PROBABLISTIC ARGUMENTATION FOR DISTRIBUTION POWER RESTORATION

BY

SANTI KAISAARD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (ENGINEERING TECHNOLOGY)

SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
THAMMASAT UNIVERSITY
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Abstract

PROBABILISTIC ARGUMENTATION FOR DISTRIBUTION POWER RESTORATION

by

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Distribution service restoration aims at finding a sequence of switching operation to restore the load in the healthy areas after the occurrence of the power outage. The tasks of a system operator are to construct, evaluate and choose the feasible restoration plan for dealing with the problem under considering multiple objectives and constraints. This thesis proposed an integrated approach for distribution service restoration problem. We first propose a simulation-based framework integrating multiple knowledge sources by a heuristic which representing the expertise of experienced operators which are used to construct a possible plan and DIgSILENT PowerFactory Program which is adapted to calculate the objective functions and operational constraints. Then, we construct knowledge of restoration plan by Probabilistic Argumentation Framework that integrate different information sources e.g. the results of simulating of the plan by simulation software. We demonstrate about the degree of provability that the plan w.r.t multiple objectives and constraints can be obtained merely by harnessing the automated probabilistic and logical reasoning within Probabilistic Argumentation. A Case study has illustrated the capability of the proposed approach.

Keywords: Probabilistic Argumentation, Distribution Power System, Service Restoration
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Fault in distribution power systems is unpredictable, and often results in a power outage to customers. Because of the serious consequence for customers and electric utilities, restoring the power supply as quickly as possible is very important. The ability of quickly restore a power back to customers not only can reduce the effect of the damage to customer but also maintain the revenue earns for electric utilities. Service restoration is a key process of electric utilities that using after the occurrence of the power outage. The aim of this process is to transfer the customer in the out of service area to the supporting and lateral feeders thought a switching operation, considering criteria of multiple objectives and operational constraints. This process is performed under emergency and is a limited time to deal with the problem. It is a task for system operators. After fault areas is located and isolated, service restoration plan need to be constructed by considering under the multiple objectives and main operational constraints. For example, minimize the load unrestored, maintain the radial network topology. Each service restoration plan are different in network configuration that lead to the difference of service quality. Choosing a suitable service restoration plan that satisfy multiple objectives and operational constraints is a task of system operators. In addition, service restoration normally preformed under the emergency condition. It is a Time limited for finding the plans. Therefore, supporting system has been crucial to quickly evaluating plans to deal with a service restoration problem. Figure 1.1 shows dispatching Control Center of Provincial Electricity Authority (PEA) in Thailand.

Figure 1.1 Dispatching Control Center of (PEA), Thailand
1.1 Statement of the Problem

Although, many electric power companies deploy an outage management system (OMS) which is a function in the supervisory control and data acquisition (SCADA) to help the system operators manage and correct the power outage problem that responds to a fault on distribution power system. That system seems to be the best way to restore as much customer (load) as possible, but it still relies on experience and expertise of each system operator. Due to the difficulties of viewing all the variables involved in obtaining the solution, the number of possible solutions and limitation of time to find and choose the feasible service restoration. Figure 1.2 shows system operator in the control room.

Currently, the problem of distribution system restoration become more and more difficult when the network is more complicated. The widespread of distribution network due to the increasing of demand, the growing of considerable number of distributed generator which is un-reliability source such as wind power and solar power and increasing in level of uncertainty due to renewable resource and electric vehicles which are connect into the distribution network, are significant factors for analyzing and solving the distribution system restoration and also are the barriers and the challenge for operator to recover the distribution system.

Figure 1.2 System operator in the control room

Base on the above, it is essential to have a solution to choose the feasible service restoration plan in the short time when a fault occurs.

My research proposes a new evaluation framework, which helps the system operators to evaluate and choose the plans that satisfy multiple objectives and operational constraints in service restoration problem.
1.2 Objective of Thesis

My thesis study the distribution service restoration techniques in the real world applications to assisting operator during the service restoration process. Our focus is devoted to finding and designing an application technique to enhance restoration system to restore the restoration quickly.

1.3 Significance of Thesis

My research proposes an evaluation framework for feasible restoration plans which help the system operators for decision-making when a fault occurs in each area of the distribution power system. It is useful for a system operator of electric utilities, and their customer is as follows:

For Operator:

- To help the system operators in evaluating and choosing a feasible restoration plan in distribution system restoration
- To reduce the operators’ errors due to the wrong decision. For example, the selected restoration plan which is unfeasible may cause the under/over voltage to that is harmful to customer’s electric appliance or may cause overloading in some backup feeder/transformers that are followed by a blackout in the distribution system.
- To improve the restoration process that rapidly responds to the outage event.

For electric distribution companies

- To increase the customer satisfaction and service reliability because of fast service restoration.

For customers:

- To reduce the outage time when a fault occurs because of the quick decision of the system operator.

1.4 Thesis Organization

This thesis starts with an overview service restoration in distribution power system. Then we discuss a statement of the problem, Objective of the thesis, and significant of the thesis. Chapter 2 is a background and literature review. Chapter 3 is a methodology using in this thesis. Chapter 4 shows the results of a case study. Our thesis conclusions are in Chapter 5.
Chapter 2
Background and Literature Review

Due to the modern society relies on the electric energy in everyday life. Power outage because of the occurrence of faults is a critical issue for electric utilities. To reduce the effect on customers and maintain a sequent revenue earned of utilities, it is essential to supply the power back to all customers as quickly as possible after a power outage occurs. Service restoration in distribution power system aims to supply back to customers after a fault isolated by using a switching operation and considering the multiple objectives and operational constraints.

Current, the service restoration problem has been complicated by the growth of electric demand, enormousness, and complexity of the system. For example, the connection of many distributed generation (DG) that it is a task of the system operator to know the actual load in service restoration solving. A various approach has been proposed methods and techniques to deal with a service restoration problem from a different viewpoint and interests [1,2,3]. In this section, a literature review related to a distribution service restoration is presented. It begins with the overview of distribution emergency operation and service restoration problem focusing on a line fault (feeder fault). The second section is an overview of objectives and operational constraints. In the third section information related a distribution service restoration is presented. The review of some method and techniques related in this research are discussed in the final section.

2.1 Overview of Emergency distribution operations

Generally, Distribution power system is an overhead line and open-loop radial structure. The line is installed on the pole along the road throughout the country. The outage causes can be easily by many reasons such as tree touching, animal, human accident or natural risk for instance lightning, a rainstorm, etc. Power outage is a critical condition for both customers and electric power utilities. In [4] the authors give a brief of emergency distribution operation after a fault occurs. The sequences are as follows: fault diagnosis, fault location, fault isolation, service restoration, repair, and returning to the normal state. Figure 2.1 shows the sequence of the emergency distribution operation.

![Figure 2.1 the sequence of emergency distribution operation](image-url)
In the fault diagnosis step, system operators acknowledge the fault event form real-time control and monitoring system in the dispatching control center. For example, device alarm. In some cases, the available data is from the filed crew, operator in a substation and customer’s trouble call. Figure 2.2 shows the substation operator diagnosis in the substation control room.

![Operator in the substation](image)

Figure 2.2 Operator in the substation

The second step is a fault location. Usually, the solutions to know the fault location are the alarm detection form automatic controlled switches, field crew, and customer’s called. Figure 2.3 shows the example of fault detection alarm using in the fault location and Figure 2.4 shows the finding of fault location by field crew.
Then, after the fault step, the damaged element isolated by step in fault isolation. Switches operation is used to isolate the area of fault. As soon as the fault areas is isolated, the next step is service restoration. This step is to the power back to the customer who located in the healthy area by switching operation. The primary objective of this step is fast to restore the power to the customer as much as possible. The quick restoration depends on a capability in switching operation. System operator first selects the remote-controlled switch but manually switch that performed by field crew remain.
uses in some cases. Figure 2.5 shows the remote-controlled and manually switch. The network topology changes in the restoration step until the faulted area is repaired and the power can energize back to the faulted area. Therefore, it is necessary to maintain the electric operational constraints that related to the service quality of customer and main power network. For example, the voltage level is in the standard, an electrical element such a line is not overloaded.

2.2 Distribution Service Restoration Process and Problems

When an outage occurs in the distribution system, some customers that are in the healthy out-of-service areas should energize the power back as soon as the fault areas are located and isolated. Service restoration aims at transferring the load in the out-of-service areas to backup feeders via switching operation. A suitable restoration plan is constructed under the criteria of objectives and operational constraints as soon as a fault area is detected and located.

To illustrate the general service restoration process, consider a distribution power system of the Provincial Electricity Authority (PEA), Thailand as shown in Figure 2.6. Assume that a fault occurs at point F on feeder F1, the sequence of switching operation is as follows:

When a fault occurs, the circuit breaker CB_F1 trip to isolate the fault for power equipment protecting. All of the load on feeder one is interrupted.
Then, the system operator finds out the fault location and isolate the fault by open the section switch S1. In the distribution power system with feeder automation function, the fault location is identified and isolated by the SCADA system, but some case of fault location and isolation are performed by crew field. After the fault location and fault isolation process, the operator will look for the backup and lateral feeder to energize the electricity to the customer in a downstream of switch S1 by using the switching operation. In this case, the operator has three alternatives are as follows:

1) Close switch S4 (transfer the customer to feeder F2)
2) Close switch S6 (transfer the customer to feeder F5)
3) Close switch S7 (transfer the customer to feeder F4)

Although this case has many alternatives for service restoration problem, Choosing the service restoration plan is a task of system operators that consider under a multiple objective and operational constraints. For example, the plan must restore the load as much as possible, and electric components are not overloading capacity, a voltage of the system is in the standard quality of the utility.

Finally, the last step is repairing the damaged network element and returning the system to the normal state, respectively.
2.2.1 Switching operation and Operation Rule

In an emergency distribution operation. Switching operation is used for service restoration process by changing their statuses. To described a switching operation and switching sequence rule, a typical distribution system of PEA is employed. This model consists of three substations, three main feeders, 8 loads zone, and 8 switches. It is a part of 22 kV distribution power system. The system shows in a Figure 2.7.

![Diagram of typical distribution power system]

Figure 2.7 example of typical distribution power system

Suppose that a fault occurs between switch S1 and switch S2. The main circuit breaker CB1 trips to isolating a fault. After a fault is isolated, the first switching operation and sequence is isolating an area of fault by opening the switch S1 and switch S2. Then it is a process of service restoration. The basic switching operation and switching sequence rule can describes as follows:

Rule 1: recovering from the main feeder
After a faulted area is isolated, some out-of-service area can be restored from the same source point by reclosing the circuit breaker that were tripped.

Rule 2: Group restoration
If the supporting feeders have enough spare capacity for the entire outage loads, the entire outage loads can transfer to the supporting feeder by closing a switch.

Rule 3: Zone restoration
If the supporting feeders does not have enough spare capacity for the entire outage loads, the entire outage loads are divided into several zones. Then each zone can transfer to the supporting feeders.

Rule 4: Load Transfer
If each of the supporting feeders does not have enough spare capacity for the entire outage loads and zone restoration cannot use, load transfer is applied to solve the service restoration. The supporting feeders have to decrease by transferring some load zone to lateral feeder before the entire outage loads transfer to them.
Rule 5: Combination techniques  
This rule is applied all of rules to solve the service restoration problem. System operator use all of rule in a switching operation varying on the situations.

For the service restoration problem in Figure 2.8, possible switching operation of the service restoration plan shows in the Table 2.1

Table 2.1 Alternative switching operation for service restoration

<table>
<thead>
<tr>
<th>Solution</th>
<th>Rule</th>
<th>Operated switch</th>
<th>Switch status</th>
<th>Load unrestored</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Group restoration</td>
<td>S4/S6</td>
<td>close</td>
<td>L01</td>
</tr>
<tr>
<td>2</td>
<td>Zone restoration</td>
<td>S3, S4, S6</td>
<td>open close</td>
<td>L01</td>
</tr>
<tr>
<td>3</td>
<td>Load transfer</td>
<td>S7, S6, S8</td>
<td>open close</td>
<td>L01</td>
</tr>
<tr>
<td>4</td>
<td>Combination techniques</td>
<td>S3, S7, S4, S8, S6</td>
<td>open close</td>
<td>L01</td>
</tr>
</tbody>
</table>

2.2.2 Objective Function and Constraints
To energize the electricity back to the customers that are in the healthy out-of-service areas by switching operations, system operators construct and choose the restoration plans base on main operational constraints and acceptable objective of their utilities. Therefore, the service restoration problem is a multiple objective and multi-constraints optimization problem. Many research in [1-5], proposed and considered the objectives and constraints summarized as follows:

2.2.2.1 Objectives Functions
(1) Restoring as many load as possible
The main primary objective of service restoration is to restore as many loads as possible. In [5,6], the authors add the customer priority (For example, a hospital, large industrial factory, traffic light, etc.) in their objective consideration. Recently, in [5] a load priority model for distribution system restoration is proposed and generalized the application model in a smart grid. The priority of load is estimated base on a criteria load classification and the level of load priority. However, the out of service customers can receive the power or not depend on the fault location and network topology of distribution system.
(2) **Minimizing the number of switching operations**

Service restoration used a switching operation transferring the healthy out-of-service customer to the backup feeder when an outage occurs in the distribution systems. Therefore, the quickness of recovering the power relies on the capability of switching operation process. Minimizing the number of switching operation is the main constraint of many studies in [7-8]. In distribution power system, switches are installed because of switching operation in emergency condition and maintenances. The type of switching can divide into two types (manually controlled switch and remotely controlled switch). The operating time of both switches are different. Remotely controlled switches use only a few seconds because it can operate by system operators on the control room center. On the other hand, the manually controlled switch is preform by field crews. Operating time of manually controlled switches depend on many reason such as the weather, the access time switch of crew field. However, minimizing the number of switching operation have to considering the time operating of switch that are different in the service restoration process.

(3) **Minimize the losses**

From Financial and Economic Perspectives, power loss minimization during the service restoration should be considered [8,9,10]. However, it may be not appropriate for service restoration that are performed under an emergency condition unless the repaired step of faulted element take a long time such as 24 hours.

**2.2.2.2 Operational Constraints**

(1) **The redial network structure should be retained.**

The primary operational constraint is to maintain a radial network topology for all feeder for the coordination of protection device, fault location, and fault isolation.

(2) **The bus voltage is in the standard quality**

Because the network topology is changed between the service restoration processes, therefor it is necessary to maintain the voltage level of the system within the standard to protecting the problem in a voltage drop to customer.

Normally, voltage standard is the main part in Quality and Service Standards of electric utilities. It can divide into two main parts: normal condition and emergency condition. Table 2.2 shows a standard voltage of Provincial Electricity Authority, Thailand
Table 2.2 Standard voltage of Provincial Electricity Authority, Thailand [11]

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Voltage Standard</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Normal Condition</td>
</tr>
<tr>
<td>115kV</td>
<td>109.2-120.7kV (± 5%)</td>
</tr>
<tr>
<td>33kV</td>
<td>31.3-34.7kV (± 5%)</td>
</tr>
<tr>
<td>22kV</td>
<td>20.9-23.1kV (± 5%)</td>
</tr>
<tr>
<td>220V</td>
<td>200-240V</td>
</tr>
<tr>
<td>380V</td>
<td>342-418V (± 10%)</td>
</tr>
</tbody>
</table>

(3) All network element are not overload capacity.

To protect that between the service restoration processes will not cause further outage due to the overloading capacity of electric network element. System operator have to careful concern about the element capacity. For example, supporting feeder capacity, main power transformer capacity. Many research only consider the capacity of supporting feeder in their main constraint [2,7,8] that neglect to mention the main power transformer capacity in the substation. However, to maximize the load restored, in some case, the authors in [12] consider overloading the power transformer in the substation up to 133% of their rated capacity. In [13] the authors concern about the problem of transformer overloading in the operational constraint.

2.3 Practical Issues Related to the Service Restoration Problem

Service restoration is a combinatorial optimization problem. To extend a feasible and quickly practicable service restoration, operator constructs and selects the feasible plan by considering base on the operational constraints and multiple objective that vary to case by case. To understand the practical operational problem of the service restoration which has been addressed in this propose in this problem [2,4], this section is described and summarized in an actual issue that related to the service restoration problem as follows:

- When have fault occur following the outage of power to customers, the principal objective of service restoration in practice quickly supplies the power to the load that located in the healthy out of service areas as much as possible under the main operational constraints. For example, voltage limits.
- Service restoration aims by transferring the loads in the out-of-service area to supporting feeders through a switching operation considering the criteria of objectives and constraints. The first necessary process is diagnosed the fault and isolated the fault location. Second is find the information, such as preload of the out-of-service regions, the current load of supporting feeder and main power transformer, etc. the last one constructs the restoration plans, selected the plan and done.
- Service restoration plan is performed by changing the switches status in the distribution power system. Hence, the time taken by the service restoration relies on the number of switching operation. Therefore, minimizing the number of switching
operation should be kept to the minimum as possible. Using a small amount of the switch can reduce the possibility of switching surge that caused of the further power outage in the power system and also overcome the problem of transient disturbance. Nowadays, switch in the distribution power system can be divided into two type by the capability of operation, manually controlled switch and remote-controlled switch. The operation time of remote-controlled switch may be only 50 s while manually controlled switch are 1200-1500 s [2] that depending on many reasons such as weather, traffic conditions. Therefore, it is necessary for considering not only the number of switching operation but also the type of switch during the service restoration.

- In the distribution system, it has much type of loads. High Load priority (such as, hospital, big industrial factory, traffic light, etc.) should be first priority to take care and supply the power to them first after the occurring of outage. This is the main object of utilities but it depends on the network structure of the system and the fault location.

- Usually, the topology of the distribution power system is a radial network for three main reasons as follows: fault location, fault isolation, and system protection coordination. Therefore, it is essential to maintain the radial network topology of the system even though the network topology is changed in the service restoration process.

- To protect the system equipment from overloading, considering the limitation of system, such as power transformer, line and switches capacity limit. In constructing and selecting the service restoration plan, system operator has to considering the load variation in the service restoration problem. Time duration of outage occurrence has the effect in selecting the service restoration plan. For example, some plan can use in the light load period but it cannot use in the peak load period which may cause overloading in supporting feeder line. In addition, system operator will use technique that reduce some load of supporting feeder before transferring all of loads in the out of service area avoiding the overloading of the supporting feeder or some load may be out of service until the area part of faulted is cleared.
2.4 Load informations

To achieving some objective function and operational constraints in the service restoration after identifying a fault location and isolation a faulted area, load information is essential in considering and constructing a service restoration plans. In [7,14] the authors consider the pre-fault load current in the service restoration problem. On the other hand, a peak load current used during service restoration. However, in normal operating condition. Loading current of the distribution system changes related to the load type and customer’s behavior. Fig. 2.7 shows an example of feeder load variation in the distribution system of the Provincial Electricity Authority (PEA) of Thailand. Load variation is a characteristic of load varying the type of loads customer’s behavior. In [2] the authors used a load variation in the plan constructing step by taking load variation in his consideration. He suggests that load variation should consider during the building the service restoration plans. The reason why considering available load information is essential can describe are as follows:

2.4.1 Pre-fault load
If the system operators consider the pre-faulted load current for constructing a service restoration plan, it may cause the component overloading such as backup feeder overloading, power transformer overloading.

2.4.2 Peak load
If the system operators consider the peak load current for constructing a service restoration plan, it provides a service restoration plan with high-level voltage profile, lower feeder current, lower system losses. To preventing the component overloading, the peak load should use in constructing service restoration plan. However, using a peak load may lead to losing the opportunity to restore some loads in restoration and need to more switching operation.

2.4.3 Load variation
If the duration for fault repair takes a long time, constructing a service restoration plans using a load variation can stop the need for further switching operation. The reducing the number of switching operation can reduce the likelihood of switching surge caused the power outage and the risk of power outage due to using more switching operation.
2.5 Methodology applied to restoration algorithms

Currently, service restoration in distribution power system remain is a main problem for electric utilities. With the growth of the power distribution network and many connected of distributed generation (DG), it makes a service restoration more and more complicated. Many research have been proposed to solve the service restoration problem form different prospective or interest. In [15-20] heuristics method and expert system[21-26] have been proposed by using the knowledge base of system operator to get a service restoration plan. The objective of them is to fast determine restoration plans which satisfy for distribution personal. In[4] the authors summarize the modern algorithms for distribution service restoration problem. Several studies, such as, In [27-30] apply a soft computing algorithm to find a better solution. Their approach points to find the restoration plan that satisfy some criteria more than make a quantitative comparison with another plans. In the practical, to solve the service restoration problem that is a multiple objectives multi constraints optimization problem, system operator will chose the feasible restoration depending on situations varying case by case. In the same cause, each system operator may be have a different thinking and decision-making depending on the experience of operator. Therefore, the providing of relative performance of each restoration plan and enough information is better than give only the best feasible restoration plan.

Wen-Hui Chen [7] proposed a new concept for choosing restoration plans in distribution power systems using the Grey Relational Analysis (GRA) and the Analytical Hierarchy Process (AHP) approach. His concept analyzed the preference ranking of each restoration plan by GRA and applied AHP to handle with assessing the weighting values of each objective function. This concept is fast to find a relationship among service restoration plan but the result could get worse in case of the compared valve become diverse. The main weakness in his concept is lacked the ability to deal with uncertainty which exciting in operator’ heuristic rule.
In [1] the authors proposed method combining the fuzzy multi criteria evaluation and the grey relational analysis to deal with imprecise linguistic descriptions in the operators' heuristic rules and judge the ranking of preference for each feasible restoration plan. Their approach is not well suitable to practical because it lack to consider a numerical weight or priority of each objective functions and consistent way.

In [7] the quantitative evaluation framework has been present for evaluating restoration plans and highlighted the concept of relative performance index. Optimization techniques like Ant-Colony Optimization can be applied when the number of possible plans is very large [2,31]. Even though a large number of restoration problem already proposed, in the practical power restoration is remain a manual process responsible by experienced operators. This is perhaps proposed are not general or flexible enough to be applied in actual practice of service restoration.
Chapter 3

Methodology

Service restoration process in distribution system is usually refer as emergency operation. It concentrates on constructing and choosing a feasible plan to deal with a problem that vary to situation and situation. In this section, we proposed a method for distribution service restoration. First section presents the simulation-based framework for distribution service restoration to constructing and finding a possible service restoration plans. Heuristic representing the expertise of experienced operators are used to construct a possible plan. The software program used to compute objective functions and operational constraints was DigSILENT PowerFactory. Then we structure knowledge of a restoration plan by a Probabilistic Argumentation Framework integrating different information source notably the result of simulating the plan by simulation software. We demonstrate that the degree of provability that a plan ensures multiple objectives and constraints can be obtained simply by harnessing the automated Probabilistic Argumentation.

3.1 A Simulation-Based Framework for Distribution Service Restoration

The process of service restoration aims at finding a service restoration plans to restore the load in the out of service areas by using the switching operation. Possible plan need to be constructed, then compared according to how their executions shall realize declare objectives and constraints. In this section, we proposed a Simulation-Based Framework for Distribution Service Restoration. Heuristic representing the expertise of experienced operators are used to construct possible plans and DigSILENT PowerFactory Program was adopted to compute the plans under considering multiple objectives and constraints. The framework is graphically illustrated by Figure 3.1.
To demonstrate the proposed framework, we observed and described current practices at Provincial Electricity Authority (PEA) in Thailand. Figure 3.2 shows a distribution power system under its management that consists of 3 substations, 5 feeders, 26 loads, 19 switches and 12 load zones. This system has a main power circuit breaker to protect the line and install the switches (manual control and remote control switches) to isolate the faulted area. Electricity from substations flow through a feeder’s line and switches to be consumed at loads. Load supported by the same feeder from a zone. Each zone connects to others via switches. Each feeder line is separate between them by opened tie switches. The spare capacities of supporting/backup feeders and total load of zones are observed frequently by Supervisory Control and Data Acquisition (SCADA) system which is real time data monitoring. Feeder and zone loads often vary during time of day depending on the characteristic of loads. Table 3.1 is a typical example of SCADA’s observations at the peak load and light load period. Figure 3.4 shows SCADA’s observations for daily load (the loads within 24 hours).
Figure 3.2 A power distribution network of Provincial Electricity Authority, Thailand

Table 3.1 Pre-fault feeder and zone load data (SCADA’s observations)

<table>
<thead>
<tr>
<th>Light Load Case</th>
<th>Feeder [MW]</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone [MW]</td>
<td></td>
<td>Z1</td>
<td>Z2</td>
<td>Z3</td>
<td>Z4</td>
<td>Z5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22</td>
<td>0.22</td>
<td>1.53</td>
<td>0.57</td>
<td>0.64</td>
</tr>
<tr>
<td>Zone [MW]</td>
<td></td>
<td>Z8</td>
<td>Z9</td>
<td>Z10</td>
<td>Z11</td>
<td>Z12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.89</td>
<td>1.89</td>
<td>0.64</td>
<td>5.20</td>
<td>1.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Load Case</th>
<th>Feeder [MW]</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone [MW]</td>
<td></td>
<td>Z1</td>
<td>Z2</td>
<td>Z3</td>
<td>Z4</td>
<td>Z5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.35</td>
<td>0.35</td>
<td>2.39</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>Zone [MW]</td>
<td></td>
<td>Z8</td>
<td>Z9</td>
<td>Z10</td>
<td>Z11</td>
<td>Z12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.53</td>
<td>2.53</td>
<td>1.03</td>
<td>8.36</td>
<td>2.66</td>
</tr>
</tbody>
</table>
Now suppose that a fault occurs at Z1 in feeder 1. The circuit breaker CB1 will trip automatically to isolate the fault, causing a power outage in all zones from Z1 to Z5. Assume that the operator has opened switch S1 to isolate the fault. Now he needs to find a plan to restore power for all loads in the outage area, which consists of zones from Z2 to Z5 (see Figure 3.2). The first step is to construct possible plans. Here by experience the operator often applies several heuristics, for example: H1 (Group restoration): If supporting feeders have enough spare capacity for the entire outage area, then close a normally opened switch between these feeders and the outage area; H2 (Zone restoration): If the supporting feeder does not have enough spare capacity, then close a normally opened switch to transfer some load of the outage area to a lateral feeder; H3 (Load transfer): The capacity of a supporting feeder can be increased by transferring some part of its load to other feeders. One application of a heuristic gives rise to one switching operation, hence to construct a plan, the operator may need to apply different heuristics multiple times, as illustrated by Table 3.2 Once the operator has constructed possible plans, he needs to evaluate how each plan satisfies predefined objectives and constraints. Table 3.3 below lists common objectives and constraints.

Figure 3.3 SCADA’s observations for daily load (the loads within 24 hours).
Table 3.2 Construction of possible plans by applying heuristics

<table>
<thead>
<tr>
<th>Plans</th>
<th>Switching operations</th>
<th>Applied heuristics</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>Close S8</td>
<td>H1</td>
</tr>
<tr>
<td># 2</td>
<td>Close S3</td>
<td>H1</td>
</tr>
<tr>
<td># 3</td>
<td>Close S6</td>
<td>H1</td>
</tr>
<tr>
<td>#4</td>
<td>Open S4, Close S3,S6</td>
<td>H2</td>
</tr>
<tr>
<td>#5</td>
<td>Open S4, Close S3,S8</td>
<td>H2</td>
</tr>
<tr>
<td>#6</td>
<td>Open S5, Close S3,S8</td>
<td>H2</td>
</tr>
<tr>
<td>#7</td>
<td>Open S5, Close S3,S8</td>
<td>H2</td>
</tr>
<tr>
<td>#8</td>
<td>Close S17, S8, Open S15</td>
<td>H3,H1</td>
</tr>
<tr>
<td>#9</td>
<td>Close S17,S8, Open S16</td>
<td>H3,H1</td>
</tr>
<tr>
<td>#10</td>
<td>Close S17,S3,S8, Open S15,S4</td>
<td>H3,H2</td>
</tr>
<tr>
<td>#11</td>
<td>Close S17,S3,S8, Open S15,S5</td>
<td>H3,H2</td>
</tr>
<tr>
<td>#12</td>
<td>Close S17,S3,S8, Open S16,S4</td>
<td>H3,H2</td>
</tr>
<tr>
<td>#13</td>
<td>Close S17,S3,S8, Open S16,S5</td>
<td>H3,H2</td>
</tr>
</tbody>
</table>

3.1.1 Objective and Constraints In DlgSILENT

The DlgSILENT Program Language (DPL) is applied to compute the objective function and constraints in each plan in table 3.2. The DlgSILENT Program Language (DPL) is a flexible interface for automating the task in DlgSILENT PowerFactory Program. Users can generate advanced calculation functions and specify the calculation commands that can be applied in any field of power system analysis.

The objective functions and operational constraints: the unrestored load, the number of switching operation, the power loss of the system, radial network, bus voltage, and current of feeder line can compute by using the DPL.
Table 3.3. Objectives and constraints

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Input parameters</th>
<th>Information sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize the unrestored load</td>
<td>$f_1 \triangleq \sum_{i=1}^{N_{bus}} L_i k_i$ (unit : MW)</td>
<td>DIgSILENT</td>
</tr>
<tr>
<td></td>
<td>$N_{bus}$: the number of restored buses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$L_i$: the load at the $i^{th}$ bus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_i$: the status at the $i^{th}$ bus</td>
<td></td>
</tr>
<tr>
<td>Minimize the operation time</td>
<td>$f_2 \triangleq \sum_{i=1}^{N_s} OT_{Ai} + OT_{Mi}$ (unit : second)</td>
<td>DIgSILENT</td>
</tr>
<tr>
<td></td>
<td>$N_s$: the number of switching operations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$OT_{Ai}$: the operation time of a remote-controlled switch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$OT_{Mi}$: the operation time of a manually-controlled switch</td>
<td></td>
</tr>
<tr>
<td>Minimize the power loss</td>
<td>$f_3 \triangleq \sum_{j=1}^{N_b} (</td>
<td>I_j</td>
</tr>
<tr>
<td></td>
<td>$N_b$: the number of branches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$I_j$: the current of the $j^{th}$ branch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_j$: the resistance of the $j^{th}$ branch</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Input parameter</th>
<th>Information sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain the radial network: $C_1$</td>
<td>-</td>
<td>DIgSILENT</td>
</tr>
<tr>
<td>Bus Voltage in range</td>
<td>$V_j = \text{the voltage at } j^{th} \text{bus}$</td>
<td>DIgSILENT</td>
</tr>
<tr>
<td>$C_2 \triangleq V_{min} \leq V_j \leq V_{max}$</td>
<td>$V_{min}$: minimal standard voltage</td>
<td>Power company's policy[11]</td>
</tr>
<tr>
<td></td>
<td>$V_{max}$: maximal standard voltage at $j^{th}$ bus</td>
<td></td>
</tr>
<tr>
<td>Feeder line currents in range</td>
<td>$I_j = \text{the current at } j^{th} \text{line}$</td>
<td>DIgSILENT</td>
</tr>
<tr>
<td>$C_3 \triangleq I_j \leq I_{max}$</td>
<td>$I_{max} = \text{maximally allowed currents}$</td>
<td>Power company's policy[11]</td>
</tr>
</tbody>
</table>
Intuitively the more a plan minimizes important objective functions, the greater its degree of “fitness” will be. A plan falsifying a constraint will be considered as totally unfit. Here mathematically an objective (resp. constraint) is a real-valued (resp. boolean-valued) function taking two kinds of input parameters: 1) system parameters are those intrinsic to the power distribution system and often they can be computed from a physical description of the system, and 2) environment parameters are those extrinsic to the power distribution system and often they come from the environment. For example, all input parameters of objective function $f_1$ (determining the amount of unrestored load) are system parameters, while for $C_3$ (feeder line currents must be in range), $I_{js}$ are system parameters, however $I_{max}$ is an environment parameter since it is specified by the power company. This classification is not meant to be clear-cut, but often it makes sense, and more importantly, it suggests that we can obtain approximations of system parameters by physically simulating a plan. Indeed in our previous work [32], we have demonstrated the idea by specifying power distribution systems within DIgSILENT PowerFactory[33] - an industrial-strength power system simulation software. We then develop a module that reads system parameters from DIgSILENT Power Factory, environment parameters from other knowledge bases (e.g. power company’s policies) and produces as output values of objective functions and constraints. Table 3.4 shows the outputs of the module for Plan #1 (Close S8): in a light-load period, $f_1 = 0.220$ and $C_3$ is fulfilled; however, in a peak-load period, $f_1 = 0.35$ and $C_3$ is unfulfilled. Recall that $C_3 \triangleq I_j \leq I_{max}$ where $I_{js}$ are system input parameters. Therefore, the values of these $I_{js}$ are provided by DIgSILENT, as illustrated by a graphical user interface of DIgSILENT in Figure 3.5.
Table 3.4. Simulation results of plan#1

<table>
<thead>
<tr>
<th>Objectives and Constraints</th>
<th>Plan#1 in light load</th>
<th>Plan#1 in peak load</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>0.220</td>
<td>0.350</td>
</tr>
<tr>
<td>f2</td>
<td>1,200</td>
<td>1,200</td>
</tr>
<tr>
<td>f3</td>
<td>0.2301</td>
<td>0.4575</td>
</tr>
<tr>
<td>C1</td>
<td>fulfilled</td>
<td>fulfilled</td>
</tr>
<tr>
<td>C2</td>
<td>fulfilled</td>
<td>fulfilled</td>
</tr>
<tr>
<td>C3</td>
<td>fulfilled</td>
<td>unfulfilled</td>
</tr>
</tbody>
</table>

Figure 3.5 A simulation of Plan #1 by DIgSILENT
3.2 Probabilistic Assumption-based Argumentation

After, we already have compute the objective function and constraints of each possible plans by simulating software. This section we focus on the evaluation of a specific plan once its sequence of operations has been identified. We view this evaluation as consisting of two steps in an overarching argumentation-based model of service restoration shown in Figure 3.2: 1) constructing a knowledge base $\mathcal{P}$ about the plan; 2) reasoning within $\mathcal{P}$ to compute the degree of provability that the plan ensures desired objectives and constraints.

In general, the knowledge base $\mathcal{P}$ about a plan consists of a probabilistic (quantitative) part $\mathcal{P}$ (containing, for example the degree of belief of the operator about the reliability of the simulation or about the current load status (light or heavy) of the power network) and a logical (qualitative) part $\mathcal{F}$ (containing, for example the logical rules to compute the overall degree of “fitness” of the plan). We could represent the probabilistic part $\mathcal{P}$ by a Bayesian net and the logical part $\mathcal{F}$ by a separate logical theory (it is quite unnatural to represent logical knowledge in Bayesian net). The disadvantage of this approach is that we need to perform probabilistic reasoning (within $\mathcal{P}$ using various inference procedures for Bayesian nets) and logical reasoning (within $\mathcal{F}$ using logical inference procedures) separately, and then combine the results manually. To automate also this combination, we have to use a more general knowledge representation model that allows both probabilistic reasoning and logical reasoning. For this, we propose to use probabilistic assumption-based argumentation (PABA) recently proposed in [34, 37].

The logical part of a PABA framework is represented by an assumption-based argumentation framework (ABA) [10, 35].

**Definition 1.** Assuming a language $\mathcal{L}$, an ABA framework is define as a triple $\mathcal{F} = (\mathcal{R}, \mathcal{A}, \overline{-})$ where $\mathcal{R}$ is a set of inference rules of the form $l_0 \leftarrow l_1, \ldots, l_n$ (for $n \geq 0$), $\mathcal{A} \subseteq \mathcal{L}$ is a set of assumptions and is a (total) one-to-one mapping form $\mathcal{A}$ into $\mathcal{L}$, where is $\overline{x}$ referred to as the contrary of $x$. Assumption in $\mathcal{A}$ do not appear in the heads of rules in $\mathcal{R}$. Contraries of assumptions are not assumptions.
- A (backward) deduction of a conclusion \( \pi \) supported by a set of premise \( Q \) is a sequence of set \( S_1, S_2, \ldots, S_n \) where \( S_i \subseteq L, S_1 = \{ \pi \}, S_m = Q \), and for every \( i \), where \( \sigma \) is a selected proposition in \( S_i; \sigma \notin Q \) and \( S_{i+1} = S_i \cup \{ \sigma \} \). For some inference rule \( r \in R \) with head \( (r) = \sigma \).

- An argument for \( r \in L \) supported by a set of assumptions \( Q \) is a (backward) deduction \( \delta \) from \( \pi \) to \( Q \) and denoted by \( (Q, \delta, \pi) \). An argument \( (Q, \delta, \pi) \) attacks an argument \( (Q', \delta', \pi') \) if \( \pi \) is the contrary of some assumption in \( Q \). For simplicity, we often refer to an argument \( (Q, \delta, \pi) \) by \( (Q, \pi) \) if there is no possibility for mistake.

- A set of assumptions attacks a set of assumptions \( A_1 \) iff an argument supported by a subset of \( A_1 \) attacks an argument supported by a subset of \( A_1 \).

Example 1. Consider ABA \( \mathcal{F} = (\mathcal{R}, \mathcal{A}, \neg) \) where \( \mathcal{R} = \{\neg do \leftarrow \neg \neg C_3, \neg do \leftarrow \neg C_2; C_3 \leftarrow do\} \), \( \mathcal{A} = \{do, \neg C_3, \neg C_2\} \) with \( do = \neg do, \neg C_3 = C_3, \neg C_2 = C_2 \) which may represented a service restoration situation with two constraints \( C_2 \) and \( C_3 \). Argumentation for the plan under consideration (denote by \( do \) ) is simply \( A_{rg0} = (\{do\}, do) \). Arguments \( A_{rg1} = (\{\neg C_3\}, \neg do) \) and \( A_{rg2} = (\{\neg C_2\}, \neg do) \) say that the plan under consideration (denoted by \( do \) ) should be given up if it does not satisfy either constraint. Using the rule \( C_3 \leftarrow do \) we can construct another argument \( A_{rg3} = (\{do\}, C_3) \) which attacks \( A_{rg1} \). However we cannot construct any argument that attacks \( A_{rg2} \).

![Figure 3.6 Abstract Argumentation Frameworks.](image)

An ABA framework \( \mathcal{F} \) generates an abstract argumentation framework [36] consisting of arguments and attacks that can be constructed from \( \mathcal{F} \). An abstract argumentation framework could be represent graphically by a graph where nodes represent argumentation and edges represent attacks, as illustrated by Fig.3.6 (a) for the ABA of example 1.

With arguments and attacks defined, all argumentation semantics of abstract argumentation [36] can be applied for an ABA \( \mathcal{F} \), as follows.

- A set of assumptions is admissible iff it does not attack itself and attacks any \( A \subseteq \mathcal{A} \) that attacks it.
- A preposition \( \pi \) is said to be an (admissible) consequence denoted ABA \( \mathcal{F} \vdash \pi \) iff \( \pi \) is supported by some admissible set of assumptions.
Example 2. (Continue Ex 1) \(\neg do\) (but not do) is a sequence of the given ABA \(\mathcal{F}\). However, if we consider only constraint \(C_3\) (by removing the second rule \(\neg do \leftarrow \neg C_2\)), then do becomes a consequence in the new ABA because \(A_{rg2}\) can be no longer constructed (see Fig. 3.6 (b)).

The probabilistic part of an PABA framework is represented by a set of probabilistic assumptions and probabilistic rules as follows.

**Definition 2.** A probabilistic assumption-based argumentation (PABA) framework \(\mathcal{P}\) is a triple \((\mathcal{A}_p, \mathcal{R}_p, \mathcal{F})\) satisfying the following properties.

1. \(\mathcal{A}_p\) is a set of probabilistic assumptions where
   - Elements of \(\mathcal{A}_p \cup \neg \mathcal{A}_p\), where \(\neg \mathcal{A}_p = \{\neg p | p \in \mathcal{A}_p\}\) and \(\neg\) is the classical negation operator, are called probabilistic literals.
   - A possible world of \(\mathcal{P}\) is a maximal (wrt set inclusion) consistent subset of \(\mathcal{A}_p \cup \neg \mathcal{A}_p\).

2. \(\mathcal{R}_p\) is a set of probabilistic rules of the form
   
   \[
   \left[\alpha : x\right] \leftarrow \delta_1, ..., \delta_n \quad n \geq 0, x \in [0,1]
   \]

   Where proposition \([\alpha : x]\), called a probabilistic proposition, represents that the probability of probabilistic literal \(\alpha\) is \(x\).

3. \(\mathcal{F} = (\mathcal{R}, \mathcal{A}, \neg)\) is an ABA framework.

Example 3. (Cont. Ex 1) In practical of service restoration, the operator often has to predict the effect of plans by, for instance, physical simulation. Suppose that for the plan under consideration, the simulation says that \(C_3\) is satisfy only if the power is in a light load period. To represent this, one may change the rule \(C_3 \leftarrow do \leftarrow C_3 \leftarrow do, p_{lightLoad}\) where \(p_{lightLoad}\) is a probabilistic assumption. Therefore, the PABA framework representing the problem is \(\mathcal{P} = (\mathcal{A}_p, \mathcal{R}_p, \mathcal{F})\) where \(\mathcal{F}\) contains \(\neg do \leftarrow \neg C_2\); \(\neg do \leftarrow \neg C_3\) and \(C_3 \leftarrow do, p_{lightLoad}\); \(\mathcal{A}_p = \{p_{lightLoad}\}\); and \(\mathcal{R}_p\) may contain \([p_{lightLoad} : 0.6] \leftarrow \) and \([\neg p_{lightLoad} : 0.4] \leftarrow \) which together say that the probability that the system is in a light load period is 0.6

For each possible world \(\omega\) of PABA \(\mathcal{P} = (\mathcal{A}_p, \mathcal{R}_p, \mathcal{F})\), let’s define ABA \(\mathcal{P}_\omega \triangleq (\mathcal{R} \cup \mathcal{R}_p \cup \{p \leftarrow p \in \omega\}, \mathcal{A}, \neg)\), the instantiation of PABA \(\mathcal{P}\) by the truths that \(\omega\) asserts. ABA \(\mathcal{P}_\omega\) could be also called the PABA \(\mathcal{P}\) condition to \(\omega\).
For example, in Ex 3, \( \mathcal{W} = \{\{p_{\text{lightLoad}}\}, \{-p_{\text{lightLoad}}\}\} \), thus for \( \omega_1 = \{p_{\text{lightLoad}}\} \), ABA \( \mathcal{P}_{\omega_1} \) is obtained from \( \mathcal{F} \) by adding two rules: \( [p_{\text{lightLoad}}: 0.6] \leftarrow \) and \( p_{\text{lightLoad}} \leftarrow \).

Intuitively probabilistic part defined by \( \mathcal{A}_p \) and \( \mathcal{R}_p \) intends to generate a probability distribution over the set of possible world \( \mathcal{W} \). To ensure the coherence of this distribution, the authors in [34] have introduced some conditions on \( \mathcal{R}_p \). In the thesis, we define a simple class of PABAs, called Bayesian that satisfy all conditions in [34] (i.e Bayesian PABAs always generate a coherence probability distribution).

In Bayesian PABAs, \( \mathcal{A}_p \) and \( \mathcal{R}_p \) representing a Bayesian Network by having each rule \( r \in \mathcal{R}_p \) represent one entry of a conditional distribution table. Let \( P_{BN}(\omega) \) denote the probability of possible world \( \omega \) according to the Bayesian Network. The probability of a proposition \( \pi \) being acceptable with \( \mathcal{P}_\omega \) is defined as follows:

\[
\text{Prob}(\pi) \triangleq \sum_{\omega \in \mathcal{W}: \mathcal{P}_\omega \vdash \pi} P_{BN}(\omega)
\]

Example 4. (Cont. Ex 3) Let’s compute \( \text{Prob}(\text{do}) \). There are two possible worlds in \( \mathcal{W} \): \( \omega_1 = \{p_{\text{lightLoad}}\} \) and \( \omega_2 = \{-p_{\text{lightLoad}}\} \). It is easy to say that ABA \( \mathcal{P}_{\omega_1} \vdash \text{do} \) but it is not the case that ABA \( \mathcal{P}_{\omega_2} \vdash \text{do} \). Therefore, \( \text{Prob}(\text{do}) = P_{BN}(\omega_1) = 0.6 \).

3.3 Probabilistic Assumption-based Argumentation Framework for Service Restoration

In this section, we specify a typical structure of PABA for service restoration problem. Assuming a set \( \mathcal{C} = \{C_1, C_2, C_3, \ldots \} \) of constraints, \( \mathcal{O} = \{f_1, f_2, f_3, f_4 \ldots \} \) of objective functions where for each \( f_i \in \mathcal{O} \) there are numbers \( f_i^{\text{min}}, f_i^{\text{max}} \) representing the minimal and maximal values of \( f_i \). The knowledge about a particular plan is represented by such a PABA \( \mathcal{P} = \mathcal{A}_p, \mathcal{R}_p, (\mathcal{R}, \mathcal{A}, \neg) \) that: \( \mathcal{O} = \{f_1, f_2, f_3, f_4 \ldots \} \)

- The underlying language \( \mathcal{L} \) contains: a set \( \{C_1, C_2, C_3, \ldots, \neg C_1, \neg C_2, \neg C_3, \ldots \} \) of propositions representing the satisfaction/dissatisfactions of the constraints; a set \( \{f = r | f \in \mathcal{O}, r \text{ is a number}\} \) of propositions representing predicted values of objective function; and a set \( \{F_1, F_2, F_3, F_4 \ldots \} \) of propositions representing that objective functions \( f_1, f_2, f_3, f_4 \ldots \) are successfully minimized (if \( f_i \) is close enough to \( f_i^{\text{min}} \), then \( F_i \) is true).
- $\mathcal{A}$ contains the following assumptions
  - $\neg C_1, \neg C_2, \neg C_3, \ldots$, where $\neg C_i = C_i$ representing that all constraints can be considered as unfulfilled unless there are evidences on the contrary.
  - $\neg F_1, \neg F_2, \neg F_3, \neg F_4, \ldots$, where $\neg F_i = F_i$ representing that if there is no evidence that $F_i$ is fulfilled, then $\neg F_i$ is assumed.
  - $d o$, where $\overline{do} = \neg d o$, representing the selection of the plan.

- $\mathcal{A}_p$ contains the following probabilistic of assumptions
  - $P_{\text{peakLoad}}, P_{\text{lightLoad}}, \ldots$ representing the uncertain of environment parameters.
  - $P_{\text{reliableSimulation}}(f - C_i)\ldots$, representing the reliability of the simulation in predicting constraint $C_i$ (resp.objective function $f_i$).
  - $P_{\text{importance}}(f - f_i)$ representing the importance of objective function of $f_i$.

- $\mathcal{R}$ contains subsets $R_s$ and $R_g$
  - $R_s$ represents the results of simulating the plan, containing $C_i \leftarrow do, L_1, \ldots, L_n, P_{\text{reliableSimulation}}(f - C_i)$ where $C_i \in C$ is a constraint, $L_1, \ldots, L_n$ are environment atoms (e. g. $P_{\text{peakLoad}}, P_{\text{lightLoad}}$) when the simulation says that executing the plan in environment $L_1, \ldots, L_n$ fulfills constraint $C_i$; and containing $f_i = r \leftarrow do, L_1, \ldots, L_n, P_{\text{reliableSimulation}}(f - f_i)$ when the simulation says that executing the plan in environment $L_1, \ldots, L_n$ causes objective function $f_i$ to acquire value $r$.
  - $R_g$ represents how constraints and objective functions are aggregated to determine the overall fitness of the plan, so containing $\neg do \leftarrow C_i$ representing that if constraint $C_i \in C$ is not fulfilled, then the plan is not given up; and containing $\neg do \leftarrow \neg F_i, P_{\text{importance}}(f - f_i)$ representing that a good plan should minimize importance objective functions; containing $F_i \leftarrow f_i = r, r \approx f_i^{\text{min}}$

representing that $F_i$ is close to true if the value of $f_i$ is close to $f_i^{\text{min}}$.

The evaluation of the plan under the consideration amounts to computing $\text{Prob}(d o)$ which could be interrupted as the degree of provability that the plan ensures declared objectives and constraints.

Our model is intuitive in the following manner: if there is no information about a constraint, say $C_i$ then $\neg C_i$ is assumed and hence the argument using $\neg do \leftarrow C_i$ is attacked by no arguments in any possible world. Thus $\text{Prob}(d o) = 0$. Similarly, if there is no information about an objective function, say $f_i$, then $\neg F_i$ is assumed. However, this does mean that $\text{Prob}(d o) = 0$ because an argument for $\neg do$ using the rule $\neg do \leftarrow \neg F_i, P_{\text{importance}}(f - f_i)$ would need probabilistic assumption.
$P_{importanceOf - f_i}$ whose truth value depend on the possible word. As this probabilistic assumption measure the importance of $f_i$, $Prob(do)$ will be reduced by an amount proportional to this importance.
Chapter 4  
Results and Discussions  

The goal of our research is to study conventional approach that can find a feasible service restoration plan during the service restoration process. We propose this research is two frameworks.  

- The first framework is constructing and calculating the possible service restoration plans  
- The second framework is evaluating of plans.  

4.1 Possible Plans Constructing and Calculating  

To demonstrate the performance of the proposed simulated-based framework. We use a typical distribution power system of the Provincial Electricity Authority (PEA), Thailand, as shown in Figure 3.2, is employed in this research model. Heuristic representing the expertise of experienced operator as described in section 2.2.1 was used to construct the service restoration plans. After the plans have been constructed, Some objective functions and constraints were determined by DIgSILENT PowerFactory and a DPL scribe for calculating the result. The typical load profile of the feeder in a daytime operation is used in the simulation. However, other objectives and constraints such the operation time of switch cannot be computed by simulation software. In this case study, we define 13 service restoration plans in a simulation. The possible restoration plan and the result of supporting feeder line current as shown in Table 4.1. From the case study results, we can obtain 13 possible restoration plan that satisfies all of the objective functions and constraint in the light load period. The nine possible restoration plan can use during the peak load period. The result of calculating of objective functions and constraints in each possible plans is shown in Table 4.2 and 4.3. However, the result of the case study relies on the reliability of the simulation software that related to the accuracy of input data in the simulation.
Table 4.1 Possible restoration plans and load current on feeders after restoration

<table>
<thead>
<tr>
<th>Possible Plan</th>
<th>Operated Switches</th>
<th>Feeder F2</th>
<th>Feeder F3</th>
<th>Feeder F4</th>
<th>Feeder F5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Light (A)</td>
<td>Peak (A)</td>
<td>Light (A)</td>
<td>Peak (A)</td>
</tr>
<tr>
<td>p#1</td>
<td>close s8</td>
<td>170</td>
<td>207</td>
<td>111</td>
<td>139</td>
</tr>
<tr>
<td>p#2</td>
<td>close s3</td>
<td>69</td>
<td>163</td>
<td>331</td>
<td>456</td>
</tr>
<tr>
<td>p#3</td>
<td>close s6</td>
<td>248</td>
<td>407</td>
<td>111</td>
<td>139</td>
</tr>
<tr>
<td>p#4</td>
<td>open s4, close s3, close s6</td>
<td>154</td>
<td>280</td>
<td>247</td>
<td>338</td>
</tr>
<tr>
<td>p#5</td>
<td>open s4, close s3, close s8</td>
<td>69</td>
<td>163</td>
<td>247</td>
<td>338</td>
</tr>
<tr>
<td>p#6</td>
<td>open s5, close s3, close s6</td>
<td>139</td>
<td>260</td>
<td>262</td>
<td>358</td>
</tr>
<tr>
<td>p#7</td>
<td>open s5, close s3, close s8</td>
<td>69</td>
<td>163</td>
<td>262</td>
<td>358</td>
</tr>
<tr>
<td>p#8</td>
<td>close s17, open s15, close s8</td>
<td>69</td>
<td>163</td>
<td>156</td>
<td>217</td>
</tr>
<tr>
<td>p#9</td>
<td>close s17, open s16, close s8</td>
<td>69</td>
<td>163</td>
<td>156</td>
<td>217</td>
</tr>
<tr>
<td>p#10</td>
<td>close s17, open s15, open s4, close s3, close s8</td>
<td>162</td>
<td>256</td>
<td>247</td>
<td>338</td>
</tr>
<tr>
<td>p#11</td>
<td>close s17, open s15, open s5, close s3, close s8</td>
<td>152</td>
<td>243</td>
<td>50</td>
<td>93</td>
</tr>
<tr>
<td>p#12</td>
<td>close s17, open s16, open s4, close s3, close s8</td>
<td>163</td>
<td>258</td>
<td>247</td>
<td>338</td>
</tr>
<tr>
<td>p#13</td>
<td>close s17, open s16, open s5, close s3, close s8</td>
<td>153</td>
<td>245</td>
<td>262</td>
<td>358</td>
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</table>
### Table 4.2 Simulation results

<table>
<thead>
<tr>
<th>Plan</th>
<th>Switch Order</th>
<th>Number of operated switch</th>
<th>Number of remote switch</th>
<th>Number of manually switch</th>
<th>Outage period</th>
<th>$C_1$ (Radial network)</th>
<th>$C_2$ (Current)</th>
<th>$C_3$ (Voltage)</th>
<th>$f_1$ (MW)</th>
<th>$f_2$ (second)</th>
<th>$f_3$ (kWh)</th>
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</thead>
<tbody>
<tr>
<td>p#1</td>
<td>close s8</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Light load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>1,200</td>
<td>0.2301</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Peak load</td>
<td>fulfilled</td>
<td>unfulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>1,200</td>
<td>0.4575</td>
</tr>
<tr>
<td>p#2</td>
<td>close s3</td>
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<td>0</td>
<td>1</td>
<td>Light load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>1,200</td>
<td>0.1007</td>
</tr>
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<td></td>
<td></td>
<td>Peak load</td>
<td>fulfilled</td>
<td>unfulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>1,200</td>
<td>0.2220</td>
</tr>
<tr>
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<td>close s6</td>
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<td>1</td>
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<td>1.380</td>
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<td>fulfilled</td>
<td>2.330</td>
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<td>0.3510</td>
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<td>fulfilled</td>
<td>1.380</td>
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<td>0.0906</td>
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<tr>
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<td>0.2230</td>
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<td></td>
</tr>
<tr>
<td>p#5</td>
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<td>2</td>
<td>1</td>
<td>Light load</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>1,300</td>
<td>0.1116</td>
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<tr>
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<td></td>
<td></td>
<td>Peak load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>1,300</td>
<td>0.2404</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>3</td>
<td>1</td>
<td>2</td>
<td>Light load</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>2,450</td>
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<td>close s3,</td>
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<td></td>
<td></td>
<td>Peak load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
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</tr>
<tr>
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<td>3</td>
<td>Light load</td>
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<td>1.380</td>
<td>3,600</td>
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</table>
Table 4.3 Simulation results (Cont.)

<table>
<thead>
<tr>
<th>Plan</th>
<th>Switch Order</th>
<th>Number of operated switch</th>
<th>Number of remote switch</th>
<th>Number of manually switch</th>
<th>Load Demand</th>
<th>$C_1$ (Radial network)</th>
<th>$C_2$ (Current)</th>
<th>$C_3$ (Voltage)</th>
<th>$t_1$ (MW)</th>
<th>$t_2$ (second)</th>
<th>$f_3$ (kWh)</th>
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</thead>
<tbody>
<tr>
<td>#8</td>
<td>close s17, open s15, close s8</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>Light load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>2.450</td>
<td>0.2655</td>
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<td>0.5355</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>3.600</td>
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<td>fulfilled</td>
<td>2.330</td>
<td>3.600</td>
<td>0.4761</td>
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<td>3</td>
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<td>fulfilled</td>
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<td>3.700</td>
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<td>3.700</td>
<td>0.3060</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>4.850</td>
<td>0.1369</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>4.850</td>
<td>0.3017</td>
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<tr>
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<td>5</td>
<td>1</td>
<td>4</td>
<td>Light load</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>4.850</td>
<td>0.1060</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Peak load</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>4.850</td>
<td>0.2417</td>
</tr>
<tr>
<td>p#13</td>
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<td>0</td>
<td>5</td>
<td>Light load</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>1.380</td>
<td>6.000</td>
<td>0.1048</td>
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<td></td>
<td></td>
<td>Peak load</td>
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<td>fulfilled</td>
<td>fulfilled</td>
<td>2.330</td>
<td>6.000</td>
<td>0.2373</td>
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</table>
4.2 Computing the fitness of a plan

In this section, we evaluate the plans that ensure declared the objective function and constrain or not. The Probabilistic Assumption-based Argumentation (PABA) is used for evaluating the possible service restoration plan, and we first propose to use PABA to represent knowledge about a restoration plan. A PABA framework consists of two part. First is a logical (qualitative) part that is an assumption-based argumentation framework (ABA). Second is a probabilistic (quantitative) part. Next, we declare the element in each of PABA framework. Then, we use automated reasoning mechanisms equipped in PABAs to compute the fitness of the plan.

We focus on plan#1. The plan is performed by closing switch S8. The load in the out-of-service zone (zone2, zone3, zone 4, and zone5, is transferred to the supporting feeder F4 (see Figure 3.2). Form the result in Table 4.4 shows that the current of F4 in the light load period is 0.258 kA while in the peak load period, the current is 0.381 kA. By the policy of electric utility such as PEA, if the type of line is Space Aerial Cable (SAC) that have a cross-section is 185 mm², the maximal all allowed current is 0.41 kA. Hence, in the light load period, we can conclude that plan#1 satisfy the constraint “the current on the supporting feeder is in rang while it not satisfy during a peak load period.

Table 4.4 Simulation results related Plan#1 assuming Light/Peak loads.

<table>
<thead>
<tr>
<th>Feeder</th>
<th>Current(kA)</th>
<th>Powered Zone</th>
<th>Buses</th>
<th>Bus voltage(kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4</td>
<td>0.258/0.381</td>
<td>Z10</td>
<td>Bus402</td>
<td>22.46/22.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z11</td>
<td>Bus404</td>
<td>22.60/22.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bus405</td>
<td>22.55/22.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z2</td>
<td>Bus104</td>
<td>22.30/22.26</td>
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<tr>
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<td>Z3</td>
<td>Bus106</td>
<td>22.39/22.30</td>
</tr>
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<td></td>
<td></td>
<td>Z4</td>
<td>Bus107</td>
<td>22.40/22.32</td>
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<td></td>
<td></td>
<td>Z5</td>
<td>Bus110</td>
<td>22.45/22.35</td>
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</tbody>
</table>

4.2.1 General Methodology

To compute the finesse of plan, we use the PABA to represent knowledge about a restoration plan. the plan#1 is constructed in PABA framework [37].

\[ P = (A_p, R_p, F), F = (R, A, \overline{A}) \]

where \( A \) contains

- \( \neg C_1, \neg C_2, ... \) where \( \overline{\neg C_i} = C_i \) representing that constraints are all assumed to be unfulfilled unless there are evidences on the contraries.
- \( \neg O_1, \neg O_2, ... \) where \( \overline{\neg O_i} = O_i \) representing that objective are all assumed to be unfulfilled.
- \( do \) with \( \overline{do} = \neg do \) represent the selection of the plan.
\( \mathcal{A}_p \) contains
- Probabilistic assumptions that represent environment variable: lightLoad, peakLoad, …
- Probabilistic assumptions that represent the importance of objectives: importance \( (O_1) \), importance \( (O_2) \), …
- Probabilistic assumptions that represent reliability of simulation results.

\( \mathcal{R} \) contains
- Rules that represent simulation results by using the form
  \[
  C_i \leftarrow do, E_1, ..., E_n, \text{reliableSimulation} \\
  O_j \leftarrow do, E_1, ..., E_n, \text{reliableSimulation}
  \]
  For example,
  \[
  C_3 \leftarrow do, \text{lightLoad}, \text{reliableSimulation}
  \]
- Rules that represent hardness of constraint/ Objective by using the form
  \[
  \neg do \leftarrow \neg C_i \\
  \neg do \leftarrow \neg O_j, \text{importance} \ (O_j)
  \]

We use the Figure 4.1 that is an example of Probabilistic (quantitative) part that is a pair \( \mathcal{A}_p, \mathcal{R}_p \).

![Figure 4.1 Probability of light load and peak load](image-url)
\[ A_p = \{ lightLoad, peakLoad, \ldots \}. \]

\[ R_p \] may contain

\[[lightLoad:0.2] \leftarrow \text{daytime}\]
\[[peakLoad:0.8] \leftarrow \text{daytime}\]

It can say that during the daytime, the probability of the power system in the light load is 0.2 while the probability of it in the peak load is 0.8

In the logical part that is an assumption-based argumentation framework (ABA). \( \mathcal{F} = (\mathcal{R}, \mathcal{A}, \cdot) \) where

\( \mathcal{R} \) consists of

- don’t do if it \( C_2 \) or \( C_3 \) are not fulfilled

\[ \neg do \leftarrow \neg C_3 \]
\[ \neg do \leftarrow \neg C_3 \]

- \( C_3 \) is fulfilled if do it

\( \mathcal{A} = \{ do, \neg C_2, \neg C_3 \} \) with \( \overline{do} = \neg do, \overline{\neg C_2} = C_2, \overline{\neg C_3} = C_3 \)

- do is an assumption that represent a decision

- \( \neg C_2, \neg C_3 \) are assumption. It represents that constraints are assumed to be unfulfilled unless there are evidences on the contrary.

Argument form ABA are constructed by connecting inference rules and assumption that is shown in a Figure 4.2.

\[
\begin{align*}
\text{Arg}_1 & : \neg do \\
\text{Arg}_2 & : \neg do \\
\text{Arg}_3 & : \neg C_3
\end{align*}
\]

\[
\begin{align*}
\text{do} & \quad \text{C}_3
\end{align*}
\]

\[
\begin{align*}
\text{support assumptions: } & \neg C_2 \\
\text{support assumptions: } & \neg C_3
\end{align*}
\]

Figure 4.2 constructing argument from ABA

An argument supported by an assumption \( \alpha \) is attacked by any argument with conclusion \( \overline{\alpha} \). Figure 4.3 shows attacking between arguments.

where:

\[
\begin{align*}
A_{rg0} & = (\{ \text{do} \}, \text{do} ) \\
A_{rg1} & = (\{ \neg C_3 \}, \neg do) \\
A_{rg2} & = (\{ \neg C_2 \}, \neg do) \\
A_{rg3} & = (\{ \text{do} \}, \text{C}_3 )
\end{align*}
\]
An argument $A$ is acceptable if there is a set of arguments such that $S$ is a conflict-free (no attack between any two argument of $S$). Any argument attacking $A$ or an argument of $S$ is attacked by some argument of $S$. we can summarize that $A_{rg3}$ is acceptable ($S = A_{rg3}$) but $A_{rg0}$ is not acceptable. Because $A_{rg2}$ attacks $A_{rg0}$ but no argument attacking $A_{rg2}$ could be found.

4.2.2 Concrete Methodology

This section, we can structure the PABA framework ($\mathcal{A}_p, \mathcal{R}_p, \mathcal{R}, \mathcal{A}$) for service restoration plan#1 by using the results in the Table 4.4. Form the data, we found that $\mathcal{R}$ should be divided two modules ($\mathcal{R}_s, \mathcal{R}_g$)[38].

$\mathcal{A}$ contains the following (qualitative) assumptions:
- radialNetwork (radial network topology)
- cFeeder: InRang (current on feeder $i^{th}$ in range)
- vBus402, vBus404, vBus405, vBus104, vBus106, vBus107, vBus110 (voltage on bus $i^{th}$ in range)
- zone10Powered, zone11Powered, zone2Powered, zone3Powered, zone4 Powered, zone5 Powered (zone $i^{th}$ is powered)

$\mathcal{A}_p$ contains the following probabilistic of assumptions:
- $lightLoad$, $peakLoad$, $importanceObjective$, $simReliable$, etc
  - $lightLoad$ is a times of low electricity usage
  - $peakLoad$ is a times of high electricity usage

$\mathcal{R}_p$ contains
- $[lightLoad: 0.2] \leftarrow daytime$
- $[peakLoad: 0.8] \leftarrow daytime$
\( \mathcal{R} \) contains subsets \( \mathcal{R}_s \) and \( \mathcal{R}_g \)

\( \mathcal{R}_s \) contains inference rule representing the results of simulation (see Table 4.4):

* \( \text{networkTopo}(\text{radial}) \)
* \( v\text{Bus}_{402}(22.46kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{402}(22.39kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{404}(22.60kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{404}(22.59kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{405}(22.55kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{405}(22.51kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{104}(22.30kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{104}(22.26kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{106}(22.39kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{106}(22.30kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{107}(22.40kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{107}(22.32kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( v\text{Bus}_{110}(22.45kV) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( v\text{Bus}_{110}(22.35kV) \leftarrow \text{peakLoad}, \text{simReliable} \)
* \( c\text{Feeder}_4(258 A) \leftarrow \text{lightLoad}, \text{simReliable} \)
* \( c\text{Feeder}_4(381 A) \leftarrow \text{peakLoad}, \text{simReliable} \)

\( \mathcal{R}_g \) contains inference rule representing how constraint and objective function are aggregated to determine the overall fitness of the plan:

* \( \neg d \leftarrow \neg \text{radialNetwork} \)
* \( \neg d \leftarrow \neg c\text{Feeder}_4 \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{402} \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{404} \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{405} \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{104} \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{107} \text{InRange} \)
* \( \neg d \leftarrow \neg v\text{Bus}_{110} \text{InRange} \)
* \( \neg d \leftarrow \neg \text{zone}_10 \text{Powered} \)
* \( \neg d \leftarrow \neg \text{zone}_11 \text{Powered} \)
* \( \neg d \leftarrow \neg \text{zone}_2 \text{Powered} \)
* \( \neg d \leftarrow \neg \text{zone}_3 \text{Powered} \)
* \( \neg d \leftarrow \neg \text{zone}_4 \text{Powered} \)
* \( \neg d \leftarrow \neg \text{zone}_5 \text{Powered} \)
Figure 4.4 example argument trees constructible from plan#1
Chapter 5  
Conclusions  

This thesis had two related objectives. The first is to propose a Simulation-based Framework for distribution system restoration that use to find a possible service restoration plan under considering the objectives and constraints. The second is to evaluate the plans by proposing a new technique called Probabilistic Assumption-based Argumentation.

We first focus on finding a feasible service restoration plan by proposing a new framework that integrating a multiple knowledge. A heuristics rule that was representing the expertise of experienced operators is used to construct plans. The software application that used to compute the objective functions and constraints of the plan was DIgSILENT PowerFactory. However, other objective functions/ constraint cannot compute by simulation software because some of them rely on non-physical properties. Such feeder line limited capacity of electric utilities. To demonstrate the suitability of the framework, a typical PEA distribution system is a case study. The result shows that the proposed framework was adequate to obtain a possible service restoration plan.

To support the system operator in evaluating to find a feasible plan that satisfies multiple objectives and constraints, we present a Probabilistic Assumption- based Argumentation to evaluate the plan. A Probabilistic Argumentation Framework is used to combine different information source about a restoration plan. Then, we demonstrate the degree of provability that plan guarantee objectives and constraints can obtain by harnessing the automated probabilistic and logical reasoning within Probabilistic Argumentation.

The superiority of our framework is maybe its argumentative feature that can deal with an incompleteness and or uncertainty of the available information both qualitatively and quantitative in the service restoration problem. When the service restoration plan is guaranteed that it satisfy objective functions and constraints, each service restoration plans can be evaluated in Probabilistic Argumentation-based Argumentation so that system operator can get observation into how a restoration plan is. We hope that our thesis will be useful for the operator in evaluating different plans and choosing a feasible plan in dealing with solving the difficulty of a service restoration problem. To further our research we plan to implement the proposed system into a real-time control operation of the distribution system in Provincial Electricity Authority (PEA) in Thailand. An example of PABA framework in the syntax of logical program is show in Listing 1. Finally, This PABA will be run on PENGINE[38] to obtain possible results. Figure 5.1 shows PENGINE. It is a PABA engine developed in [39]
Listing 1. Specifying the PABA framework in service restoration plan#1

 Assumption

\[
\text{iNas (\{radialNetwork, cFeeder, InRang, vBus402, vBus404, vBus405, vBus104, vBus106, vBus107, vBus110, zone1\text{Powered}, zone2\text{Powered}, zone3\text{Powered}, zone4\text{Powered}, zone5\text{Powered}\}).}
\]

R_S

iRule (NetworkTopo\{radial\}_1,[]).

iRule (vBus402(22.46kV),[lightLoad,simReliable]).

iRule (vBus402(22.39kV),[peakLoad,simReliable]).

iRule (vBus404(22.60kV),[lightLoad,simReliable]).

iRule (vBus404(22.59kV),[peakLoad,simReliable]).

iRule (vBus405(22.55kV),[lightLoad,simReliable]).

iRule (vBus405(22.51kV),[peakLoad,simReliable]).

iRule (vBus104(22.30kV),[lightLoad,simReliable]).

iRule (vBus104(22.26kV),[peakLoad,simReliable]).

iRule (vBus106(22.39kV),[lightLoad,simReliable]).

iRule (vBus106(22.30kV),[peakLoad,simReliable]).

iRule (vBus107(22.40kV),[lightLoad,simReliable]).

iRule (vBus107(22.32kV),[peakLoad,simReliable]).

iRule (vBus110(22.45kV),[lightLoad,simReliable]).

iRule (vBus110(22.35kV),[peakLoad,simReliable]).
%%R_G
iRule(not_d, [not_radialNetwork]).
iRule(not_d, [not_cFeeder, InRang]).
iRule(not_d, [not_vBus402, InRang]).
iRule(not_d, [not_vBus404, InRang]).
iRule(not_d, [not_vBus405, InRang]).
iRule(not_d, [not_vBus104, InRang]).
iRule(not_d, [not_vBus106, InRang]).
iRule(not_d, [not_vBus107, InRang]).
iRule(not_d, [not_vBus110, InRang]).
iRule(not_d, [not_zone10, Powered]).
iRule(not_d, [not_zone11, Powered]).
iRule(not_d, [not_zone2, Powered]).
iRule(not_d, [not_zone3, Powered]).
iRule(not_d, [not_zone4, Powered]).
iRule(not_d, [not_zone5, Powered]).
References


33. DigSILENT PowerFactory.


