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DISTRIBUTION SYSTEM PLANNING WITH CONSIDERATION OF UNCERTAINTIES ON BOTH SUPPLY AND DEMAND SIDES

Mr. Le Viet Tien

สถาบันวิทยบริการ
จุฬาลงกรณ์มหาวิทยาลัย

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วิทยานิพนธ์ฉบับนี้ นำเสนอวิธีการวิเคราะห์การวางแผนในระบบจำหน่าย โดยมีวัตถุประสงค์เพื่อลดค่าใช้จ่ายในการขยายระบบให้ต่ำที่สุด ค่าใช้จ่ายในการขยายระบบดังกล่าวประกอบด้วย การลงทุนในสายป้อนและอุปกรณ์ และค่าใช้ผันแปร โดยค่าใช้จ่ายผันแปรที่นำมาพิจารณาในวิทยานิพนธ์ฉบับนี้หมายถึง คุณค่าของความน่าเชื่อถือได้ของระบบและความไม่แน่นอนของปริมาณการใช้ไฟฟ้า วิธีการที่ใช้พัฒนาขึ้นนั้น คำนึงถึงเงื่อนไขต่าง ๆ ในทางปฏิบัติด้วย อาทิเช่น ค่าใช้จ่ายในการลงทุน ค่าใช้จ่ายของสายส่ง ดัชนีความน่าเชื่อถือได้ของระบบ แรงดันตก และความไม่แน่นอนจากการพยากรณ์โหลด

นอกจากนี้วิทยานิพนธ์ได้พิจารณาค่าใช้จ่ายอันเป็นผลมาจากพลังงานที่คาดว่าจะไม่ได้รับจากแหล่งจ่ายที่คิดผลจากความไม่แน่นอนของทั้งในส่วนของอุปสงค์และอุปทานของระบบ เพราะฉะนั้นผลตอบที่ได้จากวิธีที่นำเสนอจึงสามารถสะท้อนค่าใช้จ่ายของสังคมโดยรวมได้อย่างเหมาะสม

การประเมินค่าความน่าเชื่อถือได้ในระบบไฟฟ้าได้นำมาประยุกต์ใช้ในการแก้ปัญหาการขยายระบบไฟฟ้าแบบขั้นตอนเดียว (Single – stage expansion planning) กระบวนวิธีการวิเคราะห์ผลที่พัฒนาขึ้นได้นำไปทดสอบกับระบบทดสอบ 2 ระบบ ซึ่งพบว่าการจำลองระบบให้ผลเป็นที่น่าพอใจ

สถาบันวิทยบริการ
จุฬาลงกรณ์มหาวิทยาลัย

ภาควิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต
สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่ออาจารย์ที่ปรึกษา
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This thesis presents a method for solving a distribution system planning problem, which is aimed to minimize network expansion cost, i.e. investment and variable costs. The variable costs comprise loss cost and reliability costs, representing costs of both supply and demand uncertainties. Practical issues, e.g. cost of investment, line cost, reliability indices, load forecast uncertainty and voltage drop, are also included in our consideration.

In addition to the costs of supply side as mentioned earlier, this thesis also takes into account the cost of expected unserved energy of customers for which the uncertainties on both demand and supply sides will be included in the analysis. The obtained expansion plan therefore reflects the optimum overall social cost.

A power system reliability evaluation technique is employed to solve a single-stage distribution expansion planning problem. A generalized algorithm is developed, tested, and discussed with two small test systems.

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Department Electrical Engineering Student's signature ....
Field of Studies Electrical Engineering Advisor's signature ....
Academic Year 2005

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CHAPTER I

INTRODUCTION

1.1. Background

The primary aim of electricity supply system is to meet customer's demands for energy whereas modern power grids are complex and widespread. After electricity is produced at power plants it has to be transmitted to customers consuming electricity. In general, power is generated in a plant of which their generating cost is economical. The transmission system is used to transfer large amounts of energy from the main generation areas to major load centers. Distribution systems carry the energy to the furthest customer, utilizing the most appropriate voltage level. The function of an electricity distribution system is to deliver electrical energy from the transmission substation or small generating stations to individual customers, transforming to a suitable voltage where necessary.

Figure 1-1 illustrates the interrelation of various networks. The electricity first goes to a transformer at the power plant which boosts the voltage up to greater than 300kV for delivering through extra-high voltage (EHV) transmission lines. When electricity travels long distances it is better to have it at higher voltages since the electricity can be transferred more efficiently at high voltages. The high voltage transmission lines carry electricity for a long distance to substations. At HV/MV transforming substations, a reduction in voltage occurs for distribution to other points in the system through high voltage (HV) transmission lines. Further voltage reduction for commercial and residential customers takes place at distribution substations, which connect to the primary distribution network. The HV and MV networks also provide direct supply to large customers. However most customers are connected at LV and supplied via MV/LV distribution substations and their associated LV. In some countries an additional HV and MV voltage level is presented [1].

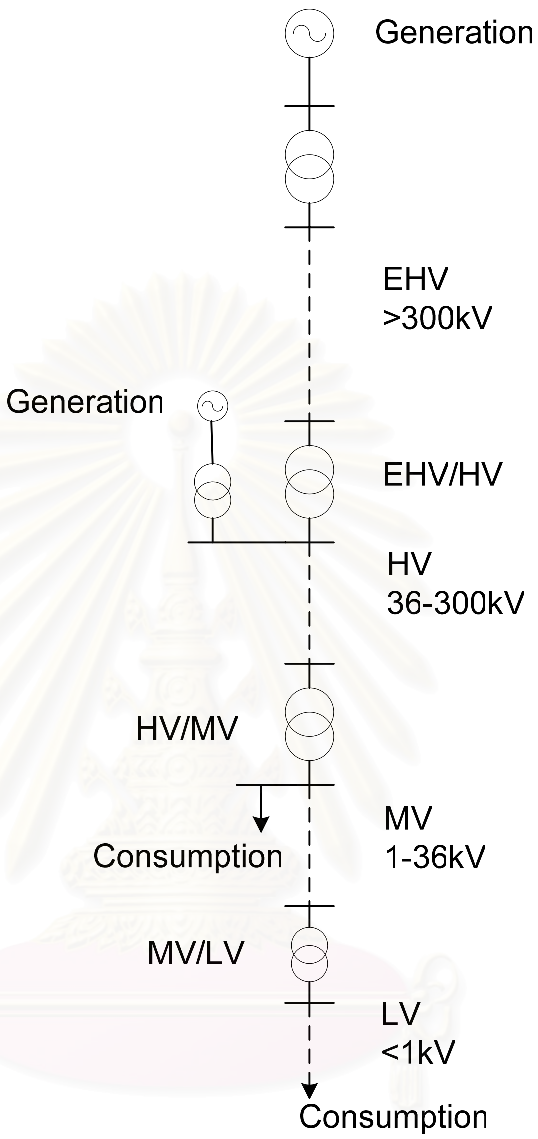

Figure 1-1 Block schematic of transmission and distribution systems [1]

1.2. Distribution System Planning

With the increase dependency on electricity supply, the necessity to achieve an acceptable level of reliability, quality, and safety at an economic price becomes even more important to customers. Therefore system planning is essential to assure that the growing demand of electricity can be satisfied by distribution system additions which are both technically adequate and reasonably economical.

Distribution System Planning (DSP) is an important decision-making activity of electric utilities. It is a practical problem with a long history of continued efforts and contributions for improved solutions. It is also a complicated problem due to a large number of variables involved in the expansion process. A general form of DSP can be started by acquiring following information.

(i) Load-generation model at goal years,
(ii) Existing network configuration,
(iii) All possible routes including length and right of way, and
(iv) Line types.

Planning objectives concerning the quality of supply, tariff price levels and stable employment are in common use in industrialized countries. The detail requirements of individual technical regulation may have a significant effect on such matters as the quality of supply, safety and the costs of providing electricity supplies to customers. Utilities usually plan their investment programs for a number of years ahead, e.g. short-term (5 years ahead), medium-term (10 years ahead) and long-term (20 years ahead).

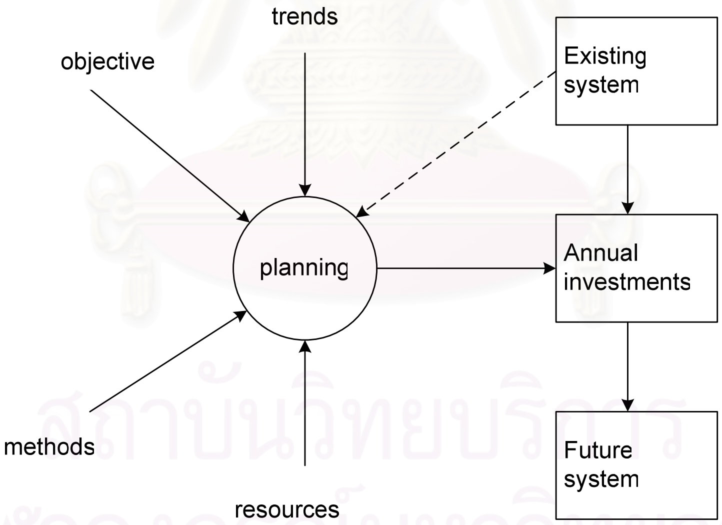

Figure 1-2 Planning as part of the distribution system development process [1]

Figure 1-2 presents the concept of distribution system development process. It is clearly seen that many questions and information need to be addressed for the planner, e.g. existing system in information; trends of the voltage level and types of the system configuration; key objectives for the planned system, e.g. cost and reliability. The methodology used for the planning is also of importance. More over, the available resources,

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e.g. construction, type of lines etc., are also needed to be taken into account. With all these required information, the system planners will have tasks to decide the best option for this system.

A system planner has to estimate appropriated network which feeds customers with the required degree of quality, and realizes a pre-specified reliability level. In a certain area, e.g. industrial, commercial etc., the existing network usually provides a good starting point for planning future system arrangements. The need for further investment is usually to supply for load growth, or to replace ageing assets on the network. The total investment requirements must be compared with an associated financial plan which takes account of assumptions made concerning the bulk purchase prices of electricity, load growth, system losses, existing loans, new borrowing requirements, and any changes in salary costs, safety requirements etc.

1.3. Methodology

Many authors have already published papers concerning distribution system planning [2-11]. In general, they focus on minimizing several total cost, comprising new facility installation and operational costs. Several methods are used to formulate the objective function for distribution system planning. The objective functions used in [2, 3] cover fixed and variable costs, e.g. power losses. However, in other papers [5, 6, 7], it covers only the facility installation cost.

Many models and methods are proposed to solve distribution system planning. They can be categorized in several ways: by treatment of cost, e.g. linear planning, mixed integer planning, nonlinear planning and network flow planning; by treatment of planning periods, e.g. static planning, dynamic planning and pseudo dynamic planning; by treatment of planning durations, e.g. long-term planning, medium-term planning and short-term planning. Many of existing methods consider the optimum feeders minimizing only the system costs which include investment costs of distribution feeder sections, maintenance costs and feeder resistive loss costs. Nowadays, value based planning in distribution system has been receiving more attention due to increased investment costs and the necessity to quantify and justify the reliability levels in a system.

Therefore, the reliability costs [4] are usually included in the objective function to solve distribution system planning. But reliability cost in total distribution cost is considered on few publications [4].

In addition, all approaches of the previous research works can be divided into two distinct categories, i.e. single stage and multistage. The single stage [4, 5, 7, 9, 10, and 11] refers to the case where the full expansion requirements for the area are determined in one period. Multistage [2, 3, 6], on the other hand, refers to expansion of the system in successive plans over several stages representing the natural course of progression. In multistage approach, the majority of development has to rely upon the single stage concept to solve the problem with an addition of updating information, e.g. load, network configuration, etc., at each stage. Therefore, the single stage approach will be used in this thesis.

In this thesis, the power flow method is applied to solve distribution system planning by single stage calculation. System uncertainty on both demand and supply sides is also considered in objective function by adding uncertainty and energy not supply costs in order to consider about reliability of distribution system. Then the results will be analyzed with different objective functions.

This thesis is organized into five chapters. The second chapter describes about the concept of supply and demand uncertainty, which is drawn from the concept of seven-step normal distribution and energy not supply, as well as concepts of investment costs of distribution lines, and loss costs on distribution system. The third chapter describes our proposed mathematical problem based on Newton’s method to verify system constraints. The fourth chapter is the results of two test system and solutions. In this chapter, the objective functions, i.e. cost of investment, costs of power loss, and adding terms which are uncertainty demand and energy not supply costs, are taken into account to solve distribution system planning and compared. Finally, the fifth chapter concludes our work and recommendation on the future research concerning this thesis.

1.4. Objectives

a. To study distribution expansion system planning with consideration of uncertainties on both supply and demand sides.

b. To propose a method and develop a computer program to solve distribution system planning problems.

c. To test and compare distribution system planning results between many objective functions.

1.5. Scope of Study

a. Focusing on radial distribution system expansion planning.

b. Taking into account customer's unserved energy and practical constraints, e.g. size and cost of conductors, voltage drop, and available routes etc.

c. Using failure rate and repair time of main components from the Provincial Electricity Authority (PEA) as basic uncertainty information on the supply side.

d. The uncertainty on the demand side will be modeled by a normal density function.

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CHAPTER II

TECHNICAL AND COST ANALYSIS

2.1. Introduction

A good distribution system planning and design requires a sound knowledge of the existing electrical system and other factors for future network development. Technical factors such as investment of distribution lines, power loss, forecast peak load and reliability need to be considered. However, it is essential that any project which will be considered by a planning designer must not only analyze technical aspects but also to ensure that any proposed project development is technical sound and cost effective.

Actually, cost/benefit studies of power distribution system are beginning to receive much attention. It can be used to support decision making on whether to adopt a specific configuration to solve an individual problem. The goal of optimization is to search for the minimum objective function, as shown in fig. 2-1.

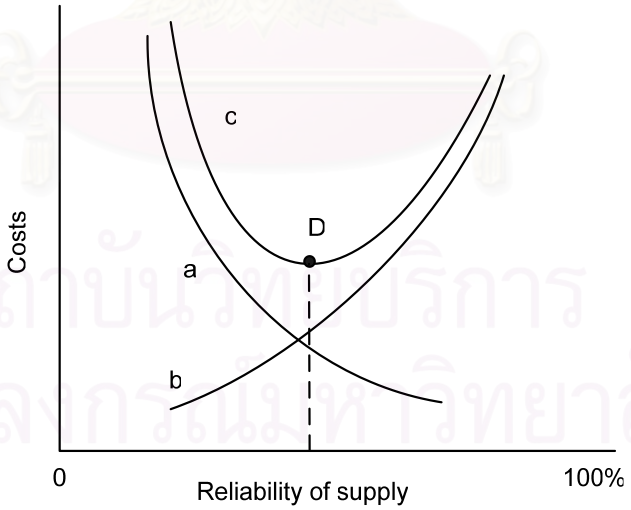

Figure 2-1: Cost and system reliability [14]

a refers to loss costs

b refers to investment costs

c refers to Total cost = a + b

In figure 2-1, curve *a* refers to loss costs which will be assume by considering loss, reliability and demand uncertainty costs. Curve *b* refers

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to costs incurred by utility in providing the availability of supply. With 100% availability, i.e. total reliability, these loss costs (curve *a*) would be zero. But these investment costs (curve *b*) increase for each additional percentage point improvement, so that to try to achieve 100% would be economically impracticable. Therefore, the total minimum cost should determine the level of system reliability, this would be at point D on curve c which refers to total cost of planning.

Therefore, this chapter will present various technical aspects which should be considered for distribution system planning. The planning designer should consider the effect of investment cost on system planning, the loss of cables on the supplies to customers and the quality of supply, e.g. reliability on distribution lines, and cost of demand uncertainty as well. This would be require that the summation of the associated costs should be minimized when planning the reinforcement scheme. It can be shown as follows.

$$\text{Total cost} = \Sigma\,\text{Investment Cost} + \Sigma\,\text{Loss Cost} + \Sigma\,\text{Reliability Costs}$$

Each cost component and its technical concerns will be described in more detail in following sections.

2.2. Investment Cost

To carry out system planning, it is necessary to make use of relevant circuits, and then combine these circuits in order to represent a suitable planning.

Normally, aluminium conductor and XLPE insulated power cables are used in MV distribution systems. Therefore, two types of cable which are Aluminium conductor (Al) and Aluminium Spaced Aerial Cables (SAC) will be considered for MV network in this thesis. Here, the parameters and fixed prices of cables are based on Provincial Electricity Authority (PEA) and cables hand book [13] which are shown in Appendix A, for MV (24kV and 35kV) distribution system. Typical values of cables in MV distribution system are shown for examples in table 2-1.

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Table 2-1 Aluminium conductor & XLPE insulated power cable 24kV

Number of core	Nominal Cross Sectional Area (mm^2)	Number Of Stranded	Diameter Of Conductor Approx. (mm)	Insulation Thickness (mm)	Overall Diameter Approx. (mm)	Maximum Conductor Resistance (Ω/km)	Minimum Insulation resistance (MΩ-km)	Maximum Continuous Current Rating In free air (A.)	Breaking strength (kg/km)	Cable Weight Approx. (kg/km)	Standard Length* (m)	Power (MVA)	Price** (Baht/km)
1	35	7	7.1	1.8	12.0	0.868	900	145	5,720	170	1,000/D	6.02736	83859.9
	50	7	8.5	2.2	14.5	0.641	880	175	7,890	240	1,000/D	7.2744	118390.4
	70	7	9.9	2.1	15.5	0.443	800	220	10,530	300	1,000/D	9.14496	147988.1
	95	7	11.6	2.5	18.0	0.320	750	275	14,380	410	1,000/D	11.4312	202250.3
	120	19	13.1	2.6	19.5	0.253	700	320	19,110	500	1,000/D	13.3017	246646.8
	150	19	14.4	2.6	21	0.206	650	365	22,560	600	1,000/D	15.1723	295976.1
	185	34	16.1	2.55	23	0.164	600	420	29,600	700	1,000/D	17.4585	345305.5

* Packing D: Drum

** Estimated based on cable weight.

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2.3. Power Loss Cost Calculation

2.3.1. Power Flow

For distribution network load-flow studies are necessary to determine the capability of a network under all loading conditions and network configurations.

The power flow through each section of a network is influenced by the character and loading of each node point, and by power loss. The power-flow solver which is used in this thesis is based on a standard Newton’s method using full Jacobian, updated at each iteration. This method is described in detail in many textbooks. It is also necessary to calculate loss cost which is mentioned above; on the line network.

2.3.2. Power Loss Cost

When the current or real and reactive power flows have been known, P_l and Q_l, the series real and reactive power losses, can be calculated as following equations:

$$P_l = \left[\frac{P}{V}\right]^2 R_{ij} + \left[\frac{Q}{V}\right]^2 R_{ij} \qquad (2\text{-}1)$$

$$\text{and } Q_l = \left[\frac{P}{V}\right]^2 X_{ij} + \left[\frac{Q}{V}\right]^2 X_{ij} \qquad (2\text{-}2)$$

where R_{ij} and X_{ij} refer to the circuit series resistance and reactance as shown in figure 2-2.

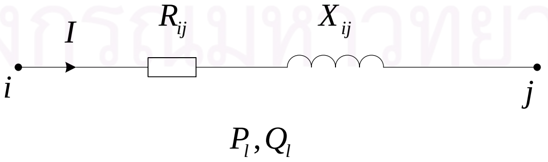

Figure 2-2 Calculation of circuit series

The flow of current through lines on the network causes power losses in the network. We consider only real power loss here, power losses in a line having resistance R_{ij} are proportional to the square of the current flowing through it, i.e. $P_{ij} = I^2 R_{ij}$.

When the power flows (real and reactive power) have been determined, loss cost can be calculated from the following equations:

$$C_{loss} = kR_{ij} \frac{(P_{ij}^2 + Q_{ij}^2)}{|V_i^2|} \tag{2-3}$$

where:

k is loss coefficient which can be generally defined as $8760 \times NYE \times C_{kwh}$. Here, NYE is the estimated life time of the expansion network, C_{kwh} = cost of one kWh which is defined as 2 Baht/kWh in this thesis,

R_{ij} refers to the circuit series resistance of line *ij*,

P_{ij} and Q_{ij} refer to the real and reactive power flows form node *i* to node *j*,

V_i refer to voltage at node *i*.

2.4. Reliability Costs Calculation

Reliability is an essential factor representing quality of supply. The main factors used to judge supply reliability to customers are the frequency of interruptions, average duration of each interruption, and the value a customer places on the supply of electricity at the time that the service is not provided [1].

In general, customer receives supply via a distribution network. The reliability of this supply depends on the reliability of lines and configuration of the network. Distribution reliability is the ability of the distribution system to perform its function under stated conditions for specified period of time. Therefore, distribution system reliability is an essential issue since it is directly involved with customers.

In addition, the actual peak load will differ from the forecast value with zero probability. It is realized that some uncertainty can exist and described by a probability distribution. Therefore, the uncertainty on both supply and demand sides will be shown in following sections, i.e. sections 2.4.1 and 2.4.2, and analyzed by an example.

2.4.1. Expected Userved Energy Cost Calculation

Outages occurring on a power system can be a reason in some loss of the electrical energy being supply. This load is usually termed ‘Energy Not Supply’ (ENS) or ‘Expected Userved Energy’ (EUE). Therefore, the Expected Unserved Energy cost (EUE cost) is modeled as a function of outage frequency, outage duration, and outage loads. With EUE, we need to know reliability index, lines and loads to judge reliability of distribution system planning.

2.4.1.1. Distribution Reliability Index

The main factors used to judge reliability of supply to customers are the frequency of interruptions, the duration of each interruptions and the value a customer places on the supply of electricity at the time that the service is not provided. These factors depend on variables such as the reliability of individual items of equipment, circuit length and loading, network configuration, distribution automation, load profile and available transfer capacity.

Supply uncertainty is aimed at estimating the influence of the unavailability of each line on the outages at each customer. It is represented by a two stage model as shown in figure 2-3.

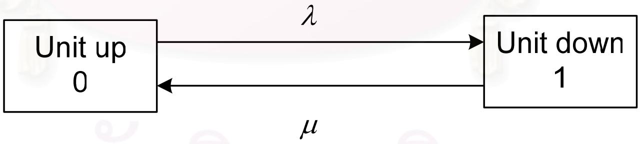

Figure 2-3 Two state model

The steady state probability of each state can be represented by the unavailability and the availability as described by equation 2-4 and 2-5 respectively.

$$\text{Unavailability} = U = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \quad (2\text{-}4)$$

$$\text{Availability} = 1 - U \quad (2\text{-}5)$$

where

λ refers to expected failure rate,

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μ refers to expected repair rate,

m refers to mean time to failure = $1/\lambda$, and

r refers to mean time to repair = $1/\mu$.

The parameters λ and μ are state transition rates when the system transits from one state to other.

Most distribution systems are designed and constructed as simple radial feeder system. However, if meshed systems are constructed, they are generally operated as radial system by using normally open switches in the mesh as shown for example in figure 2-4. One of switches is normally closed while the other switch is normally open to run the system in a radial configuration.

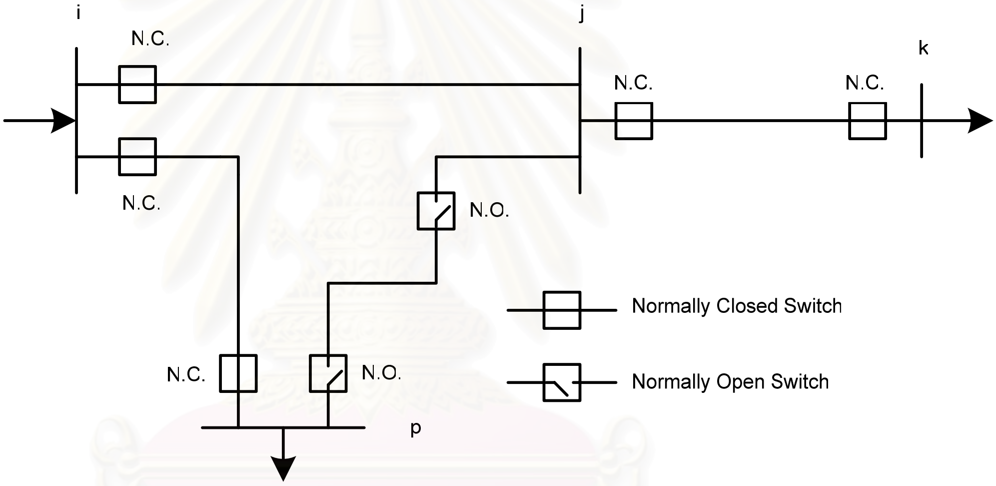

Figure 2-4 Simple distribution system feeders.

A customer connected to any load point of such system required all components between himself and the supply point to be operating. Therefore, there are the three basic reliability parameters, i.e. the average failure rate, λ, the average outage or repair time, r, and the average annual outage time, U. The calculation parameters considered here are their average or expected values.

The average failure rate of outage per year for load point j based on a series system [12] is given by

$$\lambda_j = \lambda_1 + \lambda_2 + \ldots + \lambda_i + \ldots + \lambda_n = \sum_{i \in I} \lambda_i \tag{2-6}$$

where λ_i is the failure rate (frequency/year) of component *i*, and *I* is the set of the components whose failure results in an outage at given load point *j*.

The expected annual outage time is given by

$$U_j = \sum_{i \in I} \lambda_i t_{ij} \tag{2-7}$$

where t_{ij} is the outage time at the given load point *j* caused by a failure of component *i* (hours).

So that, the average outage duration is then given by

$$r_j = U_j / \lambda_j \tag{2-8}$$

Outage occurring on a power system resulting in some loss of the electrical energy being supply is given by

$$E_j = \lambda_j r_j L_{avgj} \tag{2-9}$$

where L_{avgj} is the average peak load at the load point *j*.

The cost of the Expected Unserved Energy, or power and energy not supplied, are given by

$$EUE\cos t = \sum_{j=1}^{n} C_j = T \sum_{j=1}^{n} c.E_j \qquad \text{(Baht)} \tag{2-10}$$

where

T is the average outage duration (hours),

c (Baht/kWh) is the per-unit cost value for energy not supplied for the load point *j* when the outage time is t_{ij}, and

n is the number of load points in the system.

2.4.1.2. Calculation Example

Most distribution system configuration is of a radial type. However, if they are of mesh type, they are usually operated as radial using open points in the mesh as described in the previous section. A radial system reliability calculation based on the concept of a series system is illustrated below.

Suppose that the system is divided into three sections A, B, and C, as shown in figure 2-5, from which the values in the bracket is the limited capacity of the line in each section. It is assumed that all sections which are of aluminium cables, and their characteristics are referred to Table 2-1. Their cross area, i.e. sections A, B, and C, are 95 mm^2, 35 mm^2, and 35 mm^2, respectively. It is assumed that the length of sections A, B, and C are 2 km, 3 km, 1 km respectively. In additional, two forecast peak loads, i.e. load points *k* and *l*, are 6MW and 5MW, respectively. The objective is to calculate the power and energy not supply for customers in each section and the whole system.

The failure of the lines is approximately proportional to the line length. Assuming that the failure rate (λ) of each line is 0.01 f/km/yr, whereas the average repair time for each failure is assumed to be 4 hours. The outage cost (c) is assumed at 68 Baht/kWh. Based on the provided information, the failure rate and repair time for each line is shown in table 2-2.

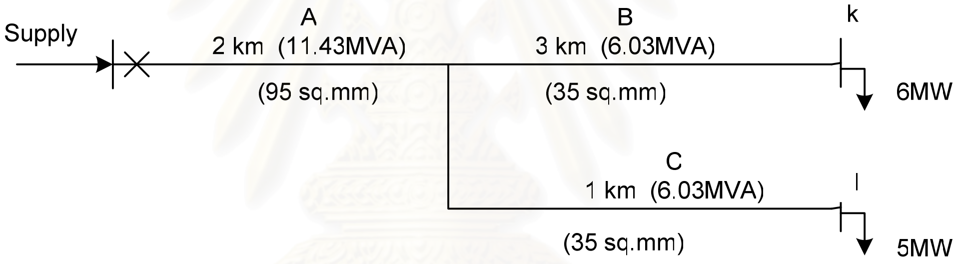

Figure 2-5 Example network for radial system

Table 2-2 Component data for the radial system

Line	Length (km)	λ (f/yr)	r $(hours)$
A	2	0.02	4
B	3	0.03	4
C	1	0.01	4

The reliability index can be evaluated using the principle of series systems. The expected annual outage time U and expected unserved energy cost C can be calculated from equations (2-7) and (2-10), respectively. With the information and reliability calculation concept shown in the previous section, we can calculate the reliability index of each load section caused by faults on different section as shown in table 2-3, from which the total energy not supply cost, i.e. EUE, is 179,520

Baht/yr, and both load points face the same failure rate and annual outage time of 0.06 f/year and 0.24 hours/year respectively.

Table 2-3 Results for basic radial system

Load point j	Fault section	λ_i $(f\ /\ yr)$	r_i $(hours)$	U_i $(hours\ /\ yr)$	$\lambda_i r_i c L_{avgi}$ $(Baht\ /\ yr)$	C_j $(Baht\ /\ yr)$
k	A	0.02	4	0.08	0.02*4*68*6000 =	32,640
	B	0.03	4	0.12	0.03*4*68*6000 =	48,960
	C	0.01	4	0.04	0.01*4*68*6000 =	16,320
	Subtotal	0.06	4	0.24		97,920
l	A	0.02	4	0.08	0.02*4*68*5000 =	27,200
	B	0.03	4	0.12	0.03*4*68*5000 =	40,800
	C	0.01	4	0.04	0.01*4*68*5000 =	13,600
	Subtotal	0.06	4	0.24		81,600
					Total =	179,520

2.4.2. Impact of Peak Load Uncertainty Calculation

2.4.2.1. Probability of Peak Load

The forecast peak load which can be known by system planner normally differs from the actual value due to unforeseen factor, e.g. economic growth, weather changes etc. It is fixed parameters and not flexible. And it can be realized that some uncertainty can exist; it can be described by a probability distribution. Therefore the real load forecasting has value around the forecasted peak load with a probability density function (2-11)

The probability density function *f(x)* of a normal distribution is defined by following equation.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-L_i)^2}{2\sigma^2}} \qquad -\infty < x < \infty \tag{2-11}$$

where

L_i is forecast peak load

σ is the standard deviation

Therefore, the graph of *f(x)* shown by following Figure 2-6

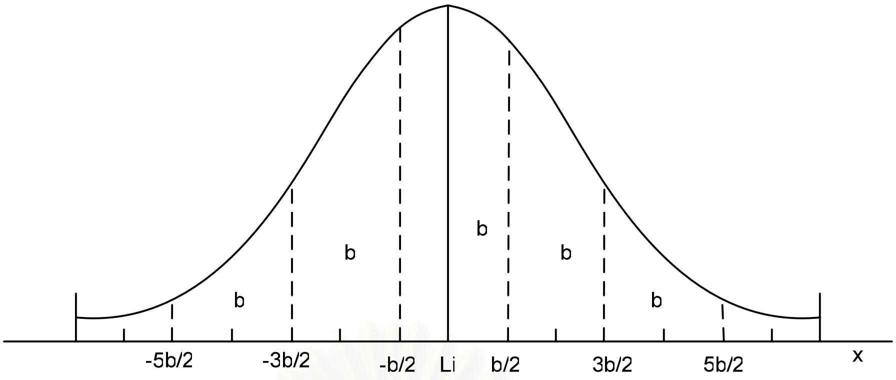

Figure 2-6 Approximate of the normal distribution

The uncertainty in load forecasting can be assumed by dividing the load forecast probability distribution into class intervals, the number of which depends upon the accuracy desired. The peak load is the class interval mid-value, while its probability is presented by the area of each class interval.

Suppose that the system can supply adequately forecasted peak load *i* within a considered stage *T*. Normally, realized load value can be greater or less than the forecast peak load about $\pm ib$ with specified probability. If peak load is greater than the forecast peak load, sources can supply inadequately, i.e. *ib* is defined by plus sign. On the contrary, if peak load is less than the forecasted value, sources can supply adequately, i.e. *ib* by negative sign.

So that, probabilities of load forecasting are defined as following,

$$\int_{\pm ib}^{db} = \ldots \int_{-2b}^{db}, \int_{-b}^{db}, \int_{0}^{db}, \int_{b}^{db}, \int_{2b}^{db}, \ldots \qquad (2\text{-}12)$$

where: $\int_{i}^{db}$ is probability which is the area under the curve represent the probability of forecast peak load, in interval $(L_i - \frac{b}{2}, L_i + \frac{b}{2})$, in fig. 2-6. Therefore, it is calculated by following equation.

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$$\int_0^{db} = \int_{L_0-\frac{b}{2}}^{L_0+\frac{b}{2}} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-L_0)}{2\sigma^2}} dx \tag{2-13}$$

To use the standard spreadsheet, we have to do the change:

$$t = \frac{x-L_0}{\sigma} \rightarrow dt = \frac{1}{\sigma} dx$$

So that, bounds of probability can be change:

$$L_0 - \frac{b}{2} \rightarrow -\frac{b}{2\sigma}$$

$$L_0 + \frac{b}{2} \rightarrow +\frac{b}{2\sigma}$$

Hence,

$$\int_0^{db} = \int_{L_0-\frac{b}{2}}^{L_0+\frac{b}{2}} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-L_0)}{2\sigma^2}} dx = \frac{1}{2}\Phi(\frac{b}{2\sigma}) - \frac{1}{2}\Phi(\frac{-b}{2\sigma})$$

$$= \frac{1}{2}\Phi(\frac{b}{2\sigma}) + \frac{1}{2}\Phi(\frac{b}{2\sigma}) = \Phi(\frac{b}{2\sigma}) \tag{2-14}$$

where:

$$\Phi(\frac{b}{2\sigma}) = \int_0^{\frac{b}{2\sigma}} \frac{2}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$

$\Phi(\frac{b}{2\sigma})$ has characteristic which is $\Phi(-\frac{b}{2\sigma}) = -\Phi(\frac{b}{2\sigma})$

The value of $\Phi(\frac{b}{2\sigma})$ is shown in following table with value of $\frac{b}{2\sigma}$, in table 2-4.

Similarly, we have other probability

$$\int_b^{db} = \int_{\frac{b}{2\sigma}}^{\frac{3b}{2\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt = \frac{1}{2}\left\{\Phi(\frac{3b}{2\sigma}) - \Phi(\frac{b}{2\sigma})\right\} = \int_{-b}^{db} \tag{2-15}$$

$\int_b^{db}$ is the area 2 in fig. 2-6. and $\int_{-b}^{db}$ is the area 3, $f(x)$ is symmetric function so that the area 2 equal the area 3.

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Similarly,

$$\int_{2b}^{db} = \int_{-2b}^{db} = \frac{1}{2}\left\{\Phi(\frac{5b}{2\sigma}) - \Phi(\frac{3b}{2\sigma})\right\}... \qquad (2\text{-}16)$$

Hence, $\int_{\pm ib}^{db} = 1$ because $\int_{-\infty}^{\infty} f(x)dx = 1$

Table 2-4 The standard spreadsheet

t	$\Phi(t)$	t	$\Phi(t)$	t	$\Phi(t)$
0.00	0.0000	0.90	0.6319	1.80	0.9281
0.05	0.0399	0.95	0.6579	1.85	0.9357
0.10	0.0797	1.00	0.6827	1.90	0.9426
0.15	0.1192	1.05	0.7063	1.95	0.9488
0.20	0.1585	1.10	0.7287	2.00	0.9545
0.25	0.1974	1.15	0.7499	2.15	0.9643
0.30	0.2358	1.20	0.7699	2.20	0.9722
0.35	0.2737	1.25	0.7887	2.30	0.9786
0.40	0.3108	1.30	0.8064	2.40	0.9836
0.45	0.3473	1.35	0.8230	2.50	0.9876
0.50	0.3829	1.40	0.8385	2.60	0.9907
0.55	0.4177	1.45	0.8529	2.70	0.9931
0.60	0.4515	1.50	0.8664	2.80	0.9949
0.65	0.4843	1.55	0.8789	2.90	0.9963
0.70	0.5161	1.60	0.8904	3.00	0.9973
0.75	0.5467	1.65	0.9011	3.50	0.9995
0.80	0.5763	1.70	0.9109	4.00	0.9999
0.85	0.6047	1.75	0.9199		

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2.4.2.2. Calculation example

The forecast peak load normally differs from the actual value due to unforeseen factors, e.g. economic growth, weather changes etc. For this reason the seven step approximation is chosen to model the peak load uncertainty, and shown in figure 2-7.

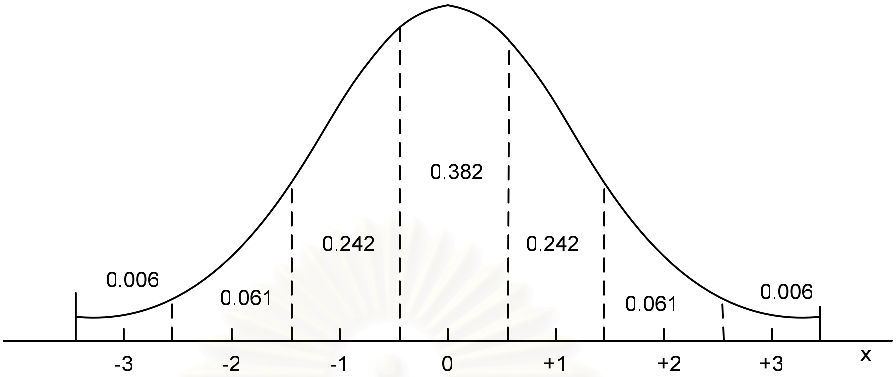

Figure 2-7 Seven-step approximate of the normal distribution

Figure 2-7 shows the graph of *f(x)* which is a bell-shaped curve with forecast load and its standard deviation of 6 MW and 2% respectively. Parameter x in figure 2-7 represents the forecast peak load, as x=0, and its deviation defined according to the standard score, i.e. x=-3, -2, -1, 0, +1, +2, +3. Therefore, the forecast peak load is not only a single value but also has other possible values with different probability, i.e. $L_i \pm k\sigma, k = 0,1,2,3$. The areas under the curve represent the occurring probability of each interval also shown in figure 2-7.

In this example, the forecast peak load is 6 MW, with uncertainty assumed to be normally distributed using a seven step approximation the standard deviation of 2%. The configuration of this example is shown in figure 2-8. It is assumed that a 35 mm^2, 3 km length Aluminium cable is supplying a load point of 6.03 MVA capacity.

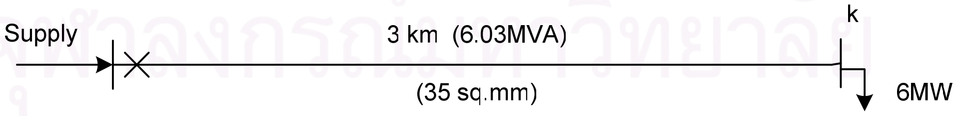

Figure 2-8 Example network

The uncertainty forecast peak load with standard deviation (2%) = 6x2/100=0.12 MW will be presented in figure 2-9, from which we can clearly see the uncertainty on demand side which will be needed to calculate load uncertainty cost.

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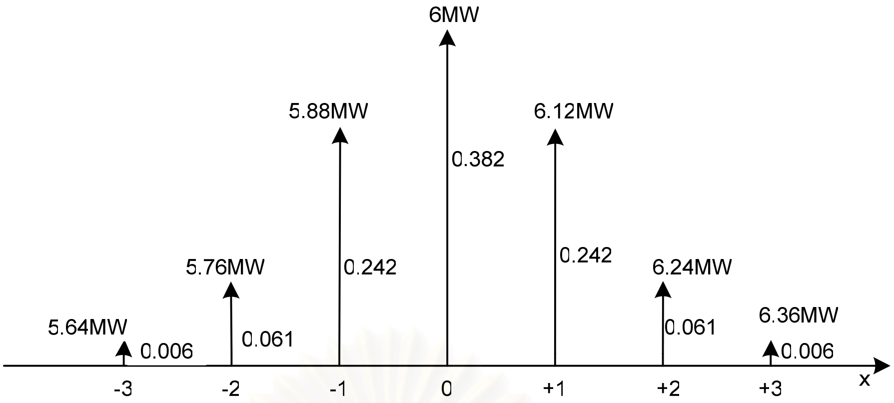

Figure 2-9 Seven-step approximate of the normal distribution with 6MW forecast load and 2% standard deviation.

Figure 2-9 illustrates that the load forecast uncertainty is modeled as seven possible values which are 5.64 MW, 5.76 MW, 5.88 MW, 6 MW, 6.12 MW, 6.24 MW, and 6.36 MW with probability of the load as shown in this figure. If the power factor of the power flow through the feeder is assumed to be of 1.0, we can see that the load of more than its capacity of 6.03 MVA will be cut-off. Therefore, the load of 6.12, 6.24, and 6.36 MW will be interrupted with probability of 0.242, 0.061, and 0.006 respectively.

2.4.3. Reliability Costs

2.4.3.1. The Computation of Reliability Cost

Based on sections 2.4.2 and 2.4.3, a reliability cost algorithm will be presented by the EUE cost and load forecast uncertainty. The reliability cost is modeled as a function of EUE cost with load forecast uncertainty consideration.

Suppose that, we will consider the uncertainty of load point *j* with P_j MW as shown in figure 2-10, from which there are two load points, i.e. load points *i* and *j*, and a line connecting between *i* and *j* with capacity of S_{ij}, and X_{ij} of power flow.

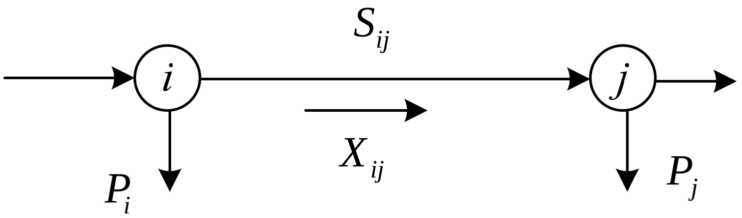

Figure 2-10 Branch system

It is assumed that uncertainty is of a% and the standard deviation is $b = P_j a\%$ MW. Therefore, the load forecast uncertainty, at load point *j*, is shown as follows:

$$P_{D,j,k} = P_j \pm kb \tag{2-16}$$

where

$P_{D,j,k}$ refers to load forecast uncertainty at load point j and k uncertainty level,

k refers to uncertainty levels, i.e. k =0, 1, 2, and 3.

Therefore, the EUE cost for load forecast uncertainty, i.e. load point j at uncertainty level k, is shown in equation (2-17).

$$EUE\cos t_{j,k} = p_k \lambda_{ij} r_{ij} c(P_{D,j,k} \text{ - Capacity of line } i\text{-}j) \tag{2-17}$$

where λ_{ij}, r_{ij}, and c refer to section 2.4.1,

p_k is the probability of load forecast uncertainty at level k.

Normally, if we consider load forecast uncertainty, the power flow of X_{ij} in figure 2-10 will change to be $(X_{ij} + kb)$ at uncertainty level k of load point j. So, we can evaluate the impact of load uncertainty by comparing the expected load value with the capacity of line. If the load at any uncertainty levels is higher than the line capacity, $X_{ij} + kb > S_{ij}$, that load will be curtailed.

Therefore, the demand uncertainty cost, at load point j if uncertainty occurs, is shown as follows:

$$C_{D,j} = \sum_{q=k}^{+3} EUE\cos t_{j,q} \tag{2-18}$$

The demand uncertainty cost, if uncertainty occurs, are given by

$$C_D = \sum_{j=1}^{n}\sum_{q=k}^{+3} EUE\cos t_{j,q} \tag{2-19}$$

Therefore, the reliability costs are given by

$$\text{The reliability costs} = EUE\cos t + C_D \tag{2-20}$$

Subject to the uncertainty constraints:

$$\text{If } X_{ij} + kb \le S_{ij} \Rightarrow C_D = 0 \text{ (no impact of load)} \tag{2-21}$$

$$\text{If } X_{ij} + kb > S_{ij} \Rightarrow C_D \text{ exist (load uncertainty impact)} \tag{2-22}$$

2.4.3.2. Calculation Example

The example in section 2.4.1.2 will be used to illustrate the impact of load forecast uncertainty which is assumed to be normally distribution based on seven-step approximation with the standard deviation of 2%. The detailed calculation has been shown in table 2.5.

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Table 2-5 Result of basic radial system with load forecast uncertainty consideration

Load Point	Fault Section	λ (f/yr)	r (hrs)	U (hrs/yr)	No. of standard deviation	Load (MW)	Prob. of the load	Uncer.	$EUE\cos t_{j,k}$ *of load forecast uncertainty		$EUE\cos t_j$ (Baht/yr)
									(Baht/yr)	(Baht/yr)	
k	A	0.02	4	0.08	-3	5.64	0.006	Not occur	0	0	
					-2	5.76	0.061	Not occur	0	0	
					-1	5.88	0.242	Not occur	0	0	
					0	6	0.382	Not occur	0	0	0.02*4*68*6000=32,640
					+1	6.12	0.242	Occur	0.242*0.02*4*68*(6120-6030)=	118.48	
					+2	6.24	0.061	Occur	0.061*0.02*4*68*(6120-6030)=	29.87	
					+3	6.36	0.006	Occur	0.006*0.02*4*68*(6120-6030)=	2.94	
	B	0.03	4	0.12	-3	5.64	0.006	Not occur	0	0	
					-2	5.76	0.061	Not occur	0	0	
					-1	5.88	0.242	Not occur	0	0	
					0	6	0.382	Not occur	0	0	0.03*4*68*6000=48,960
					+1	6.12	0.242	Occur	0.242*0.03*4*68*(6120-6030)=	177.72	
					+2	6.24	0.061	Occur	0.061*0.03*4*68*(6120-6030)=	44.80	
					+3	6.36	0.006	Occur	0.061*0.03*4*68*(6120-6030)=	4.41	
	C	0.01	4	0.04	-3	5.64	0.006	Not occur	0	0	
					-2	5.76	0.061	Not occur	0	0	
					-1	5.88	0.242	Not occur	0	0	
					0	6	0.382	Not occur	0	0	0.01*4*68*6000=16,320
					+1	6.12	0.242	Occur	0.242*0.01*4*68*(6120-6030)=	59.24	
					+2	6.24	0.061	Occur	0.061*0.01*4*68*(6120-6030)=	14.93	
					+3	6.36	0.006	Occur	0.061*0.01*4*68*(6120-6030)=	1.47	
									$C_{D,k}$ =	**453.86**	
									EUE_k =		**97,920**

* refered to equation (2-17)

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Table 2-5 (continued)

Load Point	Fault Section	λ (f/yr)	r (hrs)	U (hrs/yr)	No. of standard deviation	Load (MW)	Prob. of the load	Uncer.	$EUE\cos t_{j,k}$ *of load forecast uncertainty		$EUE\cos t_j$ (Baht/yr)
									(Baht/yr)	(Baht/yr)	
l	A	0.02	4	0.08	-3	4.7	0.006	Not occur	0	0	
					-2	4.8	0.061	Not occur	0	0	
					-1	4.9	0.242	Not occur	0	0	
					0	5	0.382	Not occur	0	0	0.02*4*68*5000=27,200
					+1	5.1	0.242	Not occur	0	0	
					+2	5.2	0.061	Not occur	0	0	
					+3	5.3	0.006	Not occur	0	0	
	B	0.03	4	0.12	-3	4.7	0.006	Not occur	0	0	
					-2	4.8	0.061	Not occur	0	0	
					-1	4.9	0.242	Not occur	0	0	
					0	5	0.382	Not occur	0	0	0.03*4*68*5000=40,800
					+1	5.1	0.242	Not occur	0	0	
					+2	5.2	0.061	Not occur	0	0	
					+3	5.3	0.006	Not occur	0	0	
	C	0.01	4	0.04	-3	4.7	0.006	Not occur	0	0	
					-2	4.8	0.061	Not occur	0	0	
					-1	4.9	0.242	Not occur	0	0	
					0	5	0.382	Not occur	0	0	0.01*4*68*5000=13,600
					+1	5.1	0.242	Not occur	0	0	
					+2	5.2	0.061	Not occur	0	0	
					+3	5.3	0.006	Not occur	0	0	
									$C_{D,k}$ =	0	
									EUE_k =		**81,600**

* refered to equation (2-17)

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From table 2-5, it can be seen that the reliability costs without uncertainty consideration is (32,640+48,960+16,320+27,200+ 40,800+13,600) = 179,520 (Baht/yr). But when uncertainty is considered, we can see that the demand uncertainty costs occurs at load point k from uncertainty levels +1 to +3 due to the load forecast uncertainty of load point k are greater than the capacity of line B. Therefore, the demand uncertainty cost which is sum of EUE costs from uncertainty level +1 to +3 at each section of load point k being (118.48 + 29.87 + 2.94 + 177.72+ 44.780+4.41+59.24+14.93+1.47) = 453.86 (Baht/yr)

2.5. Conclusions

System uncertainties play an important role in distribution expansion plan. This chapter clearly shows their impacts on the society cost which covers both supply and demand. The EUE cost is used to represent the cost occurred to customers if the supply is not reliable. The impact of load uncertainty is also important when the forecasted values are closed to the limit of the component.

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CHAPTER III

MATHEMATICAL FORMULATION

3.1. Introduction

Fundamental concept of a distribution network utility is to deliver electricity with good quality and acceptable tariff to customers. Therefore, a system planner should consider not only the technical aspect but also the economical aspect, resulting a proper plan for society.

In this thesis, a generalized Distribution System Planning (DSP) algorithm will be developed for a single-stage expansion problem. It can be used to determine the optimal route configuration and select appropriate conductor types and sizes from the listed options. The assessment of various routing options will include capital investment of network expansion, power loss, and system reliability.

The main interest is to minimize an objective function or to select the best available option to obtain the most suitable distribution system expansion plan. Normally, the objective function is the costs of installing facilities and power losses. However in this thesis, the quality of supply to customers comprising the cost of demand uncertainty and the expected unserved energy are also considered. This chapter will present a mathematical formulation and solving algorithm for the DSP, based on the concept presented above.

3.2. Methodology

3.2.1. Problem Definition

A primary goal of the distribution expansion is to satisfy demand with acceptable safety, reliability, and cost. The DSP problem generally concerns about minimizing cost or selecting the lowest costs of new facility installation, power loss, demand uncertainty and reliability under constraints that must ensure the following requirements at all stages.

- Every demand center is served for all stages.

- Voltages are within guidelines at every node.
- All expenditure is within the budget for every stage.

The criterion is to find the best electrical network of minimum costs for the additional circuits subjected to specified constraints. In another way the problem concerns the selection of the best from the available options in planner’s list. The selected one generally yields the lowest total cost for all considered factors.

3.2.2. Problem Formulation

The main objective of the DSP problem is to minimize network expansion cost, including investment, power loss, system reliability cost which is composed of the costs of expected unserved energy and demand uncertainty. The constraints to assure adequate distribution capacity for supply and demand must also be considered. In general, the network cost is increased if new additional circuits are installed, from which the cost of power loss generally decrease.

Mathematical statement of the problem can be written as in equation (3-1).

Minimize:

$$C(t) = \sum_{\gamma} C_{ij,r,s,t} n_{ij,t} + k \sum_{\gamma} R_{ij,r,s,t} \frac{(P^2_{ij,r,s,t} + Q^2_{ij,r,s,t})}{|V^2_{i,t}|} + \text{System Reliability Cost} \quad (3\text{-}1)$$

$$\gamma = (i, j) \in A, r \in R_{i,j}, s \in S_{ij,r}$$

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subject to

$$\sum X_{it} = P_{i,t} \quad (3\text{-}2)$$

$$V^{\min} \le V_{i,t} \le V^{\max} \quad (3\text{-}3)$$

$$\sum C_{ij,r,s,t} n_{ij,t} \le B_t \quad (3\text{-}4)$$

where

A is the arc set containing all possible links for the system,

t is the number of stages or years to be considered,

$C_{ij,r,s,t}$ is the cost of the s^{th} size of the r^{th} routing of the link *ij* at stage *t*,

$n_{ij,t}$ is the decision variable for the s^{th} size of the r^{th} routing of the link *ij* at stage *t* ($n_{ij,t}$ = 1 if link *ij* exists, and $n_{ij,t}$ = 0 otherwise),

k is loss coefficient which can be generally defined as $8760 * NYE * C_{kwh} * LSF$,

LSF is loss factor at load *i*,

$R_{ij,r,s,t}$ is the resistance of the conductor in ohms/kilometer for the s^{th} size of the r^{th} routing of the link *ij* at stage *t*,

P_{ij}, Q_{ij} are active and reactive power in link *ij*,

$P_{i,t}$ is demand vector (element P_i represents demand at node *i*) for the t^{th} year,

$V^{\min}$, $V^{\max}$ minimum and maximum allowable voltage magnitude,

$V_{i,t}$ is voltage at node *i* for the t^{th} year,

B_t is the expansion budget for stage t, and

System Reliability cost, refered from equation (2-20) in chapter 2, is the cost of Expected Unserved Energy and peak load uncertainty given by (3-5).

$$\text{System Reliability Cost} = EUE\cos t + C_D \tag{3-5}$$

where

$EUE\cos t$, refers to from equation (2-10) in chapter 2, is the cost of the expected unserved energy, and

C_D is the cost of peak load uncertainty.

The meanings of equation listed above can be summarized hereafter.

In equation (3-1), *C* is the total cost for expansion at each stage; (3-2) is the power balance equation applied to every node; (3-3) is the voltage drop limit for all load centers; and (3-4) is a budgetary requirement for new facility in each considered period.

3.3. Detailed Algorithm

In general distribution system planning, the system planner will define options to supply demand at each existing and future nodes. The problem is then how to select the best one out of several or hundreds available options. In this regards, this proposed selecting algorithm is based on the options in which possible link between any nodes, type of routing and size of additional lines, and their fixed costs are defined. All input options comprise forecast system peak load, possible routings, and fixed cost defined as mentioned earlier. The system planner can determine possible routing list, type and size of conductors, fixed cost of additional lines and facilities. The list can be updated during its analysis. Therefore, we have a number of option options to pick up for the best. From those options, any possible configurations of future network are known or predefined. After that, the total cost of those possible expansions plan which has been referred in chapter 2 is calculated. The best solution should not only satisfy technical, i.e. power balance at each node, voltage drop limit, conditions, but also resulting in minimum cost. From this best solution, we know the required configuration of planning and also type of routing, size of conductor. Detailed algorithm is shown below.

First we define the number of considering stages. For example, we divide a 10-year planning period into 3 stages. The first stage is for the existing network. The second stage is the network which has to be expanded for the next few years. Then, the final stage is assumed to be the network needed to supply the demand in the final year, i.e. 10th year. Then, the best network expansion plan for each defined stage will be determined taking into account all possible options, e.g. route, conductor size etc. as described in the previous section. Equation (3-1) and its constraints (3-2)-(3-4) will be analyzed for each option at each stage. A flow chart describing the selection algorithm is shown in figure 3-1. Details of each step can be described below.

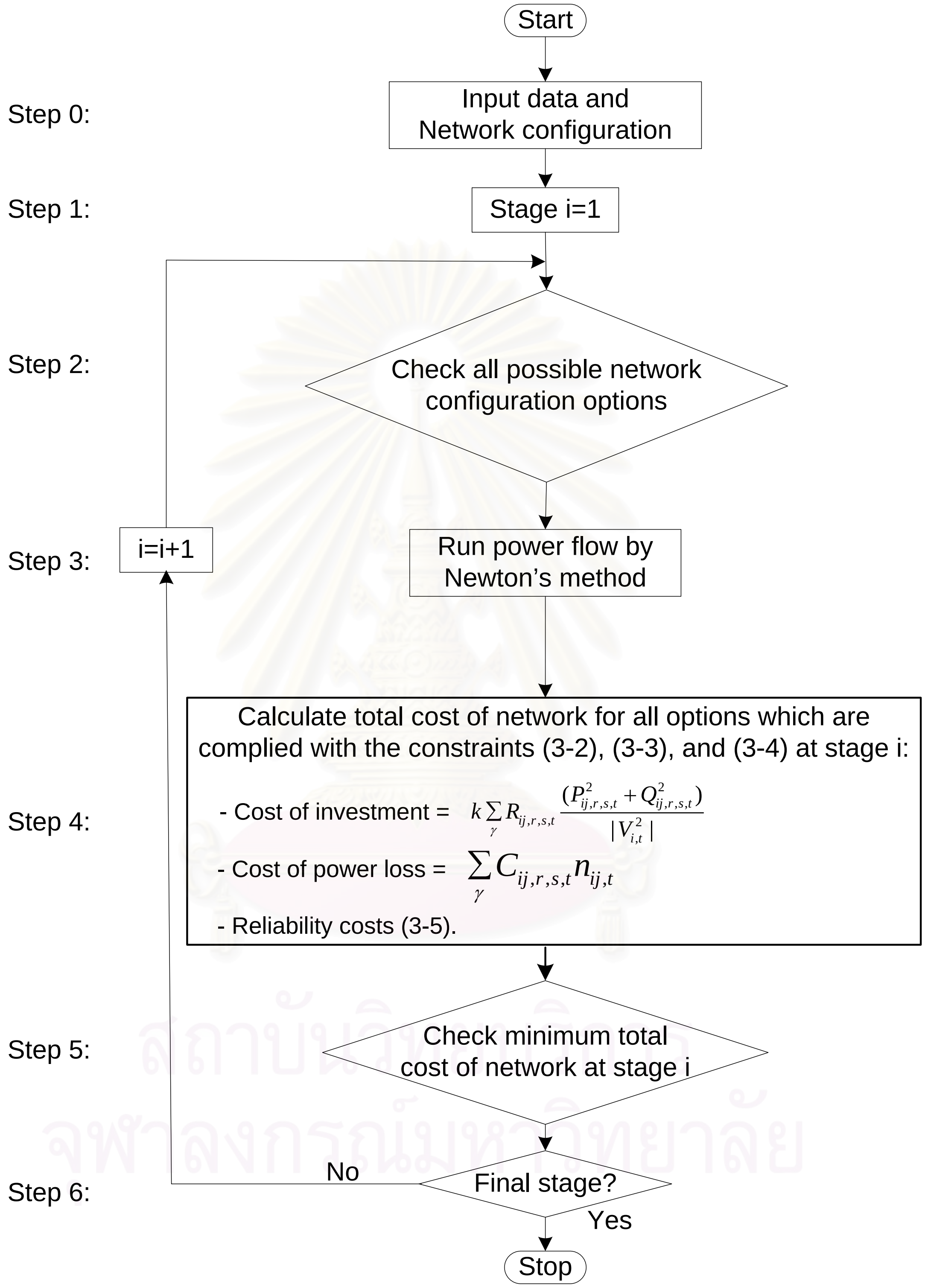

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Figure 3-1 Flow chart of calculation procedure

Step 0: Input data and configuration network

Any initial configuration and input data which is the forecast system peak load, possible additional lines, system characteristics, fixed cost, etc., are provided at step 0.

Normally, the planner must predict the future system peak load for each particular considering period to estimate DSP and nodes to supply future loads. Then, it is based on the future nodes to establish possibility of additional lines. Any feeder links between two nodes may have multiple routing options *(rt)*, and multiple options *(ss)* for links and conductor sizes. Fixed cost for every option and all the requiring data for all equipment are assumed to be known.

In additional, all of distribution reliability index, e.g. failure rate, repair time, standard deviation for system uncertainty etc., must be defined in this step.

Step 1: Considered stage

In this step, the existing distribution network, as defined for the first stage calculation, is a starting point for the planner. Various types of lines and their capacity, location and the demand of load centers, and source nodes are all the factors to be taken into account for future system expansion. To aid the formulation, design criteria and assumptions, source node and load center, are given.

Source node

It is assumed in this thesis that there is only one source node, node 1, as shown in figure 3-2. This is viewed as the equivalent infinite bus receiving power supply from transmission network of which the system characteristics is beyond the scope of this thesis. It is also assumed that this node is capable of supplying all load and voltage requirements for the considered period.

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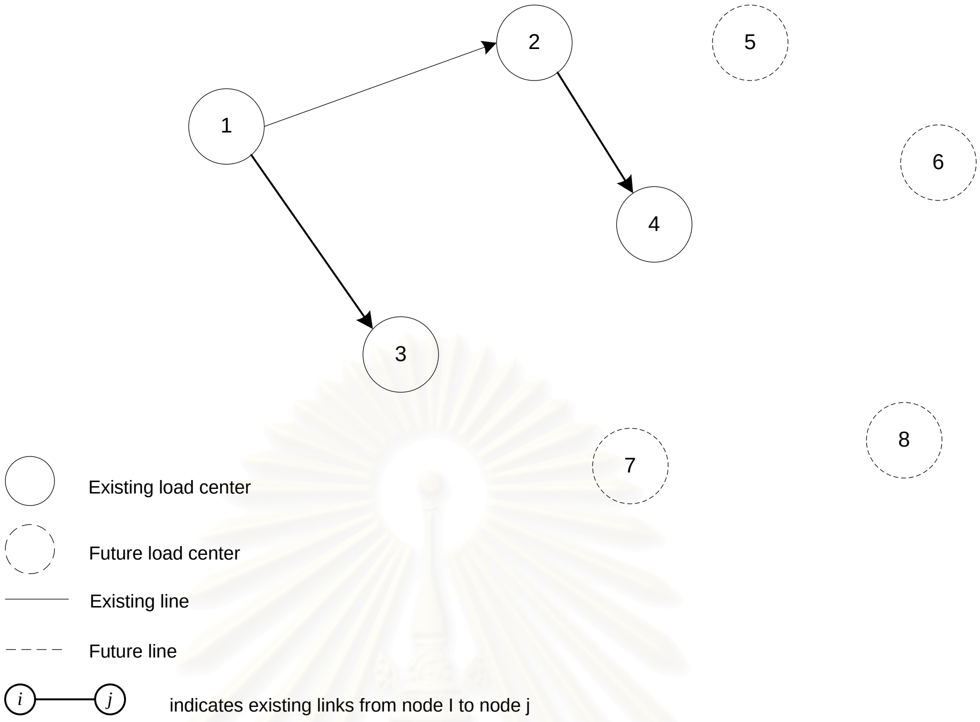

Figure 3-2 Existing and future load centers

Load center

Location of the loads and their peak loads are assumed to be certainly known for the first stage. For future stages, the peak loads are assumed to be knows but with uncertainty as modeled by the seven-step mentioned in the previous chapter. The future nodes, i.e. 5, 6, 7, 8, are also shown in figure 3-2.

Step 2: Check all possible network configuration options

Existing and future feeders are defined as part of the available options. Possible routing options are considered between any two load centers. For each routing option, a number of conductor sized will be considered. Figure 3-3 shows an example in which two routing options (e.g. overhead and underground lines) and two conductor sizes, as six links between nodes *i* to nodes *j* are presented.

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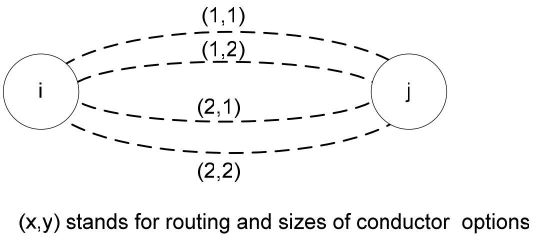

Figure 3-3 Routing and conductor size options of link *ij*

Any option will be possibly selected to be additional links for updating DSP configuration. Therefore, the number of DSP configurations in which all future nodes are supplied is generated by the predefined options. Each option will be analyzed to get the best solution which yield the lowest total cost of the considered expansion period.

Step 3: Run power flow by Newton’s method

After all possible options are defined, a power flow program will be run to check whether all variables comply with constraints, i.e. line capacity, power balance, voltage drop limit, and budgetary requirement. The developed power flow program is based on a standard Newton’s method which is described in detail in many textbooks [15, 16].

Step 4: Calculate the total cost of network at stage i

In this thesis, the total cost as mentioned in the previous chapter is used to solve DSP by considering options for routing and size options of links, load growth, and uncertainty on both supply and demand sides. It is necessary to described fixed and variable costs for the investment of additional circuits in more details.

Fixed costs

Fixed cost refers to expenditure for installation of any equipment, e.g. conductors, circuit breaker, fuses, recloser etc. However in this thesis we will assume that the cost of conductors as shown in the appendix has already covered all the other equipment cost. It contains the cost of material, transportation, and local prices.

Variable costs

Variable costs refer to costs that are functions of loss, supply and peak load sides. Normally, variable costs are cost of loss on the lines when considering development system. In this chapter, variable costs not only cost of loss but also costs of expected unserved energy and cost of peak load uncertainty. Therefore, reliability and uncertainty are taken into account in the variable cost component.

This step, we will concern the load forecast uncertainty which will be analyzed by using the seven-step approximate of the normal distribution.

From constraints in equations (2-21) and (2-22) in the section 2.4.3.1, we can know when the uncertainty will be occurred on the system and how can we calculate the demand uncertainty costs at any load point in which the uncertainty occurs. There are three constraints which are power balance at each node (flow conservation), voltage constraints, and budgetary requirement.

Flow conservation

The power flow must be comply with the well-know KCL equation, i.e.

$$P_{j,t} = \sum_{\alpha} X_{i,j,r,s,t} - \sum_{\beta} X_{j,p,w,y,t} \tag{3-6}$$

$\alpha = (i, j) \in A \,|\, i \in SP_j, r \in R_{ij}, s \in S_{ij,r}$,

$\beta = (j, p) \in A \,|\, j \in SP_p, w \in R_{jp}, y \in S_{jp,w}$,

where

A is the arc set containing all possible links for the system,

SP_j, SP_p are the sets of all possible source nodes to *j* and *p* respectively.

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In this formulation, the first term is limited to the number of possible links that can serve node *j*, whereas the second term is limited to the number of all possible links for which node *j* is a source possibility.

Voltage constrains

The voltage drop in the line section *ij* when carrying the current I_{ij} can be approximate according to (3-7)

$$\Delta V_{ij} = I_{ij}(r_{ij}\cos\theta + x_{ij}\sin\theta) \tag{3-7}$$

where r_{ij} and x_{ij} are the line section resistance and reactance respectively and θ is the power factor angle. The line section resistance normally influences the line section voltage drop. Because the value of reactance x_{ij} per unit length is fairly constant for a wide range of conductor sizes, where as that of resistance r_{ij} per unit length varies widely for distribution conductors and cables [3]. Therefore, $\sin\theta$ tends to zero. Then, for planning purpose, the effects of reactance on the voltage drop calculations may be neglected. So the voltage drop of the section line, in percent, is expressed as

$$\%\Delta V_{i,j,r,s,t} = \frac{S_{i,j,r,s,t}}{V_{nom}^2} l_{i,j,r,s} r_{i,j,r,s} \tag{3-8}$$

where V_{nom} refers to nominal voltage in kV

Therefore, the constraints for Kirchhoff's law, and voltage drop must be satisfied. If constraints are not violated, then proceed to step 5.

Budgetary requirements

Budget in regulated utilities, generally, is affected by capital investment costs which may be paid over a number of years. The distinction is necessary to ensure that the present customers are not charged for the plants and investments that will be used predominantly by future customers.

Then, the lowest total cost will be determined in the next step.

Step 5: Verify the lowest total cost

In this step, the total cost of all options or options will be compared. The lowest one which complies with all the defined constraints will then be selected. Therefore, the minimum total cost of DSP can be calculated and then the most suitable network to be expanded will be determined.

3.4. Conclusion

We have proposed the distribution expansion algorithm which is a process to select the best available options to obtain the most suitable system expansion plan. The test results from this developed algorithm will be shown in the next chapter.

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CHAPTER IV

SYSTEM EXPANSION TEST RESULTS

4.1. Introduction

A computer program has been developed to select the best option out of a number of system expansion options, which yields the lowest cost for DSP. The program is developed for solving radial network expansion problem, for which it can cover in general either low or medium voltage networks.

The main concept of the analysis is to find suitable paths and proper size of conductors from the existing load points to the future load points. In this chapter, the distribution system planning will be analyzed based on possible options. First, we formulate the objective function which includes cost of investment and others as mentioned in chapter 3. The problem is to select the best option out of several possible expansion options for which forecast peak loads, network configurations and system uncertainty are taken into account. Furthermore, to ensure that the voltage constraints impact on the solution, the allowable voltage drop limit is tightened from 0.96p.u. to 1.16p.u. (on a 1.06p.u. base at source node #1) for both cases. For simplicity we assume in all the following test cases that only peak load occurs for all the considering period. Therefore, the loss factor (*LSF*) in all cases is 1.0. However, in practice, if we know the detail of the forecasted load we can use the actual *LSF* instead.

Here, two typical medium voltage distribution systems for a medium term planning, i.e. 10-year ahead, are employed to test the developed program. The first one is a simple 4-node network consisting of two existing nodes and two future nodes. The second one is a 10-node network consisting of four existing nodes and six future nodes. A 10-year period is assumed and analyzed for each case. The duration between stages 1 and 2 is assumed for the first two years, whereas the duration between stages 2 and 3 is assumed for the next eight years.

Details of the results are provided and discussed in the following sections.

4.2. Test Case 1

The first case concerns a 4-node system consisting of one source node (node#1) and three load centers shown in fig. 4-1. Nodes 1-2 are the existing nodes whereas nodes 3 and 4 are the future nodes. Stage 1 is the existing network, and stages 2 and 3 are the future nodes. All the information is related to steps 0 and 1 of the detailed algorithm described in chapter 3, and shown in table 4-1. All other concerned information, e.g. resistance of conductors, fixed costs etc., are also shown in table 4-2. The failure rate and repair time of each component is assumed as 0.01 f/yr km and 4 hours respectively. The symbols [a, b] and (a, b) in figure 4-1 indicate existing links and future link options (routing, conductor size) respectively. For an example (1,2) between nodes 2 and 3 means that it is the first routing option defined for a future link between nodes 2 and 3 with the second size of conductor, i.e. overhead line (OH) of 50A cable, and its parameters as defined in table 4-2.

In the first stage, the information of the existing network in which the future stages (e.g. stages 2 and 3) and the forecasted load at each node have been provided in table 4-1. It is assumed that a load of 6MW is located at node 2 whereas the infected power of 6MW comes from node 1, i.e. neglecting power loss in the line for beginning.

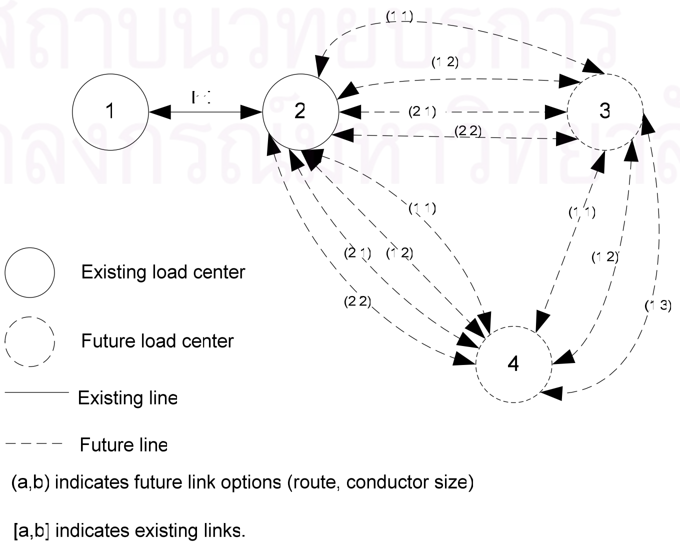

Figure 4-1 Distribution configuration

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Table 4-1 Forecasted system peak load

Load Center	Stage 1	Stage 2	Stage 3
	Existing network	Years 1-2	Year 3-10
	$P_{j,1}$ (MW)	$P_{j,2}$ (MW)	$P_{j,3}$ (MW)
1	-6	-13	-20
2	6	6	9
3	0	4	6
4	0	3	5

Table 4-2 Routing information

	i	j	TC	Rt	ss	Link size/type	r (Ω/km)	l (km)	CAP (MVA)	FC (Baht/km)
Existing system	1	2	OH	1	1	240SAC	0.164	0.5	21.8665	374260
Future routes	2	3	OH	1	1	35A	0.868	0.6	6.02736	83859.9
	2	3	OH	1	2	50A	0.641	0.6	7.2744	118390.4
	2	3	OH	2	1	35SAC	0.868	0.65	6.7115	280038.8
	2	3	OH	2	2	50SAC	0.641	0.65	8.0105	329045.5
	2	4	OH	1	1	35A	0.868	0.6	6.02736	83859.9
	2	4	OH	1	2	50A	0.641	0.6	7.2744	118390.4
	2	4	OH	2	1	35SAC	0.868	0.65	6.7115	280038.8
	2	4	OH	2	2	50SAC	0.641	0.65	8.0105	329045.5
	3	4	OH	1	1	35A	0.868	0.5	6.02736	83859.9
	3	4	OH	1	2	50A	0.641	0.5	7.2744	118390.4
	3	4	OH	1	3	70A	0.443	0.5	9.14496	147988.1

where

i : source terminal
j : Load terminal
rt : Routing option designation
ss : Link size designation
r : Line resistance in Ohms/km
l : Length in km
TC : Type of construction
FC : Fixed cost in Baht/km
OH : Overhead construction
CAP : Cable Capacity in MVA

Notice

1) All the conductors related information are taken from [13]

2) In case the underground cable (UG) needs to be considered we can also include it. However the fixed cost of the UG system is normally much higher than the OH system.

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The future load growth can be seen in table 4-1. For an example, there are two new load centers, i.e. 3 and 4, occurred in the next two years, which is defined for stage 2, of which the peak demands will be 4 and 3 MW respectively. These two load centers increase to 6 and 5 MW respectively in stage 3 or the 10th year in the future from the existing condition.

In table 4-2, possible routes, characteristics of all possible additional lines and their fixed cost, which in practice are normally defined by the planner, are listed. With more possible options, we have more choices to solve the network expansion problem. Here, types of construction (TC) are considered as an alternative option.

There are 28 (4x7) possible configuration options, i.e. 4 options from 2-3, and 7 options from nodes 2, 3 to supply node 4.

Suppose that we can supply the future load at node 3 through four possible routes from node 2 and three more routes from the future node 4, as shown in table 4-2. Node 4 has four possible supplies from node 2. The budget requirement for each expansion stage is limited at 0.5, 1.5 and 7 million Baht. With these defined possible routes and detailed information, we can run power flow to verify the results.

In this test we can divide into four cases, i.e. all components in the objective function are considered as follows:

1) Investment cost only
2) Investment cost plus loss cost,
3) Overall costs without uncertainty consideration
4) Overall costs with uncertainty consideration

The detail results of each case are presented in the following sections

4.2.1. Investment Cost Consideration

Here, total cost of DSP is obtained by considering only the lowest investment cost whereas the loss and reliability costs are neglected. The results are shown in table 4-3.

Table 4-3 System expansion solution

	From	To	Selected options	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	6.00	-6.00	1.060
Stage 2	1	2	1-1	13.02	-13.01	1.060
	2	3	2-2	7.01	-7.00	1.058
	3	4	1-3	3.00	-3.00	1.058
Stage 3	1	2	1-1	20.03	-19.01	1.059
	2	3	2-2	6.01	-6.00	1.058
	2	4	2-2	5.00	-5.00	1.058

Table 4-4 Investment cost of the expansion decision

Investment cost	Stage 1	Stage 2	Stage 3
Baht	187,130	475,003	475,003

From table 4-3, at stage 2, we can see that the source node 2 supplies node 3 and then node 3 will supply node 4. However, when we consider for stage 3, 10-years ahead, the expanded network in which the source node 2 supplies node 3 and node 4 is a better choice.

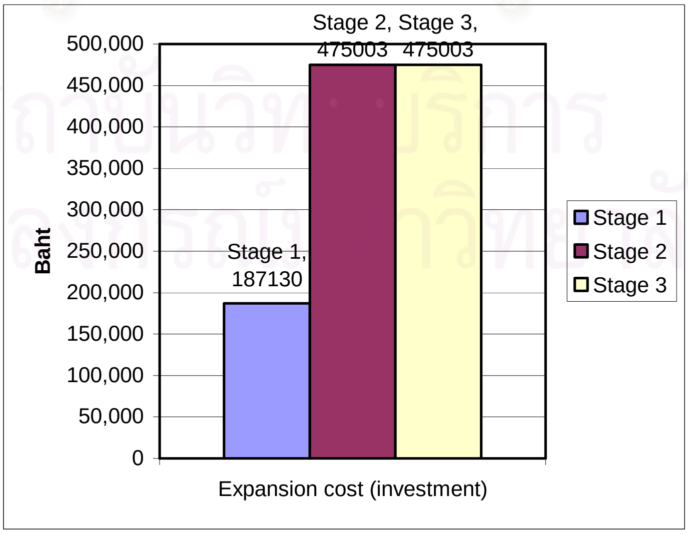

Figure 4-2 Expansion cost (investment only).

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From figure 4-2, it is clear to see the difference between the required investments of DSP at each stage. The cost at stages 2 and 3 in table 4-4 and figure 4-2, are the same since there is no further additional investment required.

In this case, the configuration of network planning in which the source node 2 supplies node 3 and 4 is the best solution.

4.2.2. Investment and Power Loss Costs Consideration

For this case, we will include the power loss cost into the objective function the only investment cost which is considered in the previous section. The impact of power loss to the expansion decision will be explored. Here, the objective function has two terms which are investment and loss costs. The results are shown in tables 4-5 and 4-6.

Table 4-5 System expansion solution

	From	To	Selected options	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	6.00	-6.00	1.060
Stage 2	1	2	1-1	13.01	-13.00	1.060
	2	3	1-2	4.00	-4.00	1.059
	2	4	1-2	3.00	-3.00	1.059
Stage 3	1	2	1-1	20.02	-20.01	1.059
	2	3	1-2	6.01	-6.00	1.058
	2	4	1-2	5.00	-5.00	1.058

Table 4-6 Results of the expansion decision (investment+loss)

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	187,130	475,004	475,004
Loss (MW)	0	0.0101	0.0243
Loss cost (Baht)	0	354,931	4,257,746
Total cost (Baht)	187,130	829,935	4,732,750

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We can see the impact of loss in table 4-6, from which loss values, at stages 1, 2, and 3, are 0, 0.0101, and 0.243 MW respectively. Therefore, the total cost of stage 2 is 829,935 Baht which is greater than the result obtained in stage 1. Similar results also occur in stage 3. The total cost is 4,732,750 Baht.

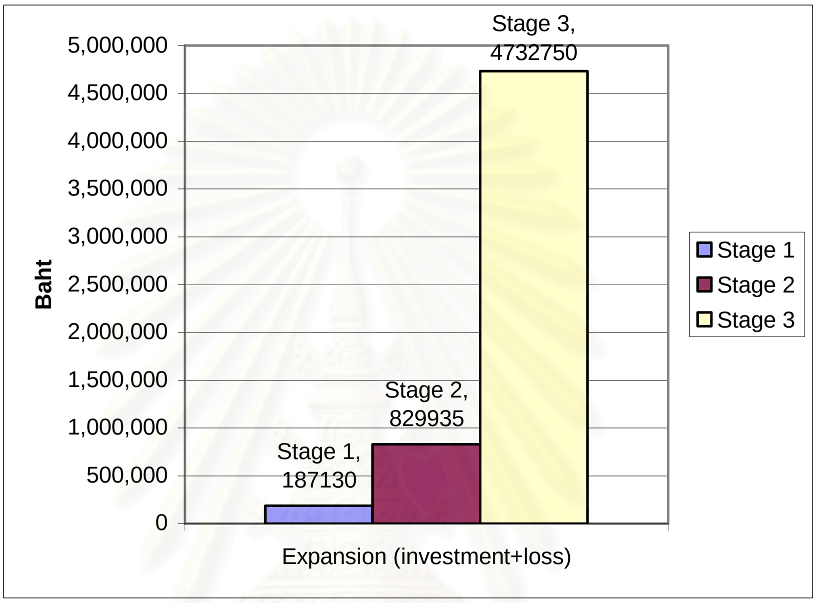


Figure 4-3 Expansion cost (investment + loss).

From table 4-5, we can see that the source node 2 supplying to load centers 3 and 4 is still the best choice for both stages 2 and 3. Therefore, we should build the line 2-3 and 2-4 from the second year onward.

4.2.3. Overall Costs without Load Forecast Uncertainty

In addition to the cost components we consider in section 4.2.2, we also take into account the reliability cost as a component in the objective function. In this section, the reliability cost covers only the EUE cost and neglects load forecast uncertainty. The Interrupted Energy Rate (IER) for the calculation is assumed at 68 (Baht/kWh).

The system expansion solutions are the same as table 4-5. However, in table 4-7, the total costs of the expansion decision including EUE cost are higher than the previous ones at each stage.

Table 4-7 Total cost of the expansion decision without load forecast uncertainty consideration

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	187,130	475,004	475,004
Loss cost (Baht)	0	354,931	4,257,746
EUE cost (Baht)	0	155,584	1,196,800
Total cost (Baht)	187,130	985,519	5,929,550

For this test, the configuration of the best expansion solution is not changed due to the total cost still satisfying with budget requirement.

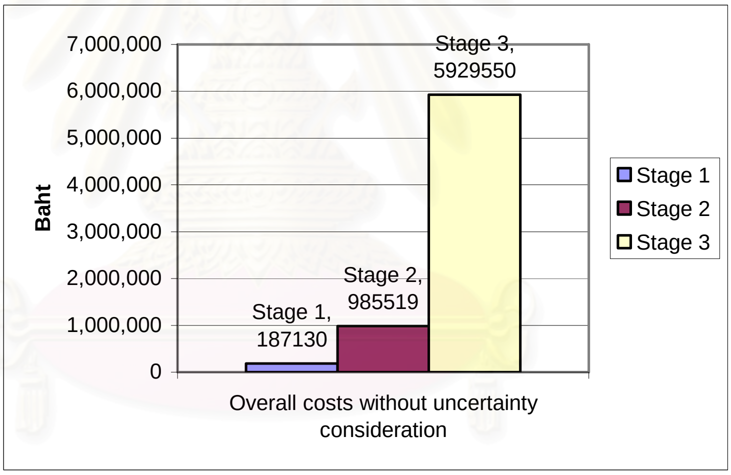


Figure 4-4 Expansion cost (overall costs) without load forecast uncertainty consideration

In table 4-7, the total costs for stages 2 and 3 are 985,519 and 5,929,550 Baht respectively. Therefore, when reliability cost impacts, the total costs of the expansion system will be increased, i.e. their values are 155,584 and 1,196,800 at stages 2 and 3 respectively.

4.2.4. Overall Costs with Load Forecast Uncertainty

In this section, the total cost comprising investment, loss and reliability are considered. We consider demand uncertainty cost which has impact only when the system operates close to the limits. Its results are the same as table 4-5.

Table 4-8 Total cost of the expansion decision with load forecast uncertainty consideration

Overall costs with uncertainty consideration	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	187,130	475,004	475,004
Loss cost (Baht)	0	354,931	4,257,746
EUE cost (Baht)	0	155,584	1,196,800
Demand uncertainty cost (Baht)	0	0	0
Total cost (Baht)	187,130	985,519	5,929,550

The total cost of expansion decision in table 4-8 is also same as table 4-7 because there are no load uncertainty impacts on the best solution. Therefore, its demand uncertainty costs are zero values.

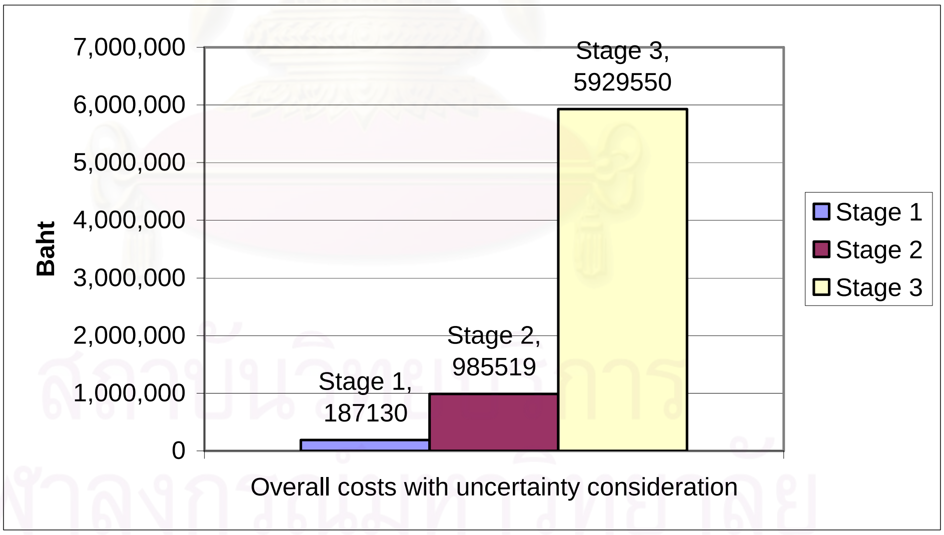


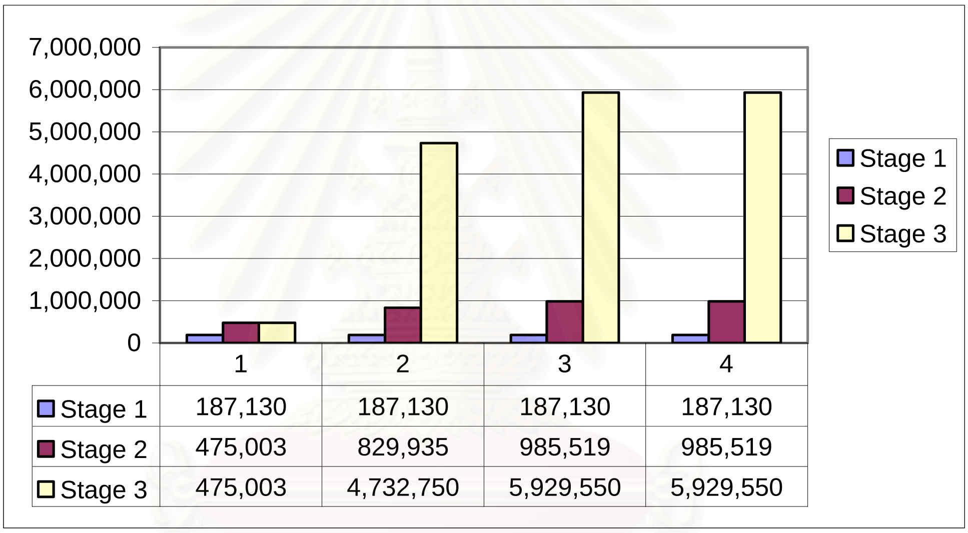
Figure 4-5 Expansion cost (overall costs) with load forecast uncertainty consideration

4.2.5. Result Comparison

The above results of DSP are analyzed and compared in this section. The impacts of total cost of network are considered. Firstly, the total cost obtained by minimizing investment cost is taken into account.

Second, loss cost which is added to the objective function is assumed. Then, we consider reliability cost which is added in the objective function without uncertainty consideration. Lastly, overall costs with uncertainty consideration namely investment, loss, reliability costs, are calculated. They are divided into four subfigures which are areas 1, 2, 3, and 4 respectively in figure 4-6.

From those results, we can see the comparing of the total costs of DSP with each cost consideration as following figure 4-6. First, at each consideration, the total costs of DSP, at stages 2 and 3, are greater than those, at stage 1, due to loss cost and reliability costs.



	1	2	3	4
Stage 1	187,130	187,130	187,130	187,130
Stage 2	475,003	829,935	985,519	985,519
Stage 3	475,003	4,732,750	5,929,550	5,929,550

Figure 4-6 Compare the total cost of DSP with each cost consideration.

Second, costs of the best option with loss and reliability consideration are no different, but they are higher with only investment consideration.

Finally, the total cost, at stages 2 and 3, are the same when we consider load forecast uncertainty. Because load uncertainty impact does not occurs on the best solution. The reason will be described, at stages 2 and 3, in following tables 4-7 and 4-8 when we consider the demand uncertainty in planning.

In table 4-9, there is no impact of demand uncertainty costs for each option at stage 2 since the line capacity of each line can cover maximum load which may occur according to the term $X_{ij} + kb$ (k=0, ± 1, ± 2, ± 3) values described in chapter 2.

Table 4-9 Costs analysis at stage 2 with load forecast uncertainty consideration

No. of available option	Investment cost (Baht)	Loss cost (Baht)	EUE cost (Baht)	Uncertainty impact cost (Baht)	Total cost of DSP at each consideration			
					(Investment)	(Investment+loss)	Overall costs (Baht)	
							Without uncertainty consideration	With uncertainty consideration
1	4.75E+05	4.07E+05	1.56E+05	0	4.75E+05	8.82E+05	1.04E+06	1.04E+06
2	4.75E+05	3.88E+05	1.56E+05	0	4.75E+05	8.63E+05	1.02E+06	1.02E+06
3	4.75E+05	4.12E+05	1.59E+05	0	4.75E+05	8.87E+05	1.05E+06	1.05E+06
4	4.75E+05	3.92E+05	1.59E+05	0	4.75E+05	8.67E+05	1.03E+06	1.03E+06
5	4.75E+05	3.74E+05	1.56E+05	0	4.75E+05	8.49E+05	1.00E+06	1.00E+06
6	4.75E+05	3.55E+05	1.56E+05	0	4.75E+05	8.30E+05	9.86E+05	9.86E+05
7	4.75E+05	3.79E+05	1.59E+05	0	4.75E+05	8.54E+05	1.01E+06	1.01E+06
8	4.75E+05	3.59E+05	1.59E+05	0	4.75E+05	8.34E+05	9.93E+05	9.93E+05
9	4.75E+05	5.54E+05	1.49E+05	0	4.75E+05	1.03E+06	1.18E+06	1.18E+06
1	4.75E+05	5.39E+05	1.49E+05	0	4.75E+05	1.01E+06	1.16E+06	1.16E+06
11	4.75E+05	5.25E+05	1.49E+05	0	4.75E+05	1.00E+06	1.15E+06	1.15E+06
12	4.75E+05	4.17E+05	1.59E+05	0	4.75E+05	8.92E+05	1.05E+06	1.05E+06
13	4.75E+05	3.99E+05	1.59E+05	0	4.75E+05	8.74E+05	1.03E+06	1.03E+06
14	4.75E+05	4.23E+05	1.63E+05	0	4.75E+05	8.98E+05	1.06E+06	1.06E+06
15	4.75E+05	4.03E+05	1.63E+05	0	4.75E+05	8.78E+05	1.04E+06	1.04E+06
16	4.75E+05	3.81E+05	1.59E+05	0	4.75E+05	8.56E+05	1.02E+06	1.02E+06
17	4.75E+05	3.63E+05	1.59E+05	0	4.75E+05	8.38E+05	9.97E+05	9.97E+05
18	4.75E+05	3.87E+05	1.63E+05	0	4.75E+05	8.62E+05	1.02E+06	1.02E+06
19	4.75E+05	3.67E+05	1.63E+05	0	4.75E+05	8.42E+05	1.00E+06	1.00E+06
20	4.75E+05	5.78E+05	1.52E+05	0	4.75E+05	1.05E+06	1.21E+06	1.21E+06
21	4.75E+05	5.63E+05	1.52E+05	0	4.75E+05	1.04E+06	1.19E+06	1.19E+06
22	4.75E+05	5.49E+05	1.52E+05	0	4.75E+05	1.02E+06	1.18E+06	1.18E+06

Table 4-10 Costs analysis at stage 3 with load forecast uncertainty consideration

No. of available option	Investment cost (Baht)	Loss cost (Baht)	EUE cost (Baht)	Uncertainty impact cost (Baht)	Total cost of DSP at each consideration			
					(Investment)	(Investment+loss)	Overall costs (Baht)	
							Without uncertainty consideration	With uncertainty consideration
1	4.75E+05	4.89E+06	1.20E+06	2,387.1	4.75E+05	5.36E+06	6.56E+06	6.67E+06
2	4.75E+05	4.63E+06	1.20E+06	2,387.1	4.75E+05	5.11E+06	6.30E+06	6.42E+06
3	4.75E+05	4.97E+06	1.22E+06	2,441.4	4.75E+05	5.45E+06	6.67E+06	6.79E+06
4	4.75E+05	4.69E+06	1.22E+06	2,441.4	4.75E+05	5.17E+06	6.39E+06	6.51E+06
5	4.75E+05	4.52E+06	1.20E+06	0	4.75E+05	4.99E+06	6.19E+06	6.19E+06
6	4.75E+05	4.26E+06	1.20E+06	0	4.75E+05	4.73E+06	5.93E+06	5.93E+06
7	4.75E+05	4.60E+06	1.22E+06	0	4.75E+05	5.07E+06	6.30E+06	6.30E+06
8	4.75E+05	4.32E+06	1.22E+06	0	4.75E+05	4.79E+06	6.02E+06	6.02E+06
9	4.75E+05	5.01E+06	1.22E+06	0	4.75E+05	5.48E+06	6.71E+06	6.71E+06
10	4.75E+05	4.75E+06	1.22E+06	0	4.75E+05	5.22E+06	6.45E+06	6.45E+06
11	4.75E+05	5.09E+06	1.25E+06	0	4.75E+05	5.57E+06	6.82E+06	6.82E+06
12	4.75E+05	4.81E+06	1.25E+06	0	4.75E+05	5.29E+06	6.54E+06	6.54E+06
13	4.75E+05	4.60E+06	1.22E+06	0	4.75E+05	5.08E+06	6.30E+06	6.30E+06
14	4.75E+05	4.35E+06	1.22E+06	0	4.75E+05	4.82E+06	6.04E+06	6.04E+06
15	4.75E+05	4.69E+06	1.25E+06	0	4.75E+05	5.16E+06	6.41E+06	6.41E+06
16	4.75E+05	4.41E+06	1.25E+06	0	4.75E+05	4.88E+06	6.13E+06	6.13E+06

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On the other hand, the results for stage 3 shown in table 4-10 illustrate that the uncertainty impact does occur in cases of options 1, 2, 3, and 4 with demand uncertainty costs of 2,387.1, 2,387.1, 2,441.4 and 2,441.4 Baht respectively. For example, option 1, the network expansion configuration as shows in table 4-11 shows that the load forecast uncertainty of load point 3 does have impact since its peak load is 6MW and the highest uncertainty is 0.12MW. Therefore, uncertainty occurs at uncertainty level +1 due to (6MW+0.12MW)=6.12MW is greater than the capacity of line 2-3, selection option 1-1, 6.0274MVA.

Table 4-11 System expansion in which load forecast uncertainty occurs at stage 3

Stage	From	To	Selected options	Cable capacity	Power flow
Stage 3	1	2	1-1	21.8665	20.0279
	2	3	1-1	6.0274	6.0081
	2	4	1-1	6.0274	5.0056

In addition, we can see overall costs, when load forecast uncertainty is considered, in figures 4-7 and 4-8. It is clear that the overall costs, with uncertainty consideration, are greater than those, without uncertainty consideration, if load forecast uncertainty occurs.

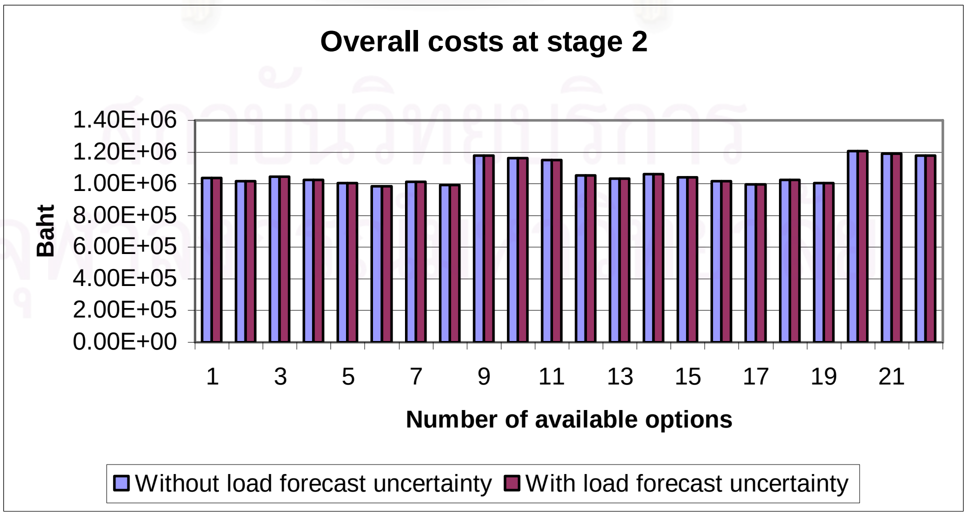

Figure 4-7 Compare overall costs at stage 2

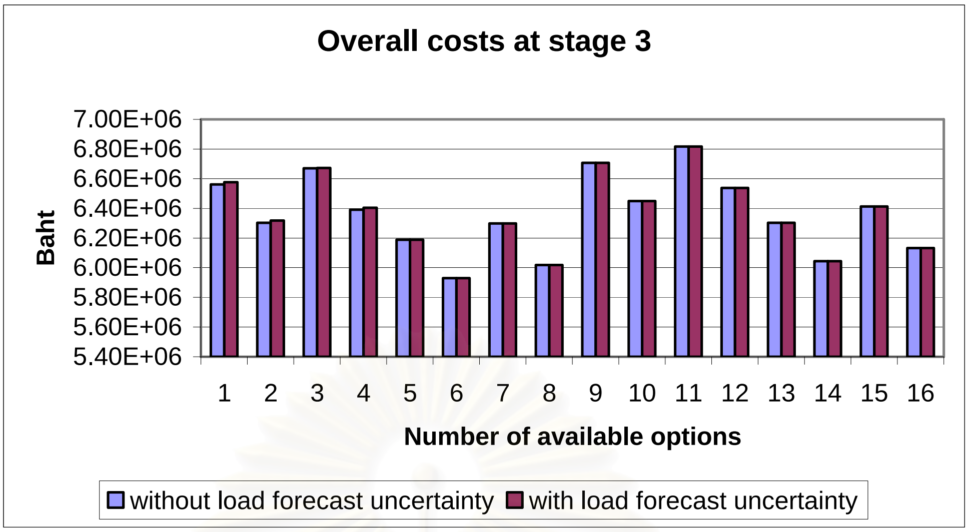

Figure 4-8 Compare overall costs at stage 3

In figure 4-7, demand uncertainty does not occurred at stage 2. Therefore, two lines, with and without uncertainty consideration, are the same. But at stage 3, in figure 4-8, the demand uncertainty occurs in the first four cases.

4.3. Test Case 2

For this case, a 10-node system consisting of four existing nodes is employed for the test. The system diagram, possible links, and future nodes, are shown in figure 4-7.The system and component information are provided in tables 4-12, and 4-13.

In table 4-12, the future loads as well as the source loads are provided. The details of input data and some possible routings to supply future nodes are provided in table 4-13. In this test case there are possible routings and load centers to be considered. Several routings and load centers can be modified and analyzed to get better results by using forecast system peak load and options. All the defined constraints are checked in our calculation and the result needs to be complied with budgetary requirements which are limited at 1, 4, and 15 million Baht for each stage. Here, investment, loss, reliability system costs are considered and analyzed.

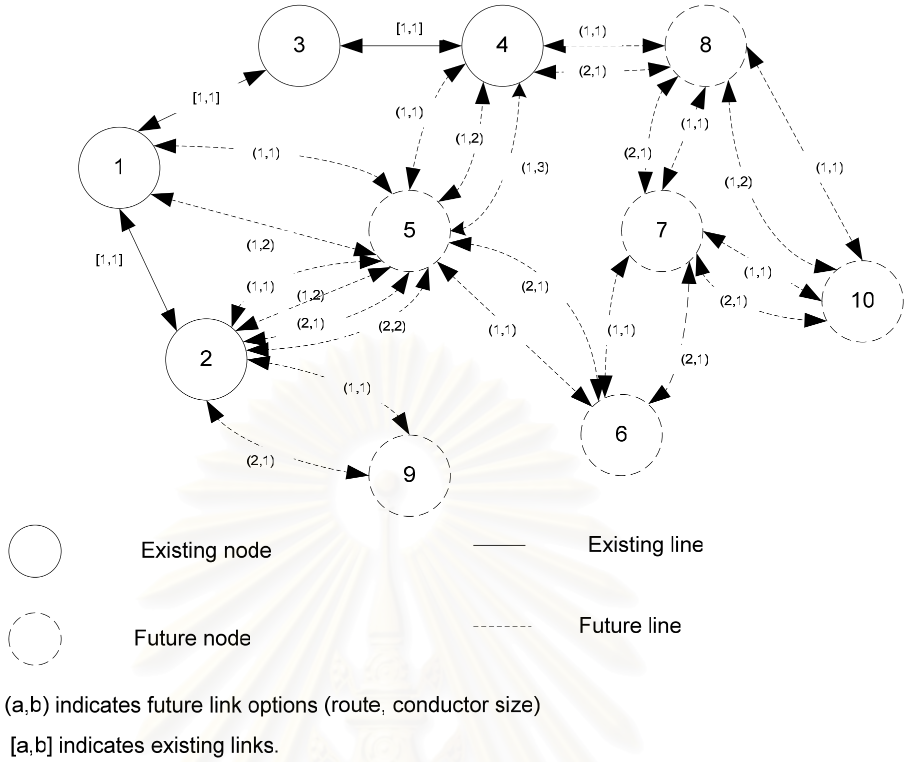

Figure 4-9 Distribution configuration.

Table 4-12 Forecast system peak load

Load Center	Stage 1 $P_{j,1}$ (MW)	Stage 2 $P_{j,2}$ (MW)	Stage 3 $P_{j,3}$ (MW)
1	-6	-20	-29
2	4	5	5
3	2	3	4
4	4	4	5
5	0	0	2
6	0	1	2
7	0	2	3
8	0	0	1
9	0	2	3
10	0	3	4

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Table 4-13 Routing information

	i	j	TC	rt	ss	Link size/type	r (Ω/km)	l (km)	CAP (MVA)	FC (Baht/km)
Existing system	1	2	OH	1	1	70SAC	0.443	0.5	9.959	385053
	1	3	OH	1	1	240SAC	0.125	0.6	21.8665	840116.3
	3	4	OH	1	1	185SAC	0.164	0.4	18.4025	700096.9
Future routes	1	5	OH	1	1	35A	0.868	0.7	6.02736	83859.9
	1	5	OH	1	2	50A	0.641	0.7	7.2744	118390.4
	2	5	OH	1	1	35A	0.868	0.5	6.02736	83859.9
	2	5	OH	1	2	50A	0.641	0.5	7.2744	118390.4
	2	5	OH	2	1	35SAC	0.868	0.55	6.7115	280038.8
	2	5	OH	2	2	50SAC	0.641	0.55	8.0105	329045.5
	2	9	OH	1	1	35A	0.868	0.7	6.02736	83859.9
	2	9	OH	2	1	35SAC	0.868	0.7	6.7115	280038.8
	4	5	OH	1	1	35A	0.868	0.3	6.02736	83859.9
	4	5	OH	1	2	50A	0.641	0.3	7.2744	118390.4
	4	5	OH	1	3	70A	0.164	0.3	17.45856	345305.5
	4	8	OH	1	1	35A	0868	0.45	6.02736	83859.9
	4	8	OH	2	1	35SAC	0.868	0.45	6.7115	280038.8
	5	6	OH	1	1	35A	0.868	0.30	6.02736	83859.9
	5	6	OH	2	1	35SAC	0.868	0.35	6.7115	280038.8
	6	7	OH	1	1	50A	0.641	0.45	7.2744	118390.4
	6	7	OH	2	1	50SAC	0.641	0.45	8.0105	329045.5
	7	8	OH	1	1	35A	0.868	0.4	6.02736	83859.9
	7	8	OH	2	1	35SAC	0.868	0.45	6.7115	280038.8
	7	10	OH	1	1	35A	0.868	0.4	6.02736	83859.9
	7	10	OH	2	1	35SAC	0.868	0.45	6.7115	280038.8
	8	10	OH	1	1	35A	0.868	0.7	6.02736	83859.9
	8	10	OH	1	1	50A	0.641	0.7	7.2744	118390.4
Notice	1. All the conductors relate1d information are taken from [13] 2. Meaning of all the abbreviation can be referred to table 4-2.									

In this test, we also assume four consideration cases as follows:

1) Investment cost only
2) Investment cost plus loss

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3) Overall cost without load forecast uncertainty
4) Overall cost with load forecast uncertainty

The results and discussion are presented in the following sections

4.3.1. Investment Cost Consideration

The best solution is shown in table 4-14. In the table 4-15, the budgetary requirements are given.

Table 4-14 System expansion solution

	From	To	Selected options	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	4.00	-4.00	1.060
	1	3	1-1	6.00	-6.00	1.060
	3	4	1-1	4.00	-4.00	1.060
Stage 2	1	2	1-1	7.01	-7.00	1.059
	1	3	1-1	13.02	-13.01	1.060
	3	4	1-1	10.01	-10.01	1.059
	4	5	1-3	6.01	-6.01	1.059
	5	6	2-1	6.01	-6.01	1.058
	6	7	2-1	5.01	-5.00	1.058
	7	8	2-1	3.00	-3.00	1.057
	2	9	2-1	2.00	-2.00	1.059
	8	10	1-1	3.00	-3.00	1.056
Stage 3	1	2	1-1	8.01	-8.00	1.059
	1	3	1-1	21.04	-21.02	1.059
	3	4	1-1	17.02	-17.01	1.059
	4	5	1-3	7.01	-7.00	1.059
	5	6	2-1	5.00	-5.00	1.058
	6	7	2-1	3.00	-3.00	1.058
	4	8	2-1	5.01	-5.00	1.058
	2	9	2-1	3.00	-3.00	1.058
	8	10	1-1	4.00	-4.00	1.057

Table 4-15 Investment cost of the expansion decision

Investment cost	Stage 1	Stage 2	Stage 3
Baht	976,635	1,731,229	1,731,229

In this test case, the power loss and reliability costs are not considered. The best results are shown in table 4-14 whereas total costs of the expansion decision are shown in table 4-15. From table 4-14, we can see that the best configuration of expansion network, at stage 2, can be used at stage 3.

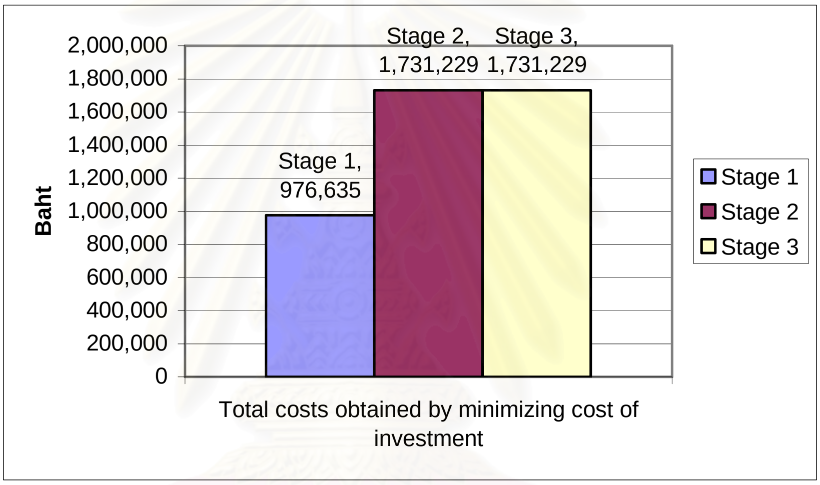

Figure 4-10 Expansion cost (investment only)

From figure 4-10, it is clear to see the budget for DSP at each stage. And, the best total costs, at stages 2 and 3, are the same because of investment consideration. In addition, we can see that the expansion cost of a large system planning will increases and requires more options to take into account.

4.3.2. Investment and Power Loss Consideration

For this case, we will see the impact of power loss to expansion decision in a large plan. The objective function has two components which are investment and loss costs. The results of expansion decision describe in tables 4-16 and 4-17.

Table 4-16 System expansion solution

	From	To	Select option	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	4.00	-4.00	1.060
	1	3	1-1	6.00	-6.00	1.060
	3	4	1-1	4.00	-4.00	1.060
Stage 2	1	2	1-1	7.00	-7.00	1.059
	1	3	1-1	10.01	-10.00	1.060
	3	4	1-1	7.00	-7.00	1.059
	1	5	1-2	3.00	-3.00	1.059
	5	6	1-1	3.00	-3.00	1.059
	6	7	1-1	2.00	-2.00	1.059
	4	8	1-1	3.00	-3.00	1.059
	2	9	1-1	2.00	-2.00	1.059
	8	10	1-1	3.00	-3.00	1.058
Stage 3	1	2	1-1	8.00	-8.00	1.059
	1	3	1-1	14.02	-14.01	1.060
	3	4	1-1	10.01	-10.01	1.059
	1	5	1-2	7.00	-7.00	1.059
	5	6	1-1	5.00	-5.00	1.058
	6	7	2-1	3.00	-3.00	1.058
	4	8	2-1	5.00	-5.00	1.058
	2	9	1-1	3.00	-3.00	1.058
	8	10	1-1	4.00	-4.00	1.058

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Table 4-17 Results of expansion decision (investment+loss)

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	976,635	1,731,229	1,731,229
Power Loss (MW)	0	0.0169	0.0384
Loss cost (Baht)	0	591,228	6,735,103
Total cost (Baht)	976,635	2,322,457	8,466,332

Here, the best expansion network configuration is the same as those at both stages 2 and 3. Therefore, this configuration is the best choice for two stages. Moreover, the impact of power loss to expansion decision will be explored by comparing table 4-16 with table 4-14. In table 4-14, future node 5 can be received from node 4. However, in this case, it can be received from source node 1. In addition, the total costs of this case, at stages 2 and 3, are greater than those, investment only, about 591,228 and 6,735,103 Baht respectively. These values are loss costs on expansion decision. The results of expansion decision are represented in following figure 4-11.

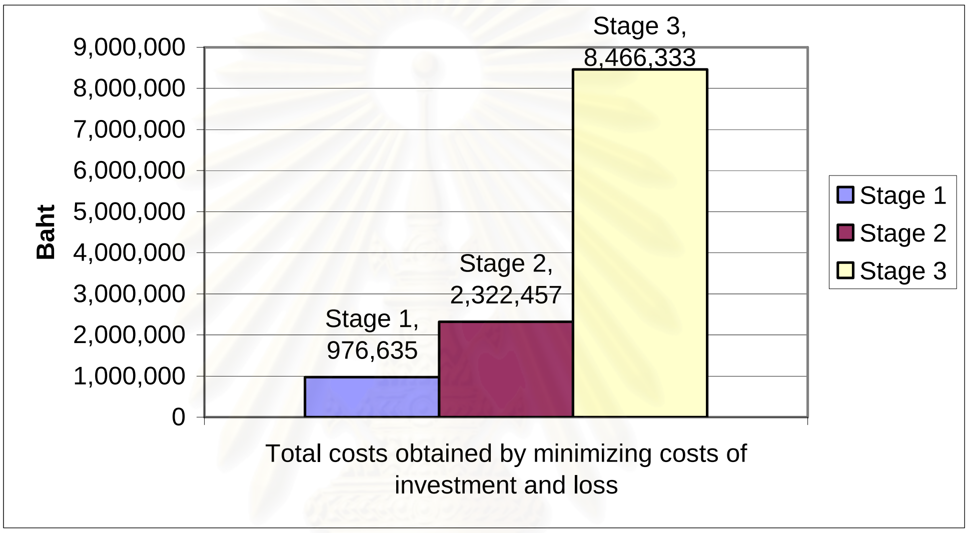

Figure 4-11 Expansion cost (investment+loss)

4.3.3. Overall Costs without Load Forecast Uncertainty

Reliability cost is applied and analyzed in previous sections for small system planning. However, it will be considered in the large planning and included EUE cost only and neglected load forecast uncertainty. The IER is also assumed at 68 Baht/kWh.

Table 4-18 Results of expansion decision without load forecast uncertainty

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	976,635	1,731,229	1,731,229
Loss cost (Baht)	0	591,228	6,735,103
EUE cost (Baht)	0	685,440	4,969,441
Total cost (Baht)	976,635	3,007,897	13,435,773

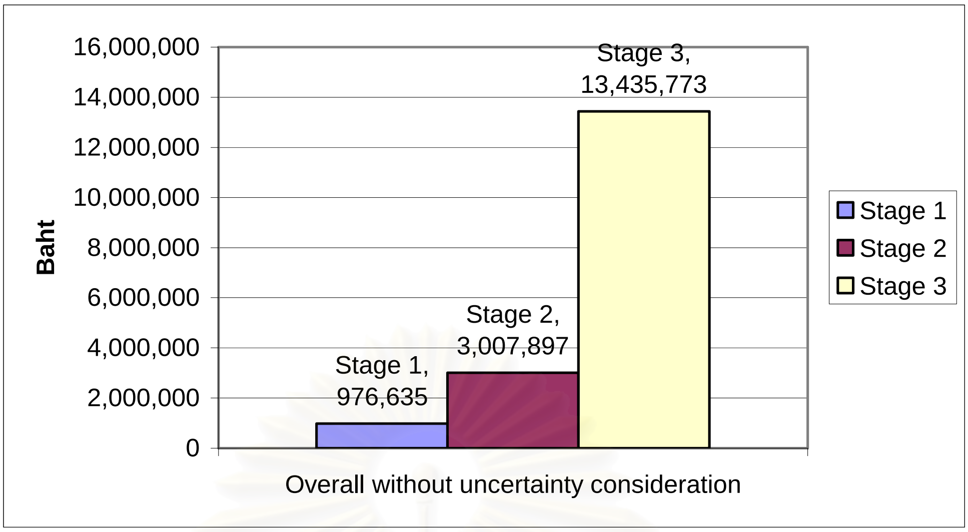

Figure 4-12 Expansion cost (overall costs) without load forecast uncertainty consideration

In this case, system expansion solution without load forecast uncertainty is still the same expansion network, table 4-16, in which we only consider the costs of investment and loss. But the total costs of expansion decision are higher than above results in which only investment and loss costs are considered. The results of expansion decision show in table 4-18 and figure 4-12.

4.3.4. Overall Costs with Load Forecast Uncertainty

In this section, we will consider the load forecast uncertainty which is referred to in section 2.4.2. The best solution of this case is the same in table 4-16 due to the total cost of expansion decision still satisfies the requirements. In the table 4-19, the total costs of expansion decision are given.

Table 4-19 Results of the expansion decision with load forecast uncertainty consideration

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	976,635	1,731,229	1,731,229
Loss cost (Baht)	0	591,228	6,735,103
EUE cost (Baht)	0	685,440	4,969,441
Load uncertainty cost (Baht)	0	0	0
Total cost (Baht)	976,635	3,007,897	13,435,773

From table 4-19, we can see that the configuration of the best expansion solution does not change due to the load forecast uncertainty does not occur, i.e. the capacity of each component of each option is still greater than the power flow and load forecast uncertainty. The total costs of the best solution, at each stage, are represented in figure 4-13.

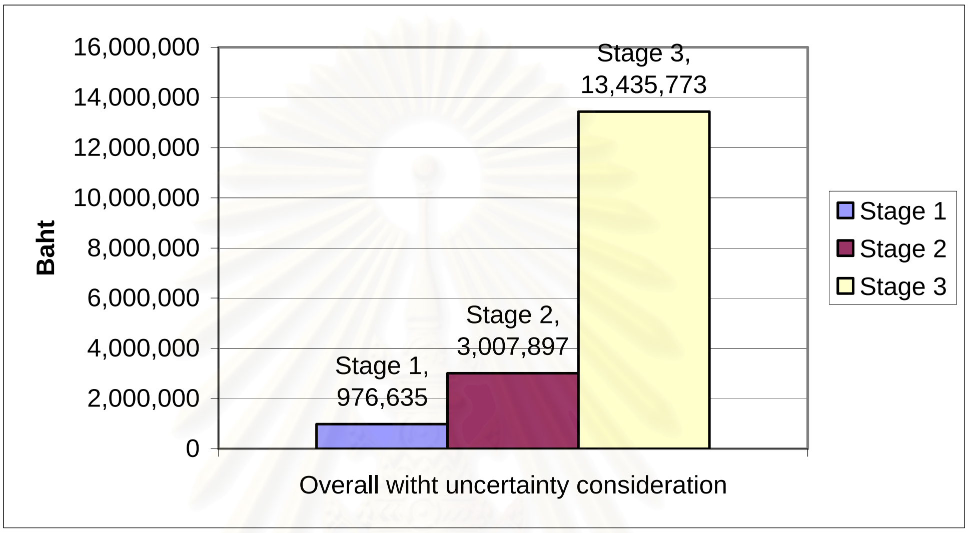

Figure 4-13 Expansion cost (overall costs) with load forecast uncertainty consideration

4.3.5. Result Comparison

From above results of test case 2, we can see that the results have differences between only investment cost which are considered and the total cost in which loss and reliability costs are added to. The differences can be more clearly appreciated by considering the total costs shown in figure 4-14.

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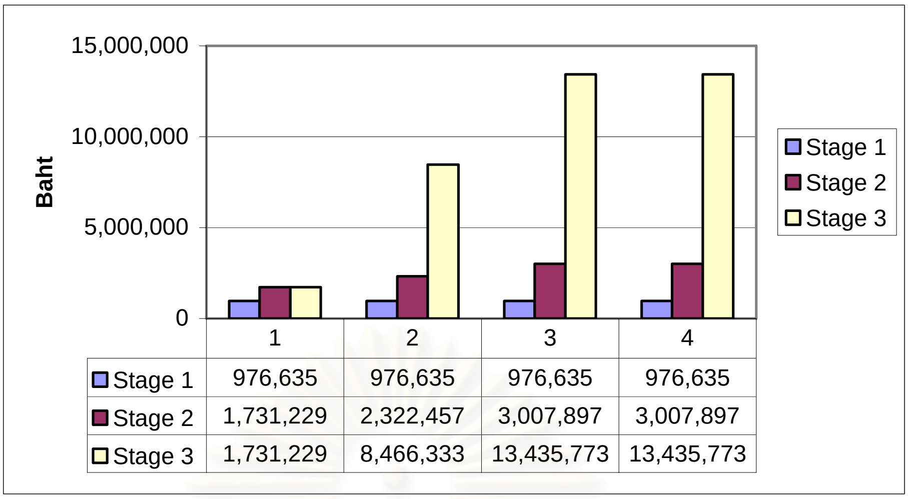

	1	2	3	4
▢ Stage 1	976,635	976,635	976,635	976,635
■ Stage 2	1,731,229	2,322,457	3,007,897	3,007,897
▢ Stage 3	1,731,229	8,466,333	13,435,773	13,435,773

Figure 4-14 Compare the total cost of DSP with each cost consideration.

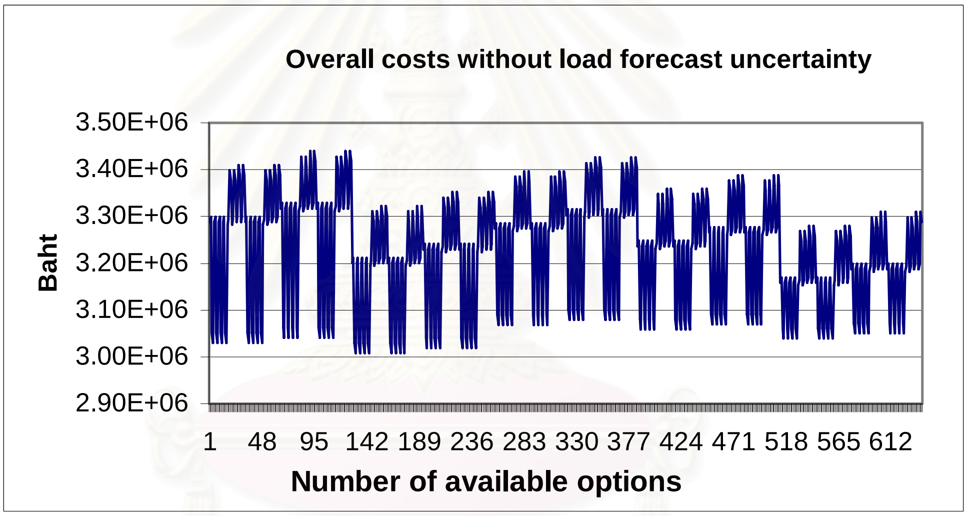

Figure 4-15 Overall costs without load forecast uncertainty at stage 2

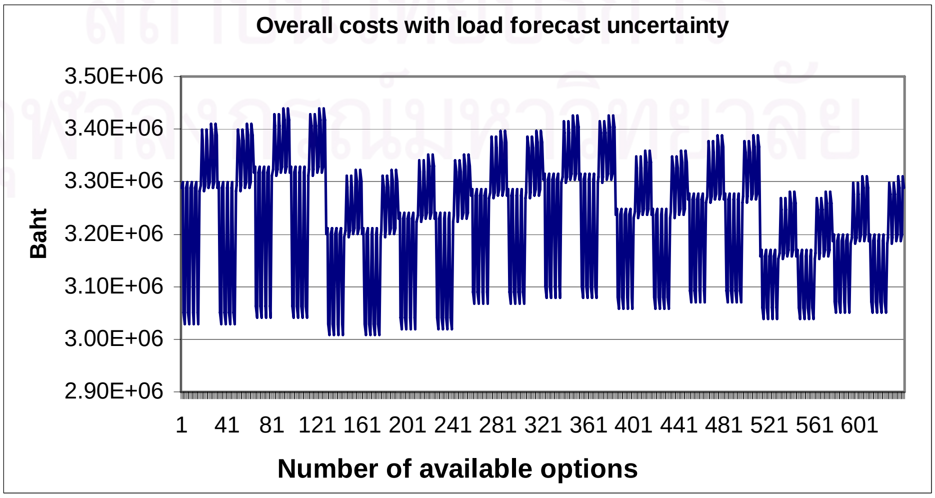

Figure 4-16 Overall costs with load forecast uncertainty at stage 2

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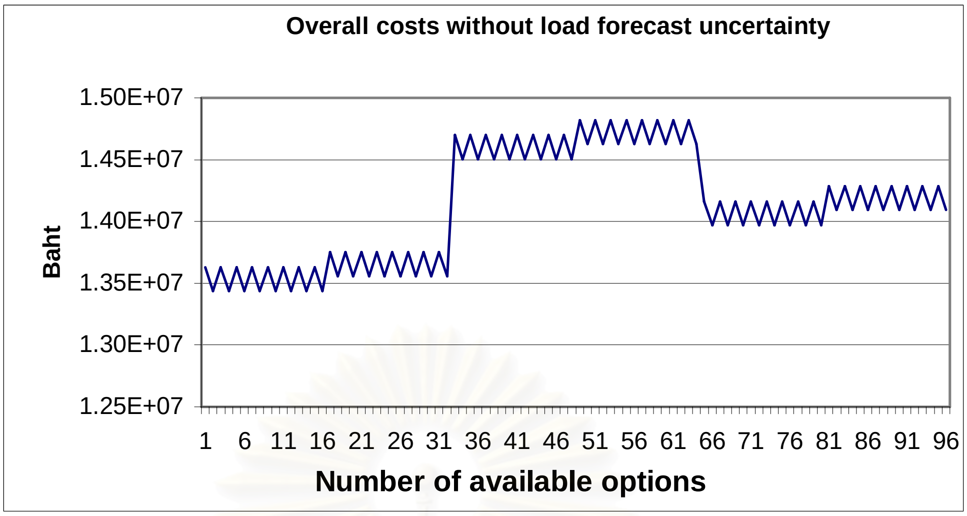

Figure 4-17 Overall costs without load forecast uncertainty at stage 3

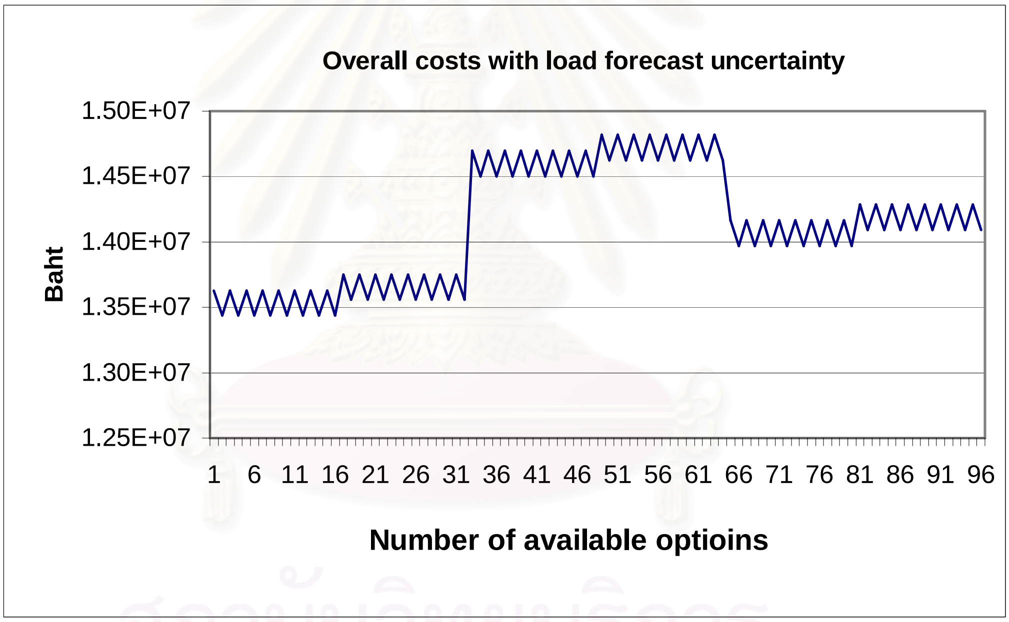

Figure 4-18 Overall costs with load forecast uncertainty at stage 3

In this test case, the load forecast uncertainty does not occur in the best decision. We can see its impact in figures 4-15, 4-16, 4-17, and 4-18. Therefore, the results of expansion solutions without load forecast uncertainty are the same as those at stages 2 and 3 when load forecast uncertainty is considered. From overall considerations, we can see that the best configuration of DSP is the same as that shown in table 4-16.

4.4. Expansion Configuration System.

Normally, the length of cables is usually limited to around 800 m or even less for LV distribution system in rural areas. But in urban areas, the system may be more expansible. Therefore, we will assume expansion configuration system which will be 5 times more than the previous 10-node system, i.e. 5 times of length of cables, with the same configuration and growth data of the test case 2.

In this section, investment, loss, demand uncertainty and expected unserved energy cost are taken into account to analyze impact of total cost of network. They are also analyzed by considering four cases as follows:

1) Investment cost
2) Investment and loss costs
3) Overall cost without load forecast uncertainty
4) Overall cost with loaf forecast uncertainty

The details of results are presented and discussed in following sections.

4.4.1. Investment Consideration

In this case, expansion decision of DSP is obtained by considering only investment cost. The results are shown in tables 4-20 and 4-21.

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Table 4-20 System expansion solution

	From	To	Selected options	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	4.00	-4.00	1.058
	1	3	1-1	6.01	-6.00	1.059
	3	4	1-1	4.00	-4.00	1.058
Stage 2	1	2	1-1	7.03	-7.01	1.056
	1	3	1-1	13.10	-13.08	1.058
	3	4	1-1	10.08	-10.06	1.056
	4	5	1-3	6.06	-6.06	1.056
	5	6	2-1	6.06	-6.03	1.051
	6	7	2-1	5.03	-5.02	1.048
	7	8	2-1	3.02	-3.01	1.045
	2	9	2-1	2.01	-2.00	1.054
	8	10	1-1	3.01	-3.00	1.042
Stage 3	1	2	1-1	8.04	-8.01	1.056
	1	3	1-1	21.18	-21.11	1.056
	3	4	1-1	17.11	-17.07	1.054
	4	5	1-3	7.03	-7.02	1.053
	5	6	2-1	5.02	-5.01	1.050
	6	7	2-1	3.01	-3.00	1.048
	4	8	2-1	5.04	-5.02	1.049
	2	9	2-1	3.01	-3.00	1.052
	8	10	1-1	4.02	-4.00	1.045

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Table 4-21 Investment cost of expansion decision

Investment cost	Stage 1	Stage 2	Stage 3
Baht	4,882,175	8,656,143	8,656,143

From tables 4-20 and 4-21, we can see that the best solution configurations are the same as previous results when we consider only investment cost. However, the cost of expansion decision is higher due to expanding configuration.

4.4.2. Investment and Power Loss Consideration

In this case, we can see the impact of loss on expansion configuration system. The results are shown in tables

Table 4-22 System expansion solution

	From	To	Selected options	Power flow (MW)		Voltage at receiving end
				From bus	To bus	
Stage 1	1	2	1-1	4.00	-4.00	1.058
	1	3	1-1	6.01	-6.00	1.059
	3	4	1-1	4.00	-4.00	1.058
Stage 2	1	2	1-1	7.03	-7.01	1.056
	1	3	1-1	10.04	-10.02	1.058
	3	4	1-1	7.02	-7.02	1.057
	1	5	1-2	3.02	-3.01	1.057
	5	6	1-1	3.01	-3.00	1.055
	6	7	2-1	2.00	-2.00	1.054
	4	8	2-1	3.02	-3.01	1.055
	2	9	2-1	2.01	-2.00	1.054
	8	10	1-1	3.01	-3.00	1.051
Stage 3	1	2	1-1	8.04	-8.01	1.056
	1	3	1-1	14.08	-14.05	1.058
	3	4	1-1	10.05	-10.04	1.056
	1	5	1-2	7.07	-7.02	1.053
	5	6	1-1	5.02	-5.01	1.050
	6	7	2-1	3.01	-3.00	1.048
	4	8	2-1	5.04	-5.02	1.052
	2	9	2-1	3.01	-3.00	1.052
	8	10	1-1	4.02	-4.00	1.047

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Table 4-23 Results of expansion decision (investment+loss)

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	4,883,175	8,656,143	8,656,143
Loss (MW)	0	0.0851	0.19488
Loss cost (Baht)	0	2,981,474	34,143,164
Total cost (Baht)	4,883,175	11,637,617	42,799,307

From table 4-23, the loss costs are higher at stages 2 and 3 than the results in the test case 2. Power losses on these solutions, at stages 2 and 3, are 0.0851 and 0.19488 MW respectively, whereas these values in test case 2 are 0.0169 and 0.0384 MW, at stages 2 and 3, respectively.

4.4.3. Overall Costs without Uncertainty Consideration

With expansion configuration system, we also take into account the reliability cost which only covers the EUE cost and neglects load forecast uncertainty. The system expansions are same as above section 4.4.2. However, the results of expansion decision without load forecast uncertainty are shown in table 4-24

Table 4-24 Results of expansion decision without load forecast uncertainty

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	4,883,175	8,656,143	8,656,143
Loss cost (Baht)	0	2,981,414	34,799,307
EUE cost (Baht)	0	2,121,600	14,725,457
Total cost (Baht)	4,883,175	13,759,217	58,180,907

In table 4-24, the EUE costs, at stages 2 and 3, are 2,121,600 and 14,725,457 Baht. Due to this, the total cost of DSP increased, which may change the decision.

4.4.4. Overall Costs with Load Forecast Uncertainty

In this section, total cost comprising of investment, loss, EUE and load forecast uncertainty is considered. The impact of load forecast uncertainty will be analyzed.

The results of the expansion configuration are the same as previous ones without load forecast uncertainty consideration. Its total costs of expansion decision are shown in table 4-25

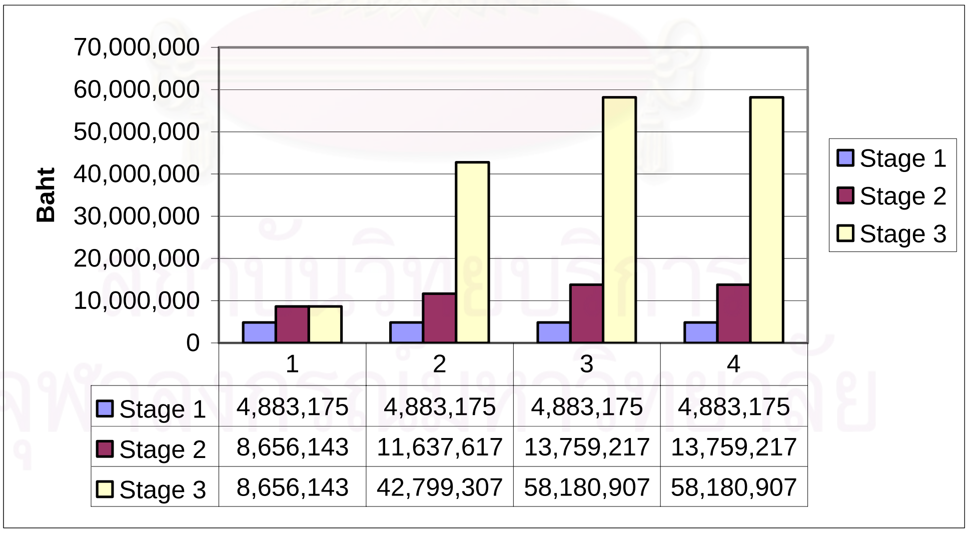
Table 4-25 Results of the expansion decision with load forecast uncertainty consideration

Item	Stage 1	Stage 2	Stage 3
Investment cost (Baht)	4,883,175	13,759,217	58,180,907
Loss cost (Baht)	0	2,981,414	34,799,307
EUE cost (Baht)	0	2,121,600	14,725,457
Load forecast uncertaint cost (Baht)	0	0	0
Total cost (Baht)	4,883,175	13,759,217	58,180,907

From table 4-25, we can see that there is no load forecast uncertainty occurring in the best solution. Therefore, its results are still the same as those without load forecast uncertainty consideration.

4.4.5. Result Comparison

From above tables, we can see that the total cost of DSP will increase in urban distribution with five times expansion of the length of cables. It is shown in figure 4-19.



	1	2	3	4
Stage 1	4,883,175	4,883,175	4,883,175	4,883,175
Stage 2	8,656,143	11,637,617	13,759,217	13,759,217
Stage 3	8,656,143	42,799,307	58,180,907	58,180,907

Figure 4-19 Compare the total cost of DSP with each cost consideration.

Comparing these results with the above results, test case 2, it is clear that the capital for planning increases when we increase length of cables (5 times in here). Therefore, the budget requirement has to be reconsidered in planning. In addition, forecast peak loads are also considered. But the results do not changed because the demand uncertainty costs are zero. They are shown in figures 4-20 and 4-21 at stage 2; and in figures 4-22 and 4-23 at stage 3.

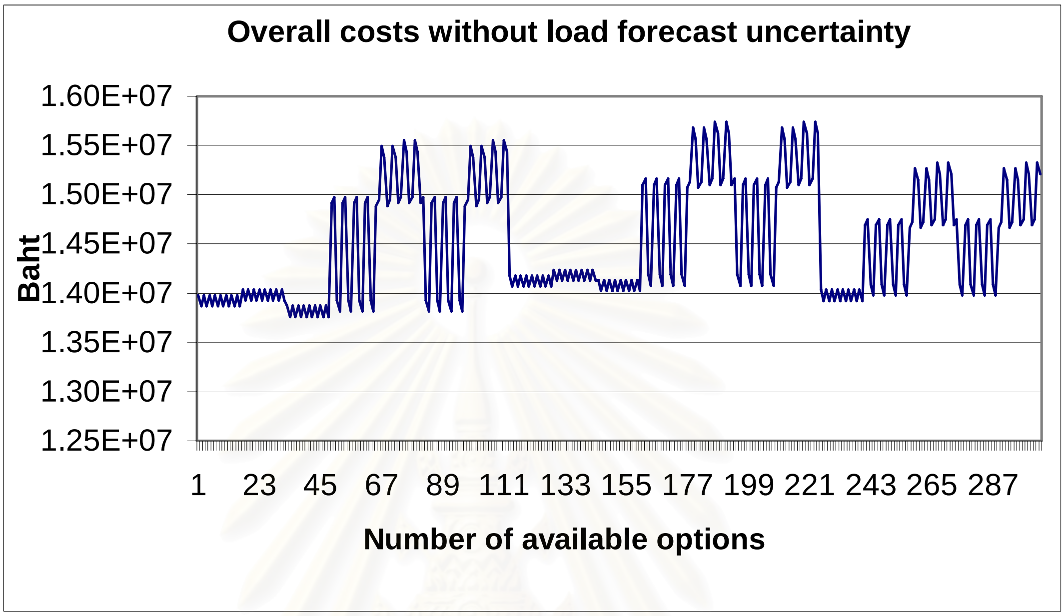


Figure 4-20 Overall costs without load forecast uncertainty at stage 2

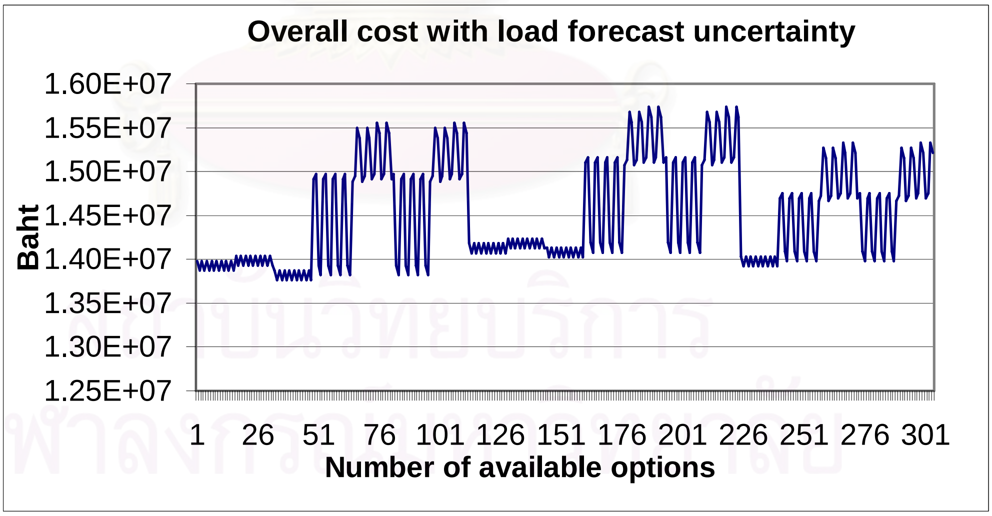


Figure 4-21 Overall costs with load forecast uncertainty at stage 2

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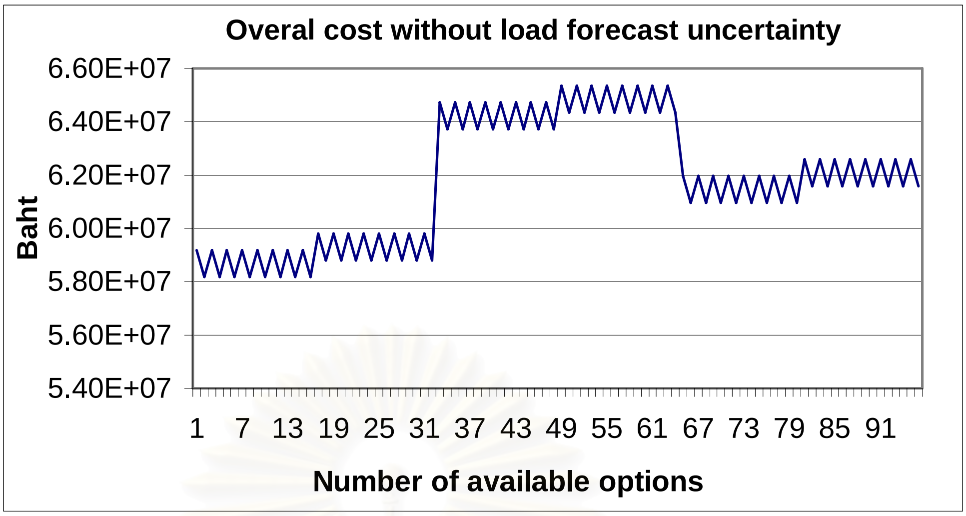

Figure 4-22 Overall costs without load forecast uncertainty at stage 3

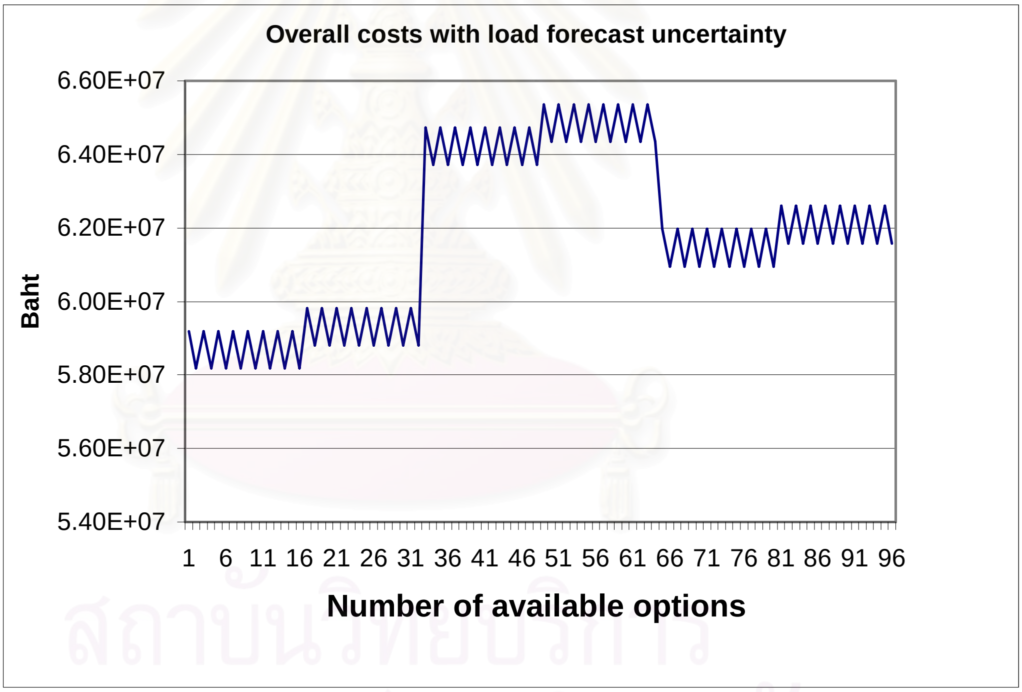

Figure 4-23 Overall costs with load forecast uncertainty at stage 3

4.5. Summary

The impacts of total cost of network are considered. Firstly, the total cost obtained by minimizing investment cost is taken into account. Second, loss cost which is added to the objective function is assumed. Then, we consider reliability cost which is added in the objective function without uncertainty consideration. Lastly, overall costs with uncertainty consideration namely investment, loss, reliability costs, are calculated

In test case 1, costs of the best option with loss and reliability consideration are no different, but they are higher with only investment consideration. Moreover, the total cost, at stages 2 and 3, are the same when we consider load forecast uncertainty. Because load uncertainty impact does not occurs on the best solution. In this test case, demand uncertainty does not occurred at stage 2. But at stage 3, the demand uncertainty occurs in the first four cases. It is clear that the overall costs, with uncertainty consideration, are greater than those, without uncertainty consideration, if load forecast uncertainty occurs.

In test case 2, the load forecast uncertainty does not occur in the best decision. Therefore, the results of expansion solutions without load forecast uncertainty are the same as those at stages 2 and 3 when load forecast uncertainty is considered. The best configuration of DSP is the same as that shown in table 4-16.

In the expansion configuration system case, it is clear that the total cost of DSP will increase in urban distribution with five times expansion of the length of cables. Therefore, the budget requirement has to be reconsidered in planning. In addition, forecast peak loads are also considered. But the results do not changed because the demand uncertainty costs are zero.

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CHAPTER V

CONCLUSIONS

This thesis proposes an algorithm to solve a distribution expansion problem. The main interest is to minimize an objective function or to select the best available option to obtain the most suitable distribution system expansion plan.

However, there are some limitations of the proposed algorithm. Firstly, the two test cases represent practical systems. The numbers of the nodes is proposed only to demonstrate the developed algorithm. Secondly, some components of the radial system which may influence the distribution system planning are neglected, e.g. switches, relay etc. Thirdly, practical information, e.g. line impedance and its fixed cost etc., are also one of the limitations in this thesis. Finally, computer time is also another limitation of this thesis since the other methods, e.g. nonlinear program, linear program etc., which may be more efficient, are not taken into account.

The algorithm has been developed to select appropriate feeder path, conductor sizes and types so that the best expected cost is obtained. It not only considers investment and loss costs but also includes reliability worth comprising expected unserved energy and demand uncertainty costs. Therefore, the objective function of the problem is composed of investment, loss, expected unserved energy and demand uncertainty costs. A power flow based on Newton’s method is employed to verify system constraints, and used as a tool in the algorithm to find optimum conductor size of feeders and optimum feeder path.

In addition, it can be seen from the test results that significant impact of uncertainties on distribution system planning is modeled and addressed in term of reliability costs, i.e. the expected unserved energy and the demand uncertainty costs. The expected unserved energy cost is used to represent the cost occurring to customers if the supply is not reliable. The impact of load forecast uncertainty is also important when the forecasted value is assumed close to the limit of the component.

Possible future work to improve the proposed algorithm is to include multiyear expansion planning, taking into account actual location based on available Geographical Information System (GIS), which enables the visualization of the model demonstrated with a wide range of options.

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APPENDICES

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APPENDIX A

Aluminium conductor and XLPE insulated power Cables information

Table A-1 Aluminium cable 24KV-OC

No. of core	Nominal Cross Sectional Area (mm^2)	Number Of Stranded	Diameter Of Conductor Approx. (mm)	Insulation Thickness (mm)	Overall Diameter Approx. (mm)	Maximum Conductor Resistance (Ω/km)	Minimum Insulation resistance (MΩ-km)	Maximum Continuous Current Rating In free air (A.)	Breaking strength (kg/km)	Cable Weight Approx. (kg/km)	Standard Length* (m)	Power (MVA)	Price** (Baht/km)
1	35	7	7.1	1.8	12.0	0.868	900	145	5,720	170	1,000/D	6.02736	83859.9
	50	7	8.5	2.2	14.5	0.641	880	175	7,890	240	1,000/D	7.2744	118390.4
	70	7	9.9	2.1	15.5	0.443	800	220	10,530	300	1,000/D	9.14496	147988.1
	95	7	11.6	2.5	18.0	0.320	750	275	14,380	410	1,000/D	11.4312	202250.3
	120	19	13.1	2.6	19.5	0.253	700	320	19,110	500	1,000/D	13.30176	246646.8
	150	19	14.4	2.6	21	0.206	650	365	22,560	600	1,000/D	15.17232	295976.1
	185	34	16.1	2.55	23	0.164	600	420	29,600	700	1,000/D	17.45856	345305.5

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* Packing D: Drum

** Estimated based on cable weight.

Table A-2 Aluminium cable 33KV– OC

No. of core	Nominal Cross Sectional Area	Number Of Stranded	Diameter Of Conductor Approx.	Insulation Thickness	Overall Diameter Approx.	Maximum Conductor Resistance	Minimum Insulation resistance	Maximum Continuous Current Rating In free air	Breaking strength	Cable Weight Approx.	Standard Length*	Power	Price**
	(mm^2)		(mm)	(mm)	(mm)	(Ω/km)	(MΩ-km)	(A.)	(kg/km)	(kg/km)	(m)	(MVA)	(Baht/km)
1	35	7	7.1	3.0	14.5	0.868	1,350	150	5,720	220	1,000/D	8.5734	115920.3
	50	7	8.5	3.2	16.5	0.641	1,300	180	7,890	280	1,000/D	10.28808	147534.9
	70	7	9.9	3.2	18.0	0.443	1,200	225	10,530	350	1,000/D	12.8601	184418.6
	95	7	11.6	3.5	20	0.320	1,100	280	14,380	460	1,000/D	16.00368	242378.7
	120	19	13.1	3.6	22	0.253	1,000	325	19,110	550	1,000/D	18.5757	289800.7
	150	19	14.4	3.6	23	0.206	950	365	22,560	650	1,000/D	20.86194	342491.7
	185	34	16.1	3.9	26	0.164	900	425	29,600	800	1,000/D	24.2913	421528.2

* Packing D: Drum

** Estimated based on cable weight.

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Table A-3 All Aluminium Spaced Aerial Cable (SAC) 25kV – CC

No. of core	Nominal Cross Sectional Area (mm^2)	Number of Stranded	Diameter of Conductor Approx. (mm)	Insulation Thickness (mm)	Sheath thickness (mm)	Overall Diameter Approx. (mm)	Max Conductor Resistance (Ω/km)	Min Insulation resistance (MΩ-km)	Max Continuous Current Rating In free air (A.)	Breaking strength (kg/km)	Cable Weight Approx. (kg/km)	Standard Length* (m)	Power (MVA)	Price** (Baht/km)
1	35	7	7.1	3.175	3.175	22	0.868	2,500	155	5,720	400	500/D	6.7115	280038.8
	50	7	8.5	3. 175	3.175	23	0.641	2,250	185	7,890	470	500/D	8.0105	329045.5
	70	7	9.9	3. 175	3.175	25	0.443	2,050	230	10,530	550	500/D	9.959	385053.3
	95	7	11.6	3. 175	3.175	26	0.320	1,850	280	14,380	650	500/D	12.124	455063
	120	19	13.1	3. 175	3.175	28	0.253	1,700	325	19,110	750	500/D	14.0725	525072.7
	150	19	14.4	3. 175	3.175	29	0.206	1,600	370	22,560	850	500/D	16.021	595082.4
	185	34	16.1	3. 175	3.175	31	0.164	1,450	425	29,600	1,000	500/D	18.4025	700096.9
	240	34	18.6	3. 175	3.175	33	0.125	1,300	505	38,220	1,200	500/D	21.8665	840116.3

* Packing D: Drum

** Estimated based on cable weight.

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Table A-4 All Aluminium Spaced Aerial Cable (SAC) 35 KV–CC

Number of core	Nominal Cross Sectional Area (mm^2)	Number Of Stranded	Diameter Of Conductor Approx. (mm)	Insulation Thickness (mm)	Sheath thickness (mm)	Overall Diameter Approx. (mm)	Maximum Conductor Resistance (Ω/km)	Minimum Insulation resistance (MΩ-km)	Maximum Continuous Current Rating In free air (A.)	Breaking strength (kg/km)	Cable Weight Approx. (kg/km)	Standard Length* (m)	Power (MVA)	Price** (Baht/km)
1	50	7	8.5	4.445	3.175	26	0.641	2,550	185	7,890	550	500/D	11.2147	421852.1
	70	7	9.9	4.445	3.175	27	0.443	2,300	230	10,530	650	500/D	13.9426	498552.5
	95	7	11.6	4.445	3.175	29	0.320	2,100	280	14,380	750	500/D	16.9736	575252.9
	120	19	13.1	4.445	3.175	31	0.253	1,950	325	19,110	900	500/D	19.7015	690303.4
	150	19	14.4	4.445	3.175	32	0.206	1,800	370	22,560	1,000	500/D	22.4294	767003.8
	185	34	16.1	4.445	3.175	34	0.164	1,690	425	29,600	1,100	500/D	25.7635	843704.2
	240	34	18.6	4.445	3.175	36	0.125	1,500	505	38,220	1,400	500/D	30.6131	1073805

* Packing   D: Drum

** Estimated based on cable weight.

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BIOGRAPHY

Mr. Le Viet Tien was born in Thanhhoa City, Vietnam, in 1980. He graduated from Hanoi University of Technology (HUT), Vietnam with a Bachelor of Electrical Engineering in 2003. In October 2003, he was rewarded AUN/SEED-Net scholarships for the Master's Degree Program to study at Chulalongkorn University. His research interests include distribution system planning and reliability evaluation on distribution system.

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List of Publications

Distribution System Planning Using Nonlinear Optimization Programming. The 28th Electrical Engineering Conference (EECON-28) 20-21 Oct 2005, Phuket, Thailand.

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