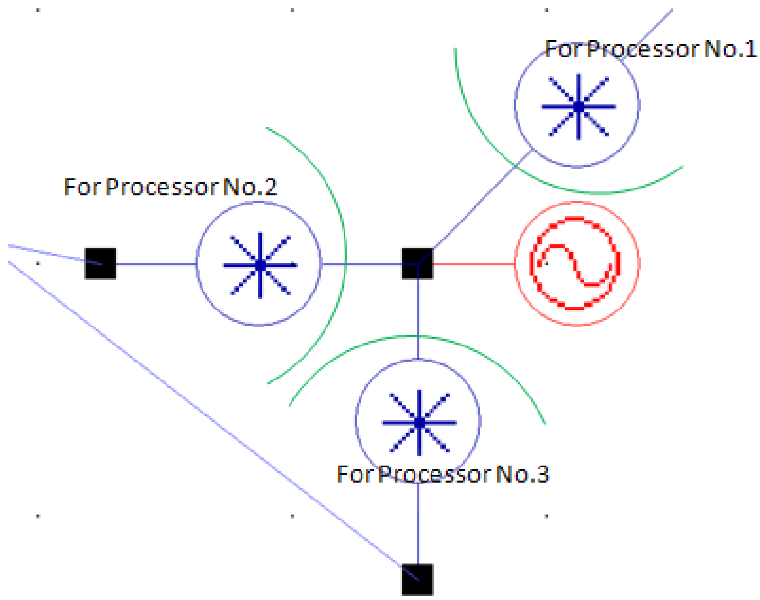


**Figure 3.6 Sample System to Be Separated**

Figure 3.7 illustrates the flow chart for dividing the system in DEW into independent circuits. By locating the starting points of the circuits contained in the system, single circuits are retrieved by utilizing a forward GTA trace.

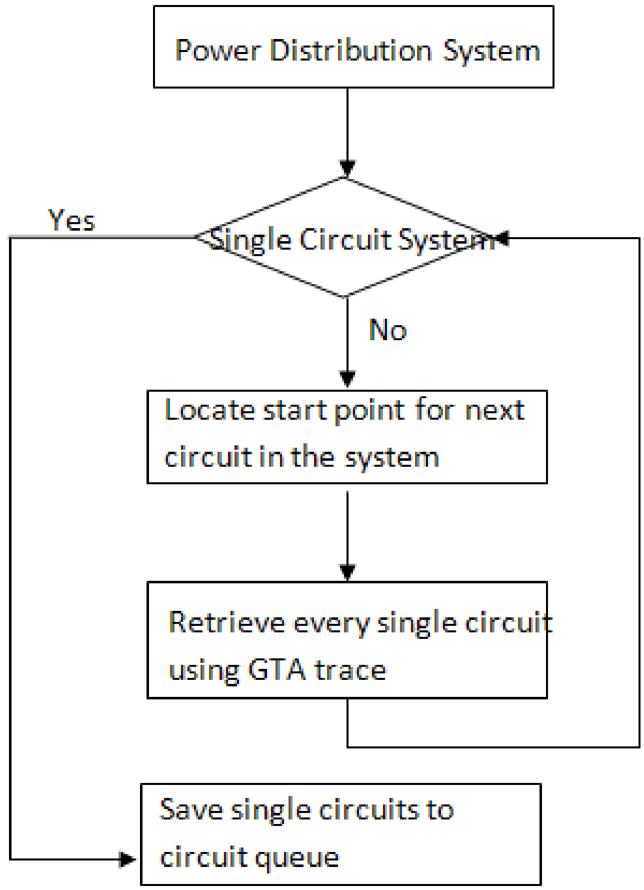


Figure 3.7 Dividing the System in DEW Flow Chart

### 3.2.2 GTA Notation for Distributed Algorithm

As the primary focus of GTA is on sets and sequences, [57], a declarative language which can describe operations on collections, with some minor modifications, is used to describe the operations of the distributed computing algorithm. Table 3.3 lists the GTA operations used in the distributed computing algorithm.

Table 3.3 GTA Operations Used in Distributed Algorithm

| $a$ | $b$ | Operation | Result | Effect |
|---|---|---|---|---|
| set or seq | expr | $a \rightarrow b$ | | For all elements in $a$, do operation expressed by $b$ |
| seq | | $a \rightarrow first$ | element | The first element of $a$ |
| Set or seq | | $a \rightarrow isEmpty$ | boolean | Returns whether there is an element of $a$ |
| element | element | $a = b$ | | Assigns $b$ to $a$ |
| element | | $fp\ (a)$ | | Runs feeder performance analysis on $a$ |
| element | expr | $a \rightarrow assign(b)$ | | Runs b on a |
| expr | | $while(a)$ | | Wait until expr $a$ is false |

Using GTA, the distributed computing problem can be defined as follows:

A power distribution system $\mathrm{S}$ to be analyzed by the processor set $\mathrm{P}$ with distributed computing, is divided into separate circuits $c_1, c_2, \ldots, c_i, \ldots, c_N$, which will be uniformly assigned to available processors $P_{NB}$ for processing by a specified algorithm. The processors that are busy are placed in the set $P_B$. Thus, $P_{NB} \cup P_B = P \quad P_{NB} \cap P_B = \emptyset$

Formula 3.1 shows the algorithm.

$$S \rightarrow (\text{while}\ (P_{NB} \rightarrow \text{isEmpty}),\ p_i = P_{NB} \rightarrow \text{first},\ p_i \rightarrow \text{assign}(\text{fp}(c_i))) \qquad 3.1$$

Figure 3.8 illustrates formula 3.1.

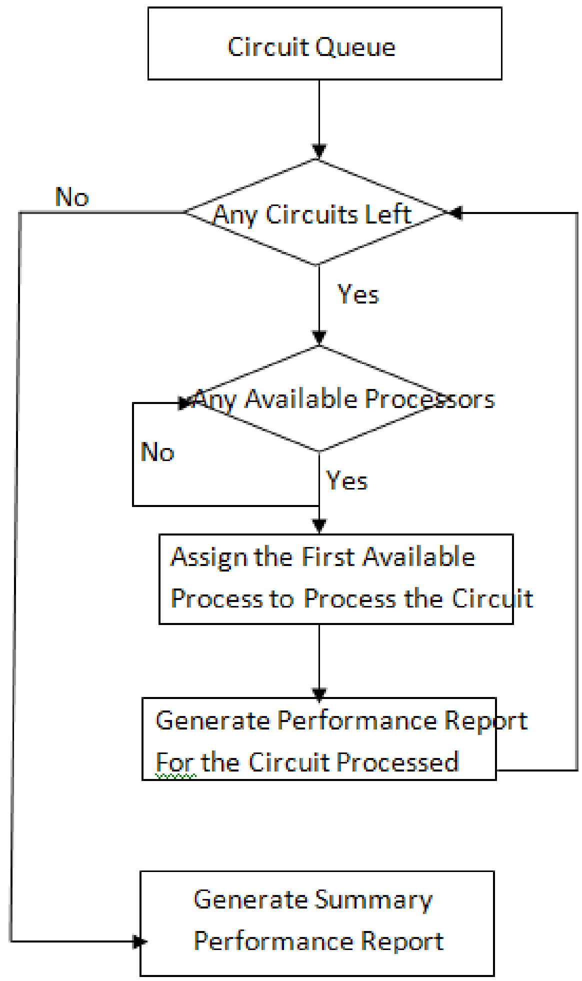


Figure 3.8 Distributed Algorithm Flow Chart

## 3.3 Feeder Performance Analysis with Distributed Algorithm Case Studies

The feeder performance analysis with distributed algorithm case studies is conducted on the same real-world electrical power distribution system model as shown in Figure 2.5 with eight identical machines connected in the Gigabit Ethernet LAN at Electrical Distribution Design Inc as the feeder performance workers and another computer as the circuit server. Tests are run with 1, 2, 4, and 8 machines.

The distributed computing environment is shown in the photo below.

Figure 3.9 Eight machines used for distributed computing

Table 3.4 illustrates the configuration information for the eight feeder performance workers

Table 3.4 Configuration Information for the Eight Feeder Performance Workers Used for Distributed Computing

| | |
|---|---|
| Model | Dell Precision T3500 |
| CPU | Intel Xeon @2,4GHz |
| RAM | 4G |

Table 3.5 illustrates the configuration information for the circuit server

Table 3.5 Configuration Information for the Circuit Server

| | |
|---|---|
| Model | Dell Latitude D630 |
| CPU | Intel Core 2 Duo T9300@2,5GHz, 2,49Hz |
| RAM | 3.5G |

Table 3.6 illustrate the processing time and speed-up for feeder performance analysis with distributed algorithm

**Table 3.6 Processing Time and Speed-Up for Feeder Performance Analysis with Distributed Algorithm**

| Number of Machines | Processing Time (Minutes) | Speed UP |
|---|---|---|
| 1 | 88 | 1 |
| 2 | 46 | 1.913043 |
| 4 | 29 | 3.034483 |
| 8 | 15 | 5.866667 |

Figure 3.10 shows a distributed computing performance plot, which illustrates the improvements in processing time as the number of computers is increased.

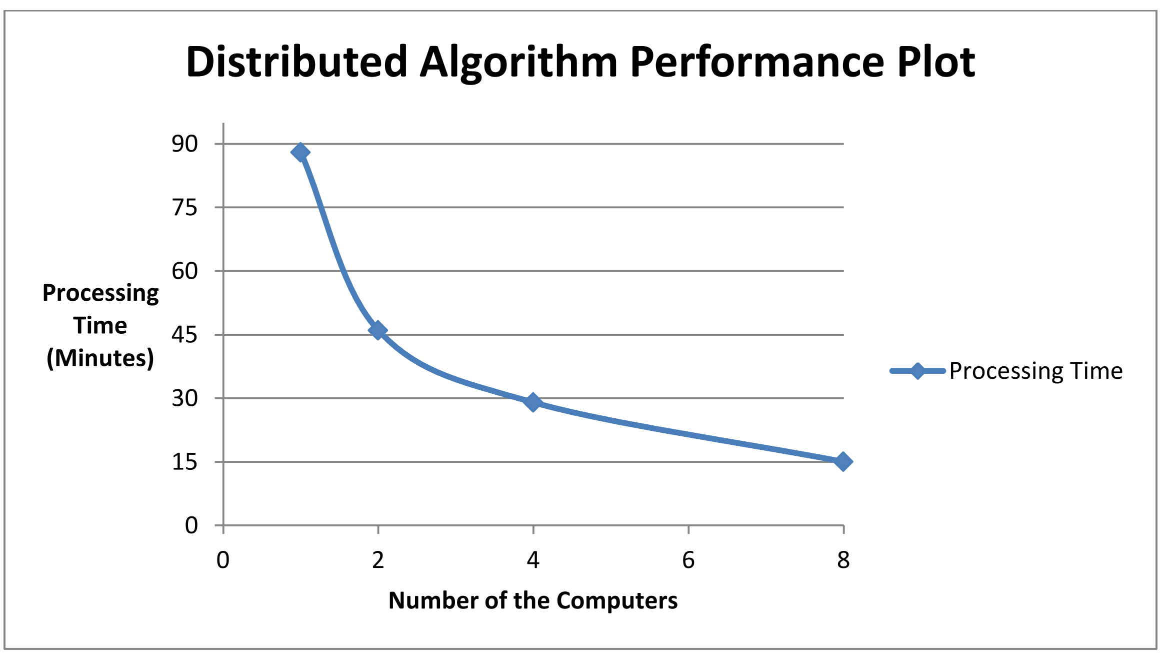


**Figure 3.10 Distributed Algorithm Performance Plot**

The following observations can be concluded from Table 3.6 and Figure 3.10:

- The processing time is significantly decreased and thus the overall performance is effectively improved.
- The overall running time is approximately linearly scaled down. However, performance analysis itself could not be parallelized in the algorithm proposed in this thesis for every single feeder, the linear scalability holds only when the quantity of feeder needed to be analyzed significantly surpass the available amount of computers.
- Overhead exists as a result of communication between circuit server and feeder performance workers
- As the overall running time is affected by computation time and communication time and it is roughly linearly scaled down, it can be concluded that the computation time dominates the communication overhead time.

# CHAPTER 4 Conclusions and Future Work

## 4.1 Conclusion

This thesis investigates feeder performance analysis of electric power distribution systems with distributed algorithm. To the best of the author's knowledge, it is the first time that this detailed performance analysis is researched, developed and tested, using a diakoptics based tearing method and Graph Trace Analysis (GTA) to split the system so that it can be analyzed with distributed computing technology.

The main contributions of this work are summarized as follows:

- **Detailed feeder performance analysis of electric power distribution system is conducted with case studies on real world systems.**
    - ✓ Built up on DEW, Power flow analysis, and LMP analysis as the groundwork, feeder performance analysis of electric power distribution system computes a modeled circuit's performance over an entire year, listing key circuit performance parameters such as efficiency, loading, losses, cost impact, power factor, three phase imbalance, and capacity usage, providing detailed operating information of the system.
    - ✓ By analyzing the whole system, it provides an overall view of the performance of every circuit in the system, providing the ability to target the inefficient circuits, three phase imbalance or cost impact and others.

- **Real time Locational Marginal Price (LMP) is used to evaluate the cost**

LMP analysis is implemented to convert non-standard LMP data to standard data. By incorporating standard LMP data with feeder performance analysis, the performance of circuits is accurately measured with concrete cost.

- **Distributed computation technology is utilized to speed up the computation**

Based on a diakoptics tearing method and Graph Trace Analysis, a distributed computing architecture is proposed. The distributed computing algorithm is described with Graph Trace Analysis. The performance improvement is demonstrated through a real world system case study.

## 4.2 Future Work

The following work is recommended as possible future improvements:

- **A performance based planning tool may be researched and developed based upon feeder performance analysis.**

Performance analysis can help planners to target the best design from among many feasible designs that might work for their system by simulating the plan first on computer. It is not only meaningful but also practical to have a planning tool researched and designed based on feeder performance analysis presented in this work.

- **The distributed computing architecture may be extended to other analysis.**

As the distributed computing architecture proposed in this work is a general one, it is possible to extend it to other analysis of electrical power distribution systems other than feeder performance analysis.

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