MAINTENACE OPTIMIZATION FOR HIGH VOLTAGE SUBSTATION USING RELIABILITY-CENTER BASED MAINTENACE TECHNIQUE

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การเพิ่มประสิทธิภาพการจัดการงานบำรุงรักษาสถานีไฟฟ้าแรงสูงโดยใช้เทคนิคการบำรุงรักษาบนพื้นฐานความน่าเชื่อถือ

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต

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วิทยานิพนธ์ฉบับนี้นำเสนอการประยุกต์ใช้การบำรุงรักษาบนพื้นฐานความน่าเชื่อถือด้วยการหาค่าเวลาการบำรุงรักษาของการบำรุงรักษาเชิงป้องกัน ซึ่งใช้ระบบความน่าเชื่อถือ (Reliability system) เป็นฟังก์ชันวัตถุประสงค์จะสัมพันธ์กับอัตราการเสื่อมสภาพ (Failure rate) โดยพิจารณาสถานีไฟฟ้าแรงสูงซึ่งประกอบด้วยบริภัณฑ์ทางไฟฟ้าหลัก คือ สวิตช์ตัดตอน เซอร์กิตเบรกเกอร์ บัสบาร์และหม้อแปลงกำลัง กำหนดระยะเวลาในการบำรุงรักษาเชิงป้องกันทุก ๆ 1 ปี 2 ปี 3 ปี 5 ปี และ 10 ปี เป็นต้น การจำลองโดยใช้โปรแกรม Matlab หาเวลาที่เหมาะสำหรับการดำเนินการบำรุงรักษาเชิงป้องกันซึ่งจะสัมพันธ์กับความน่าเชื่อถือที่มีค่าสูงสุดและในทางตรงข้ามอัตราความล้มเหลวต่ำสุด รวมถึงต้นทุนในการบำรุงรักษาในงบประมาณที่จำกัด ซึ่งกำหนดขอบเขตเพื่อเพิ่มประสิทธิภาพของระบบงานบำรุงรักษา ระบบทดสอบในงานนี้มีสถานีไฟฟ้าพื้นฐาน เช่น single bus-single breaker และ double bus-double breaker ซึ่งเป็นระบบพื้นฐาน รวมทั้งใช้สถานีไฟฟ้าย่อยหนองกี่ที่ระดับแรงดัน 115/22 kV ที่มีการจัดเรียงตำแหน่งบัสแบบ main and transfer bus system ผลการทดสอบพบว่าอัตราความล้มเหลวของระบบต่ำสุดสามารถหาได้โดยการบำรุงรักษาเชิงป้องกันในระยะเวลาที่สั้นที่สุด (กล่าวคือบำรุงรักษาทุก ๆ 1 ปี) อย่างไรก็ตามยังมีความน่าเชื่อถือสูงสุดในช่วงเวลาที่ทำบ่อยครั้งในการบำรุงรักษาเชิงป้องกัน ดังนั้นจึงเห็นได้ว่าอัตราการเกิดความล้มเหลวต่ำสุดและความน่าเชื่อถือสูงสุดของระบบจะเห็นได้ในระยะเวลาที่สั้นกว่าในการบำรุงรักษาเชิงป้องกัน มีค่าฟังก์ชันความน่าเชื่อถือเพิ่มขึ้นมากกว่าร้อย 95 ในทุกกรณีศึกษา นอกจากนี้การศึกษาต้นทุนที่เหมาะสมสำหรับการดำเนินการบำรุงรักษาเชิงป้องกันยังแสดงให้เห็นถึงการเพิ่มประสิทธิภาพในการบำรุงรักษาอย่างมีประสิทธิภาพเพื่อควบคุมค่าใช้จ่ายในการบำรุงรักษาอย่างมีประสิทธิภาพ

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่อนักศึกษา ____________

ปีการศึกษา 2560 ลายมือชื่ออาจารย์ที่ปรึกษา ____________

PHEERAPHONG THONGCHAI : MAINTENACE OPTIMIZATION FOR HIGH VOLTAGE SUBSTATION USING RELIABILITY-CENTER BASED MAINTENACE TECHNIQUE. THESIS ADVISOR : ASSOC. PROF. THANATCHAI KULWORAWANICHPONG, Ph.D., 141 PP.

PREVENTIVE MAINTENENCE/ RELIABILITY/FAILURE RATE/RELIBILITY-CENTERED MAINTENANCE/SUBSTATION ALIGNMENT

This thesis presents the application of reliability centered maintenance to optimize preventive maintenance period of an electric power substation in which the periods in total failure rate and system reliability were used as the problem objectives. In this work, high voltage substation integrating disconnecting switch, circuit breaker, mains bus bars, transformer was studied for the preventive maintenance of every 1, 2, 3, 5, and 10 years. Other conditions such as substation sensors, grounding, etc. were not considered in the study. The objective functions in the HV substation were simulated through MATLAB software package. An optimal period for performing the preventive maintenance which corresponds to the highest reliability, lowest failure rate and minimum cost was aimed after optimization. In this thesis considers the failure rate and reliability of the simplified arrangement of the HV substation system (single bus-single breaker one bay and double bus-double breaker one bay) and apply to the 115/22 kV Nongki substation located 80 km from Nakhon Ratchasima Province which is controlled and monitored by Dispatching Center (North-East) Nakhon

Ratchasima area 3 was used as a case study. It steps down voltage from 115 kV to 22 kV and has bus alignment "main and transfer bus system". Moreover, it has two 115 kV incomings, two power transformer, two medium voltage bus bars (22 kV) each bus bar have seven feeder lines to distribution load. Results showed that lowest system failure rate can easily obtained by performing preventive maintenance in the shortest period (say 1 year for this case). However, the highest reliability was also obtained in the shortest period of preventive maintenance. Therefore, lowest failure rate and the highest reliability of the system were both seen to be obtained in the shorter period of preventive maintenance. Furthermore, the study of optimal cost for performing preventive maintenance showed the successful optimization of the maintenance period. The percentage of increment reliability more than 95% of all case study for one year of PM, and more than 50% for five years of PM. Similarly, improved reliability was also obtained in a shorter preventive maintenance. It was concluded that, performing preventive maintenance especially in a shorter period may improve both reliability as well as failure rate of the substation.

School of Electrical Engineering Student's Signature____________

Academic Year 2017 Advisor's Signature____________

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CHAPTER I

INTRODUCTION

1.1 Background

Maintenance has been an increasing need to power system engineers for the effective operation of the networks. It is being developed as one of the most important industry activities both in developed and developing countries due to that maintenance problems are complicated, time-consuming as well as budget, tools and more manpower are required. This consumes higher investment if maintenance is overlooked, the machine and equipment can be damaged more quickly than the manufacturer's specified lifetime. It is therefore necessary to make the machines and related equipment work as close as possible or as accurately as they are designed. To avoid stopping for a long time, asset management is one of the most important goals of power distribution systems by focusing on saving budget to maintain the standard to suit the application. The power station is a part of the power generation and distribution system for the public and private sectors. The cost of components of the overall system are high. Therefore, effective and efficient management is great need. Due to the management of the relevant equipment in the appropriate system, it can reduce the cost of purchasing new equipment, operational and maintenance costs. Typically, the maintenance approach must consider both preventive maintenance and corrective maintenance, as appropriate, the type and function of the electrical equipment for maximum efficiency (Bi et al., 2005) and in line with corporate culture. Maintenance is stated to be as a set of activities undertaken to fix, restore, replace, rebuild or maintain the system for it to perform its designated functions (Smith and Hinchcliffe, 2004; Smithy and Mobley, 2012; Carneiro, 2013; Carneiro, Jardini and Brittes, 2012). Smith and Mobley detailed it as a state of maintaining whereby the basics of preserving and protecting are kept. That means, the system or an equipment should be kept in its existing state or preserved from the temporary failure or decline. Maintenance is mainly grouped into two groups such as (i) Corrective maintenance and (ii) Preventive maintenance. Corrective maintenance retains the system into its designated functions after failure. Preventive maintenance maintains the system functionality aiming into reducing the system degradation. IEEE Std. 493, 1998 defined an electrical preventive maintenance as the "system with the planned inspection, testing, cleaning, drying, monitoring, adjusting, corrective modification and minor repair of electrical equipment to minimize or forestall future equipment operating problems or failures which, depend upon the equipment type, may require equipment proof or testing". When it is well performed, maintenance can help to reduce maintenance costs, operating as well as unit cost. Furthermore, a well performed maintenance can minimize the total cost of ownership by prolongation of equipment life at reduced operating costs. A well maintained equipment or system may experience a low level of failure rate which indicates the high reliability. Gill, (2009) stated the importance of a well maintenance that as it can reduce dangers, minimize unnecessary outages, and extends the mean time before failure of the system or an equipment. Moreover, the direct advantages were defined to be minimal repair costs, minimum downtimes of equipment, and increased safety and comfort to personnel and equipment; while indirect advantages are increased morale of workers, better workmanship, improved productivity, and easy discovery of system deficiencies. Since the useful life of an equipment or system in the practical world is normally finite, but for degradable and repairable one the deterioration rate and hence failure rate can be minimize and then restored into the younger one by the preventive maintenance (Cheng, Zhao, Chen and Sun, 2014; Cheng, Chen, Sun and Liu, 2015; Chang and Yang, 2007).

Balzer, (2005); Balzer and Schorn (2015); Gill, (2009); Carneiro, (2013) have described several means to which maintenance activities could be undertaken. These means have been useful in previous and seemed to be useful also in future plans. These activities are*: Run-To-Failure* (*RTF*) – in this approach maintenance is not done at all. The equipment is replaced after the total degradation has occurred such that the equipment cannot work anymore or becomes unacceptable (Gill, 2009). In this technique, no maintenance activities are undertaken and risks associated with the ultimate failure are accepted. In addition, this can deliver satisfactory reliability and availability especially to non-critical uses/application, small organization with limited technical staffs. Balzer, (2005) termed it as a *Corrective Maintenance* (*CM*) which meant a replacement or repair is performed when the fault is exhibited. Moreover, the approach was dedicated to the equipment with low investment cost, minor fault effects, and where the overall cost is low. The important application of this technique is lower voltage systems, where spare parts are available in short period. *Inspect and Service as Necessary* – this technique employs more or less inspection of the system by technical personnel. The fault can be easily detected and corrected in its early stage before dangers occur (Gill, 2009). *Time Based Maintenance* (*TBM*) – it is also known as scheduled maintenance whereby the maintenance is performed at fixed intervals of calendar, operating hours or operating cycles (Hinow and Mevissen, 2011). In this approach, system components are replaced or maintained after a specified period of use. Satisfactory results can be obtained in this technique, however, it does not provide the most cost-effective option in all cases since the equipment will not stay in operation till the end-of-life (Balzer, 2005). *Condition based Maintenance* (*CBM*) – sometimes called predictive maintenance. This approach involves non-intrusive testing methods to testify the condition of equipment. Carneiro, (2013) defined it as a periodic equipment follow up based on the evaluation of accumulated field data such as visual inspection, main operational data reading, thermal inspection, partial discharges, analyses: chromatography physical-chemical, furfural, particles and solid insulation. It's an approach driven by technical condition of the equipment whereby all main technical parameters are determinant of the equipment condition. Therefore, important parameters are required to assess the condition of the equipment. *Reliability Centered Maintenance* (*RCM*) – in Gill, (2009) it was explained as a maintenance approach on which equipment condition, criticality, failure, history and life cycle cost are combined together purposely to generate logically the most effective maintenance method for each component such as system, subsystem or particular component. On the other way, it can be said that *RCM* considers the importance of the equipment to the grid. If the importance and the condition of equipment are not available *CBM* can be the next choice. According to Balzer, (2005) *RCM* can be performed into two approaches: First, *substation/equipment approach* - in this category the important question to be answered is that which equipment in the substation has the greatest impact in the operation of the substation. The solution in this approach can be easily obtained by using Failure Mode Effect Analysis (*FMEA*) on which the answer of which equipment has to be maintained is given based on the reliability of each component. Second, *system approach* – in this category, the main question to be answered is that which substations have influence on the availability and performance of the system. The solution of this approach can be obtained by using reliability calculations and assessment of the supplied clients (risk management). From this approach, the answer gives which substation in the network has to be maintained. Therefore, in *RCM* the importance and condition of a piece of equipment are properly combined together to give the result of which component should be first, second, third, fourth and so on to be considered for the maintenance based on the financial constraints of the utility. If the financial matter is of the first consideration, *RCM*, *CBM*, *CM* should be prioritized, otherwise, *TBM* with short intervals and replacement time lower than end-of-life can be opted. Smith and Hinchcliffe, (2004); Pourahmandi, Fotuhi-Firuzabad, and Dehghanian, (2017); Brown, (2004) explained *RCM* as a cost-effective technique on which the cost and reliability are integrated techno-economically.

Optimization is one of technique used to solve the system equation by minimizing or maximizing it within the required conditions. In Brown, (2009) the objective of system optimization has been stated to as to minimize the objective function without violating the constraints. The process of optimization involves defining the objective function and its constraints. For the successful optimization, the objective function should be calculable and the set of all constraints should be testable for all expected answers. Constraints may be linear/equality or nonlinear/inequality constraints or combination. When applied to the distribution system reliability, optimization may have the following goals: first is to minimize the cost without violating reliability constraint, and second is to reduce customer interruptions subject to cost constraints.

Recently, researchers have been interested in performing *RCM* based maintenance throughout the power system. However, electrical distribution systems have been the most interested point. Since electric distribution networks contain a variety number of components, reliability of the network is the reliability of its components.

1.2 Statement of the Problem

Maintenance optimization strategy is the strongest strategy that can lead to cost saving in the electric power network. Moreover, the maintenance cost can be minimized at the same time keeping the power quality in the required levels (Buhler and Balzer, 2011). Utilities are currently dedicating distribution networks into the maintenance optimization due to the cost of outages and system unavailability.

In the main power station, the major valued and important equipment are: power transformer and circuit breaker since they are technically sophisticated and have high maintenance costs. For the case of their malfunction in the operation, they affect the reliability in the electrical system. This research will utilize reliability center based maintenance management techniques to support decision-making in maintenance of station equipment. Engineers and technicians are involved to reduce maintenance costs and time. This will help to know the situation of the problem in the system, fix the system to get back to normal operation quickly and it also increases the potential for continuous power supply. The great challenge for maintenance is the large number of installed components in the system (Buhler and Balzer, 2011). The tackle this problem, maintenance optimization for an entire substation is proposed aimed in obtaining the optimal maintenance period with minimum maintenance cost.

1.3 Objective of the Study

The main objective of this research is to optimize the preventive maintenance period of the electric power substation that leads to the minimum maintenance cost of the respective electric power substation. The optimized preventive maintenance cost can have impacts in the operational as well as unit costs. For reaching the main objective, this research is composed of following sub-objective:

1.3.1 To study the design and configuration of the electric power substation based on the theories of substation engineering as well as maintenance while taking the reference to the configuration of the existing substation (applying a case study of Nongki substationa and simplified single and double breaker substation test system).

1.3.2 To perform the substation reliability integrating incomings, disconnectors, circuit breakers, mains bus bars and power transformer for every maintenance period of 1, 2, 3, 5, and 10 years; and obtain the preventive maintenance periods which results to the highest reliability and control cost of preventive maintenance.

1.3.3 To perform the substation failure rate integrating incomings, disconnectors, circuit breakers, mains bus bars and power transformer for every maintenance period of 1, 2, 3, 5, and 10 years; and obtain the preventive maintenance periods which results to the lowest failure rate and obtain the minimum cost for performing preventive maintenance periods.

1.4 Aim of Research and Limitation of Study

The aim of this thesis is to optimize the period for performing the preventive maintenance in an electric power substation. This optimal period for performing preventive maintenance is the one that reflect minimum maintenance cost of the electric power substation. The period is between 1 to 10 years for search optimal year and the cost of maintenance can control in limitation also. The study involves the analysis of an existing electric power substation called Nongki substation located 80 km from Nakhon Ratchasima Province; and is controlled and monitored by Dispatching Center (North-East) Nakhon Ratchasima area 3. It steps down voltage from 115 kV to 22 kV and has bus alignment “main and transfer bus system”. Additionally, has two incoming, two power transformer, two medium voltage bus bars each bus bar have seven feeder lines to distribution loads. The simplified arrangement of the HV substation system (single bus-single breaker one bay and double bus-double breaker one bay) were applied for case study. The problem objective of this study is to find the minimum period for performing preventive maintenance in an electric power substation. The computation was performed by using MATLAB software program. To perform the study, maintenance period of every 1, 2, 3, 5, and 10 years (period between 1 to 10 years) were used. For the above maintenance periods, total system reliability and failure rate were computed by considering the design and configuration of Nongki substation and simplified arrangement of the HV substation system. The evaluation of the cost related to the preventive maintenance was performed based on the results of the reliability as well as failure rate obtained in the maintenance periods.

1.5 Expected Benefits

1.5.1 This work is expected to be useful in providing a guidance in describing the design features of the substation, configuration and arrangement of the substation components prior for preventive maintenance.

1.5.2 Transferring the theoretical knowledge of system reliability and failure rate into the practical implementation of preventive maintenance.

1.5.3 Identifying the optimal period as well as the cost of performing preventive maintenance and its impacts into the operational and unit costs.

1.5.4 The obtained results can open the way towards studying the new substation configurations which can result into the highest reliability, lowest failure rate and minimum maintenance cost.

1.6 Organization of the Thesis

This thesis presents the maintenance optimization for high voltage substation using reliability-center based maintenance technique. It contains five chapters described as follow:

Chapter I provides a brief introduction of the study including backgrounds, statement of the problem, objectives of the study, aim of the research, limitation of the research, expected benefits and the thesis organization.

Chapter II explains the general concept of preventive maintenance, reliability centered maintenance, maintenance optimization, related and summarizes previous related works as well as optimization techniques.

Chapter III details the general idea of electric power substation, components and their configurations. It further explains the application of reliability and failure rate in the configurations of electric power substation. The formulation of objective problems with corresponding mathematical expressions of its objective and various practical constraints are also defined. Formulation involving the objective functions relating to the cost function with reliability as well cost function with preventive maintenance are given. Constraints for performing the maintenance optimization are shown in this chapter. In addition, the application of MATLAB software utilized in solving the maintenance optimization is explained. Moreover, this chapter illustrates the case study of Nongki substation, formulation of its objective problems, application of optimization techniques, and its related cost functions are given.

Chapter IV discusses the result and discussion of reliability centered maintenance for electric distribution substation. In addition, results based on the case study of Nongki substation are explained.

Finally, **chapter V** summarizes the conclusions and suggestions for the future work.

1.7 Chapter summary

This chapter has presented background of maintenance strategies performed in the power system operation and the requirements for the cost reduction in the distribution networks. Various maintenance strategies have been detailed, their importances, effects and their applicability have also be given. The importance of RCM as the current cost-effective maintenance strategy have been described. Maintenance strategies and their drawbacks have been discussed and introduction to the proposed scheme are given. Finally, the objectives, aim and limitations, expected benefits and organization of the thesis are mentioned.

CHAPTER II

LITERATURE SURVEY AND GENERAL REVIEW

2.1 Introduction

This chapter provides the general of maintenance strategies in electric power systems and their useful utilizations for minimizing maintenance cost, downtime and improving power quality. Moreover, it gives surveys on research literatures based on power system maintenance.

2.2 Literature Survey of Maintenance Strategies

This section reviews various maintenance strategies that have been used for many years in the utility industry and their impacts in the operation of power systems.

2.2.1 Run-To-Failure (RTF)

This strategy is sometimes termed as a *Corrective Maintenance* (*CM*) which meant a replacement or repair is performed when the fault is exhibited. In this approach maintenance is not done at all (Balzer, 2005; Balzer et al. 2004). Equipment is replaced after the total degradation has occurred such that the equipment cannot work anymore or becomes unacceptable (Gill, 2009; Ledezma et al. 2010). In this technique, no maintenance activities are undertaken and risks associated with the ultimate failure are accepted. In addition, this can deliver satisfactory reliability and availability especially to non-critical uses/application, small organization with limited technical staffs. Moreover, the approach was dedicated to the equipment with low investment cost, minor fault effects, and where the overall cost is low. The important application of this technique is lower voltage systems, where spare parts are available in short period. Furthermore, the cost of ownership is reduced due to the reduced scheduled maintenance but it can results to higher failure rates.

2.2.2 Inspect and Service as Necessary

This technique employs more or less inspection of the system by technical personnel. The fault can be easily detected and corrected in its early stage before dangers occur (Gill, 2009).

2.2.3 Time Based Maintenance (TBM)

It is also known as scheduled maintenance whereby the maintenance is performed at fixed intervals of calendar, operating hours or operating cycles (Gill, 2009; Hinow and Mevissen, 2011) of usage (Balzer et al., 2004). In this approach, system components are replaced or maintained after a specified period of use. Satisfactory results can be obtained in this technique, however, it does not provide the most cost-effective option in all cases since the equipment will not stay in operation till the end-of-life. This technique is adequate for intermediate risk components (Ledezma et al., 2010).

2.2.4 Extended Time Based Maintenance (ETBM)

It is typically a *TBM* maintenance strategy but the difference is only time. In this maintenance strategy, activities can be delayed or postponed but within a reasonable and accepted time. This technique is suitable and can be practiced for low risk components (Ledezma et al., 2010).

2.2.5 Condition based Maintenance (CBM)

This is sometimes called predictive maintenance. This approach involves non-intrusive testing methods to testify the condition of equipment. Carneiro (2013) defined it as a periodic equipment follow up based on the evaluation of accumulated field data such as visual inspection, main operational data reading, thermal inspection, partial discharges, analyses: chromatography physical-chemical, furfural, particles and solid insulation. It’s an approach driven by technical condition of the equipment whereby all main technical parameters are determinant of the equipment condition. Therefore, important parameters are required to assess the condition of the equipment (Balzer, 2005). As the maintenance rely on the technical condition of the equipment, the investment in extra monitoring devices is required to minimize the failure rate and maintenance activities (Balzer et al., 2004).

2.2.6 Refurbishment Maintenance (RM)

This maintenance strategy requires time-to-time or continuous condition monitoring of system component. It is applicable for high risk components. It concerns with the capital expenditures. (Ledezma et al., 2010).

2.2.7 Asset Replacement Maintenance (ARM)

This maintenance strategy is recommended for very high risk components due to its relation with the capital expenditures. (Ledezma et al., 2010).

2.2.8 Reliability Centered Maintenance (RCM)

It is a strategy that matches the preventive maintenance and restoration tasks on the component (Sabouhi et al., 2016). Gill (2009) explained it as a maintenance approach on which equipment condition, criticality, failure, history and life cycle cost are combined together purposely to generate logically the most effective maintenance method for each component such as system, subsystem or particular component. On the other way, it can be said that *RCM* considers the importance of the equipment to the grid (Balzer, 2005; Balzer et al., 2004). If the importance and the condition of equipment are not available *CBM* can be the next choice. According to Balzer (2005) *RCM* can be performed into two approaches: First, *substation/equipment approach* - in this category the important question to be answered is that which equipment in the substation has the greatest impact in the operation of the substation. The solution in this approach can be easily obtained by using Failure Mode Effect Analysis (*FMEA*) on which the answer of which equipment has to be maintained is given based on the reliability of each component. Second, *system approach* – in this category, the main question to be answered is that which substations have influence on the availability and performance of the system. The solution of this approach can be obtained by using reliability calculations and assessment of the supplied clients (risk management). From this approach, the answer gives which substation in the network has to be maintained. Therefore, in *RCM* the importance and condition of a piece of equipment are properly combined together to give the result of which component should be first, second, third, fourth and so on to be considered for the maintenance based on the financial constraints of the utility. If the financial matter is of the first consideration, *RCM*, *CBM*, *CM* should be prioritized, otherwise, *TBM* with short intervals and replacement time lower than end-of-life can be opted. Brown (2004), Balzer (2005), Sabouhi et al., (2016) and Pourahmandi et al., (2017) explained *RCM* as a cost-effective technique on which the cost and reliability are integrated techno-economically.

2.3 Reliability, Failure Rate, Configuration and PM Model

This section reviews modeling of reliability, failure rate and also describes the design of various system configurations used in electric power distribution systems. In addition, a preventive maintenance model is explained.

2.3.1 Series Reliability

System components are said to have series reliability if the failure of one or more than one component before the intended mission is reached can result to the failure of the whole system (Brown, 2002; Romeu, 2004). Therefore, the reliability of the entire system takes into an account that the reliability of individual component succeed the mission. Figure 2.1 shows the concept of reliability based on the series "*n*" identical and independent substation components.

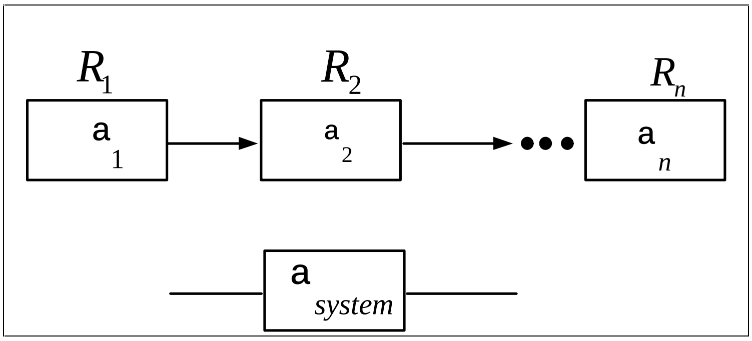


Figure 2.1 Reliability of the series system

Mathematical expression of the series reliability of "*n*" identical and independent components is shown in (2.1) whereby R_i or R_1 is the reliability of the system component and R_{system} is the total system reliability.

$$R_{system} = R_1 \cdot R_2 \cdot R_3 \cdots R_n = \left[R_i\right]^n \tag{2.1}$$

On the other way (2.1) can be expressed as shown in (Romeu, 2004). It should be noted that, the R_{system} from (2.1) assumes that the components are identical and the reliability R_i does not depend from any component. The series of reliability component in multiply term can be summarized by $R_{system} = \prod_{i=1}^{n} R_i$. By considering the distribution of time to failure of the component has the exponential function, then the reliability R_i of each component can be the same and expressed as shown in (2.2).

$$R_i(t) = e^{-\int_0^t \lambda_i(t)dt} = e^{-\lambda_i \int_0^t dt} = e^{-\lambda_i t} \tag{2.2}$$

Where: R_i is reliability of the system component

λ_i is failure rate of each component

t is mission survive time

Then, the total reliability of the system with series components can be expressed as given in (2.3).

$$R_{system}(t) = e^{-\lambda_1 t} \, e^{-\lambda_2 t} \cdots e^{-\lambda_n t} \tag{2.3}$$

In the Weibullian distribution, the reliability of the system with series components can be given as shown in (2.4).

$$R_{system}(T)=\prod_{i=1}^{n} e^{-\left(\frac{T-\gamma_i}{\eta_i}\right)^{\beta_i}} = e^{-\sum_{i=1}^{n}\left(\frac{T-\gamma_i}{\eta_i}\right)^{\beta_i}} \tag{2.4}$$

Then the failure rate of the system can be given by (2.5)

$$\lambda_{system}(T)=\sum_{i=1}^{n}\frac{\beta_i}{\eta_i}\left(\frac{T-\gamma_i}{\eta_i}\right)^{\beta_i-1} \tag{2.5}$$

And the mean time to failure rate can be given by (2.6)

$$MTTF_{system}(T)=\int_{\gamma}^{\infty} R_{system}(T)\,dt \tag{2.6}$$

Where: λ_{system} is total failure rate of the system

T is mission survive time

R_{system} is total reliability rate of the system

$MTTF_{system}$ is mean time to failure of the system

2.3.2 Parallel Reliability

If the failure of one component does not result into the system failure then the system is said to have parallel reliability. The parallel configuration has higher reliability than the reliability of any single system component. A graphical representation of parallel reliability for "*n*" identical and independent components is shown is Figure 2.2.

The probability of the system component i to n^{th} component to fail is given by Q_i for component i and lastly Q_n for component n**.** Brown (2002) can express the failure (unreliability) of all components as shown in **(**2.7**).** Reliability of the individual component can then be given as R_i = 1 **-** Q_i**.** If the unreliability of the system from **(**2.7**)** is Q_{system}, then the system reliability for the parallel components with similar individual reliability can be R_{system} = 1 **-** Q_{system} is shown in **(**2.8**)** to **(**2.10**).**

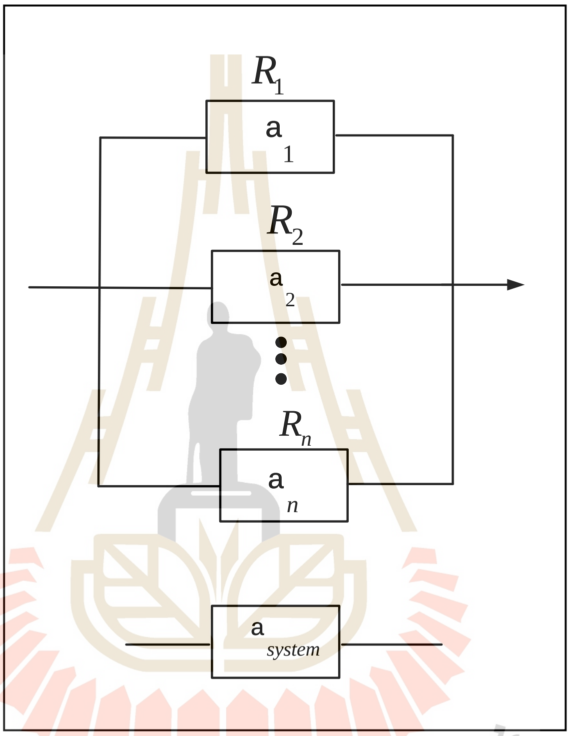


Figure 2.2 Reliability of the parallel system

$$Q_{system} = Q_1 \cdot Q_2 \cdot Q_3 \cdots Q_n \quad (2.7)$$

$$R_{system} = 1 - \prod_{i=1}^{n}(Q_i) = 1 - (Q_1) \times (Q_2) \times \cdots (Q_n) \quad (2.8)$$

$$R_{system} = 1 - \prod_{i=1}^{n}(1 - R_i) = 1 - (1 - R_1)(1 - R_2) \cdots (1 - R_n) \quad (2.9)$$

$$R_{System} = 1 - \prod_{i=1}^{n} (1 - R_i) = 1 - (1 - R_i)^n \quad \textbf{(2.10)}$$

In the Weibullian distribution, the reliability of the system with parallel components can be given as shown in (2.11).

$$R_{system}(T) = 1 - \prod_{i=1}^{n} (1 - e^{-\alpha_i T}) \quad (2.11)$$

To find the failure rate of the system with *n* components is very complicated. Therefore, assumption is made for two system components, i.e. *n*=2 and can be written as the shown in (2.12) to (2.14):

$$R_{system}(T) = 1 - \left(1 - e^{-\alpha_1 T}\right)\left(1 - e^{-\alpha_2 T}\right) \quad (2.12)$$

$$R_{system}(T) = e^{-\alpha_1 T} + e^{-\alpha_2 T} - e^{-(\alpha_1 + \alpha_2)T} \quad (2.13)$$

$$R_{system}(T) = R_1(T) + R_2(T) - R_1(T)R_2(T) \quad (2.14)$$

For equal components, (2.14) can be rewritten (2.15) to (2.16)

$$R_{system}(T) = R_1(T) + R_2(T) - R_1(T)R_2(T) \quad (2.15)$$

$$R_{system}(T,t) = \frac{e^{-\alpha_1 (T+t)} + e^{-\alpha_2 (T+t)} - e^{-(\alpha_1 + \alpha_2)(T+t)}}{e^{-\alpha_1 T} + e^{-\alpha_2 T} - e^{-(\alpha_1 + \alpha_2)T}} \quad (2.16)$$

From (2.16) it should be observed that reliability in parallel components is the function of age and mission time (Smithy and Mobley, 2012). And the mean time to failure rate can be expressed as shown in (2.17)

$$MTTF = \theta = \int_0^\infty R(T)dT = \int_0^\infty (e^{-\lambda_1 T} + e^{-\lambda_2 T} - e^{-(\lambda_1+\lambda_2)T})dT$$
$$= \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1 + \lambda_2} \quad (2.17)$$

The system failure rate (λ_S) can be found from the theoretical definition of failure rate (*FR*). Let consider *n*=2, therefore, the system failure rate is given as in (2.18) to (2.19).

$$FR = \lambda_s = \frac{Density\ Function}{Survival\ Function} = \frac{-\frac{d}{dt}R(T)}{R(T)} \quad (2.18)$$

$$FR = \lambda_S(T) = \frac{\lambda_1 e^{-\lambda_1 T} + \lambda_2 e^{-\lambda_2 T} - (\lambda_1 + \lambda_2)e^{-(\lambda_1+\lambda_2)T}}{e^{-\lambda_1 T} + e^{-\lambda_2 T} - e^{-(\lambda_1+\lambda_2)T}} \quad (2.19)$$

Where: λ_{system} is total failure rate of the system

T is mission survive time

$MTTF_{system}$ is mean time to failure of the system

2.3.3 Single bus, Single bay

This system uses a single bus-bar whereby all circuit circuits such as transmission line to power station or feeder line out of the power station. The type of configuration to have less reliability even with the presence of protection relay. Consider a single-circuit circuit diagram showing the bus configuration of the substation, as shown in the Figure 2.3, if the fault occurs at the bus bar the whole system faces outage

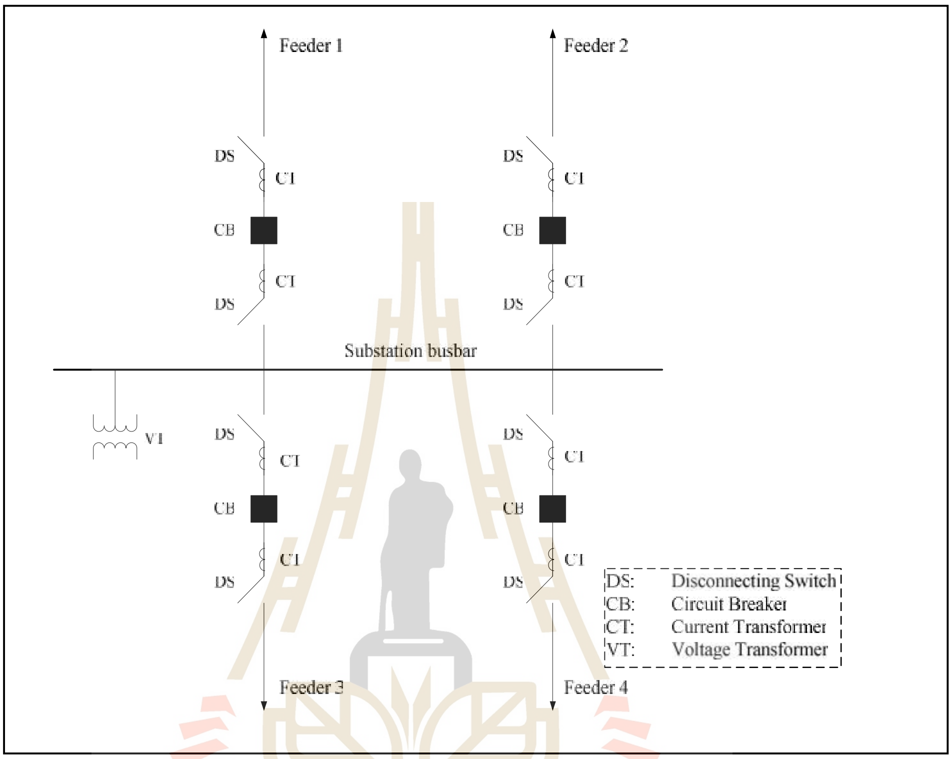


Figure 2.3 Single bus system (Chang and Yang, 2007)

The single line diagram of the single bus single bay for this thesis is given in Figure 2.4.

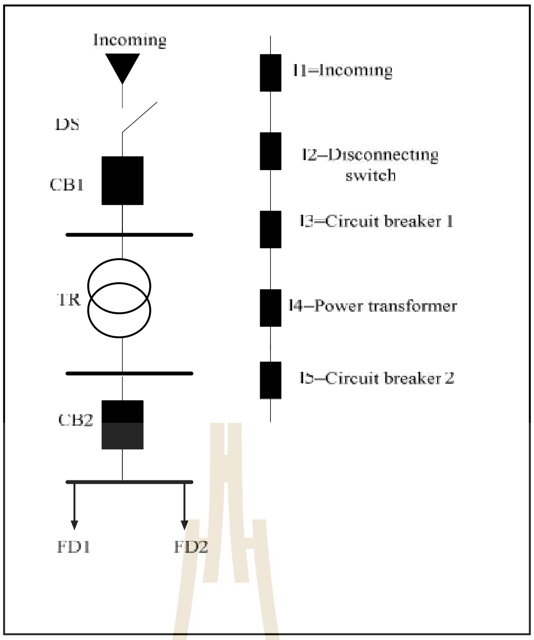


Figure 2.4 Single line diagram of single bus single bay system

2.3.4 Double bus Double breaker

This system is stated to have high reliability due to that power supply is divided into two bus lines, each line uses two CBs to prevent short-circuiting at one bus. During the line fault or maintenance of a station it will not affect the power supply. But the cost of this system is high as it uses two sets of bus-bars and two circuit breakers per one transmission line. The configuration of the system is shown in Figure 2.5 and its single line diagram in Figure 2.6.

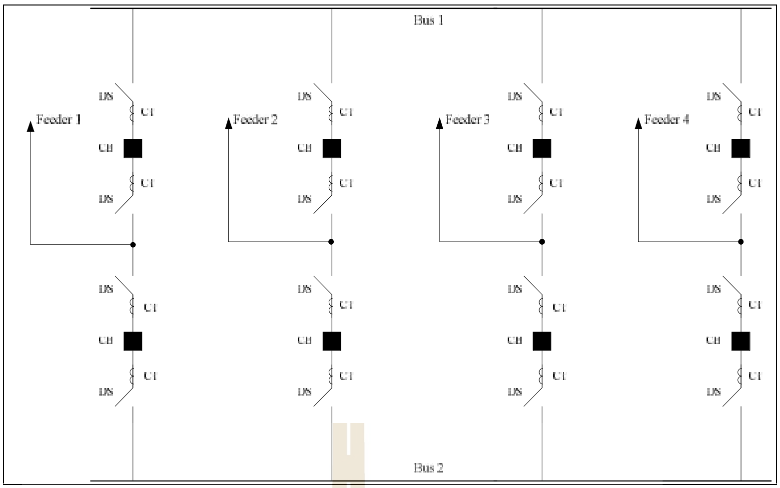


Figure 2.5 Double bus double breaker system (Chang and Yang, 2007)

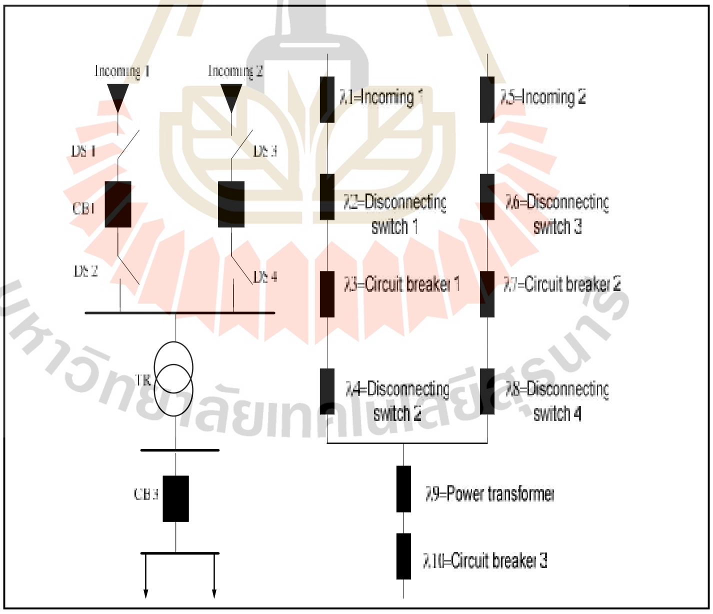


Figure 2.6 Double bus double breaker system for thesis

2.3.5 Main bus Transfer bus

This configuration is similar to single bus as it connects power to all circuits in the main bus during normal operations McDonald, (2006) and Chan, Liu, and Choe, (2007). Short-circuiting the main bus, or in the event of a main bus failure, does not cause any power failure. The transfer bus is used and closed by CB tie (if available) or DS connected to the transfer bus but is not very reliable. The configuration is shown in Figure 2.7.

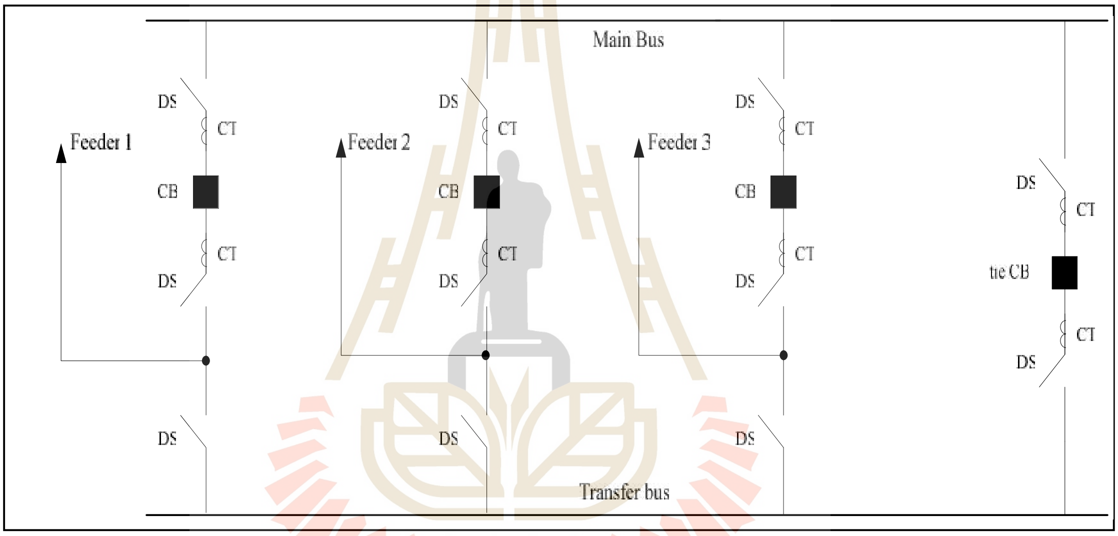


Figure 2.7 Main bus transfer bus system

2.3.6 Double -main and single-transfer bus system

This system consists of two buses and one breaker in each circuit with an addition of tie bus. The configuration has high cost due to and possesses complex relaying system for switching buses. It has ease in maintenance because of an extra bus but maintenance of the circuit breaker needs to switch off the line and cause outage. And greater mobility than the main bus and transfer bus. But with a higher price. The configuration is shown in Figure 2.8.

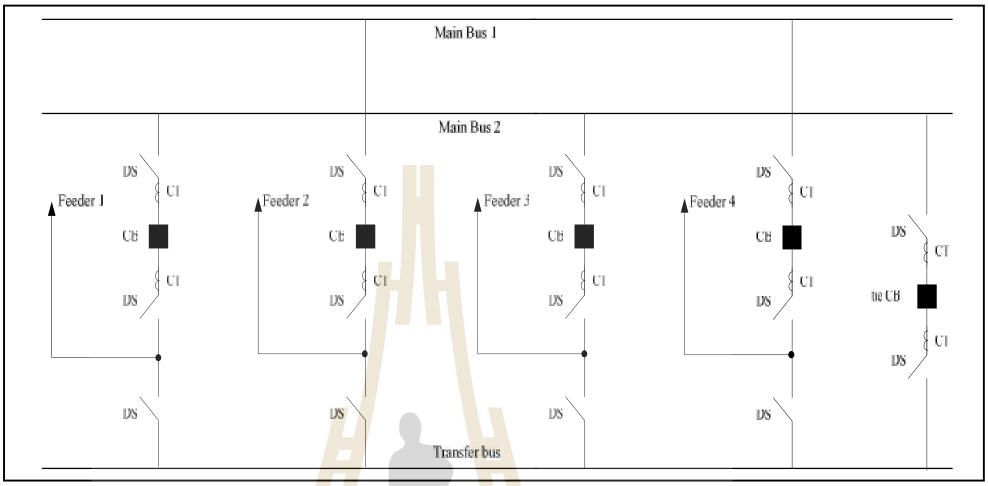


Figure 2.8: Double-main and single-transfer bus system

2.3.7 Double -bus single-breaker system

This system uses two bus-bars. Any feeder will receive power from one bus. Short-circuits, maintenance or other events one bus will not affect the rest of the bus. It can be designed as a transfer bus. It makes the power supply continuous and flexible. But the problem with this type of bus is that if there is a failure, the tie CB will cause the power to go out of the station and in addition, the bus protection system is still complicated and complicated. This type of bus configuration is shown in the Figure 2.9.

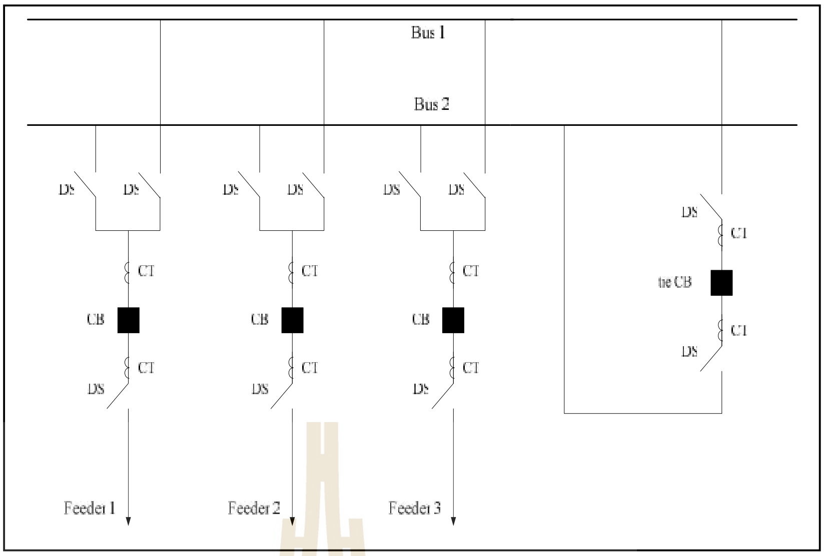


Figure 2.9 Double-bus single-breaker system

2.3.8 Ring - bus system

This system uses a bus-bar connection as shown in Figure 2.10. The feed line uses tabs from the connecting points between each adjacent CB. In the event of a malfunction or maintenance of any equipment in the system, two breakers adjacent to the fault or the point at which the equipment can be removed cause the rest to continue. However, the arrangement of this bus makes the relay protection system very complicated and in addition, the price of installation of the system is quite expensive and the expansion of the power station is also difficult.

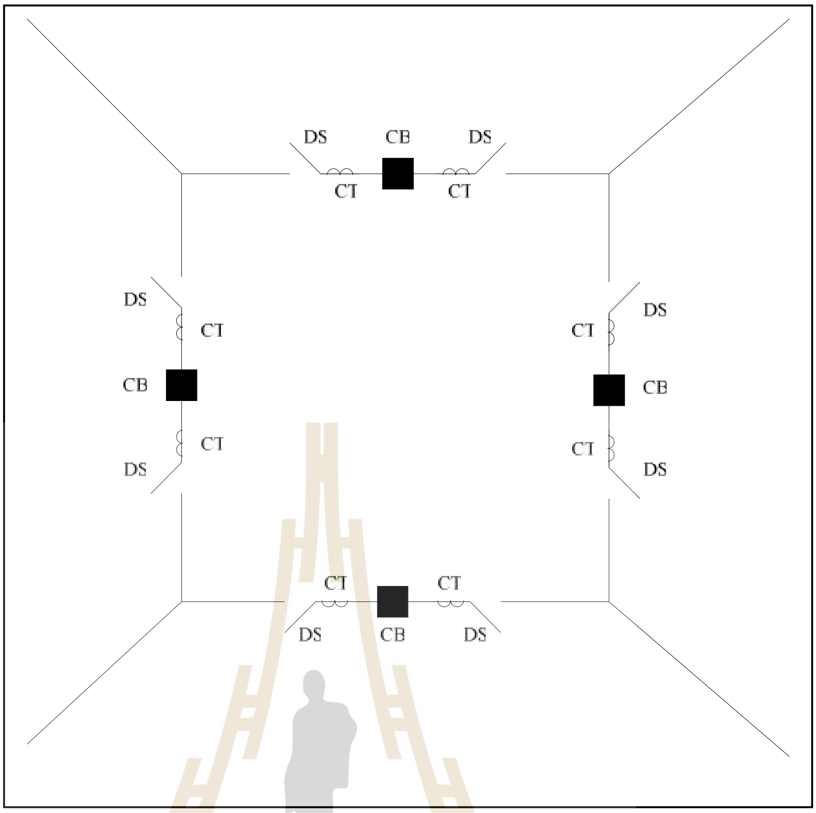


Figure 2.10 Ring bus system (Chang and Yang, 2007)

2.3.9 Breaker and a half system

This system has a similar structure to double bus dual circuit breaker but similar function to the ring bus system. It is highly reliable as one bus fault does not cause failure to another circuit. Moreover, one circuit fault isolates itself. Maintenance practices suits best with this configuration at moderate cost. The problem of this system is that it needs large are and more components for installation. This type of bus configuration is shown in the Figure 2.11.

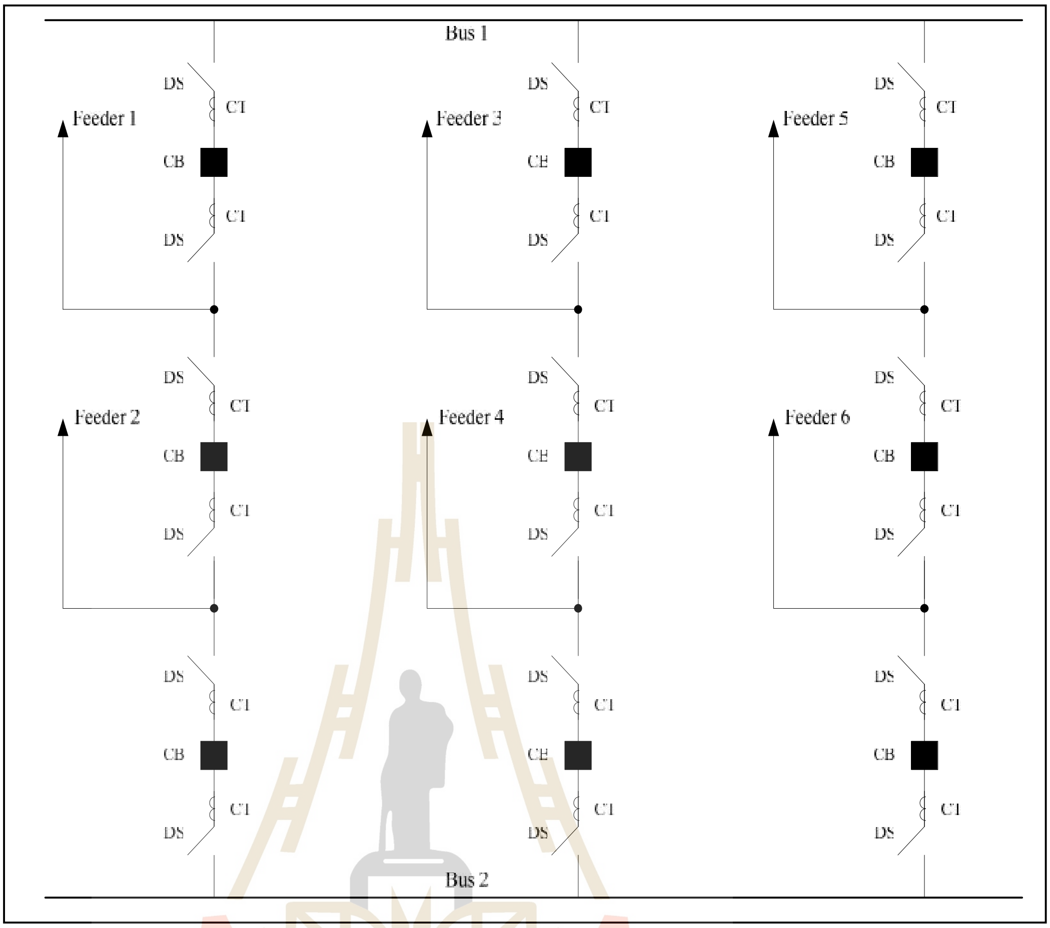


Figure 11 Breaker and half a system (Chan, Liu, and Choe, 2007)

2.4 Preventive Maintenance Model

System components are not designed to fail in their early life rather beyond their useful life. The most useful way to model the component maintenance is through failure rate with the effects of age (Brown, 2009). Theoretically, a new built component must have lowest failure rate as possible. However, this quite different in the real world practice. It is due to the fact that a new built component, especially complex electrical components, may experience industrial flaws such as poor design, substandard items, inadequate manufacturing control, damages during transportation, installation, improper installation (Brown, 2009; Bathtub Curve, 2011). The behavior of failure rate with time of the system component after installation, useful life and nearly to its end of time is modeled as shown in Figure 2.12. This figure is normally termed as Bath tub and as seen it shows three kinds of failure rates which are Decreasing Failure Rate (DCR), Constant Failure Rate (CFR) and Increasing Failure Rate (IFR).

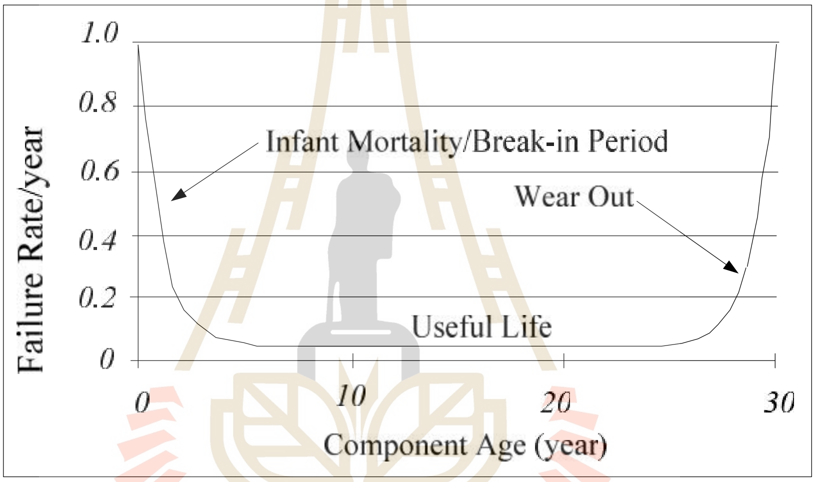


Figure 2.12 Bathtub curve (Brown, 2009).

The Bath tub comprises of three zones i.e. Infant Mortality/Break-in Period, Useful life and Wear Out zone. The Infant Mortality/Break-in Period zone is the one in which the equipment is characterized by high failure rate due to manufacturing defects, transportation problems, installation problems as well as component incapability to withstand system stresses. The best way to minimize the early failure is pass the equipment in ‘burn-in’ period by stressing the equipment nearly to its working conditions for about 48 hours (Bathtub Curve, 2011). The successful operation of equipment in this zone indicates absence of manufacturing defects, installation or transportation problems and it is working in its design conditions.

The Useful life is then follows after Infant Mortality/Break-in Period and it is characterized by almost a constant failure rate. When this period elapses the Wear out starts on which the failure rate undergoes exponential increment until equipment fails. This may be resulted by equipment degradation due to aging or stresses. Three zones can be represented by using statistical distributions, for example Infant Mortality/Break-in Period is represented by Gamma or Weibull distributions, Useful life by exponential and Wear-out by Gamma or Normal distribution.

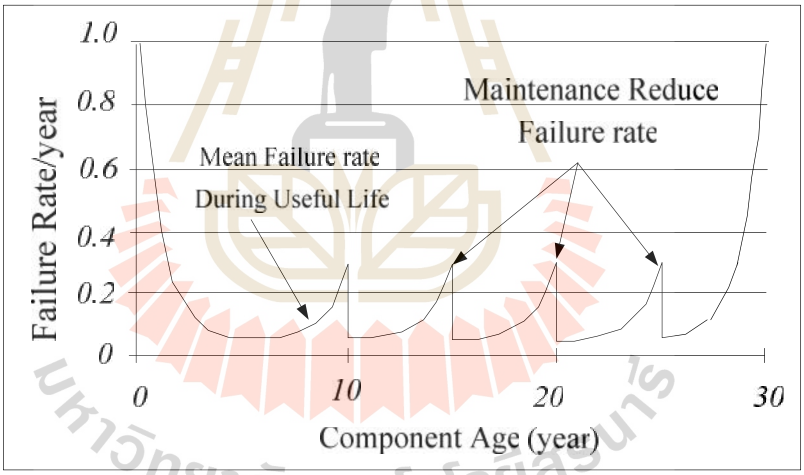


Figure 2.13 Saw tooth Bathtub curve (Brown, 2009).

The failure rate may be termed as Hazard rate which means the probability of the component to fail at time *t* while it is still working at time *t*. A bathtub with the modified curve in the constant failure rate to represent hazard rate function is called Saw tooth bath tub and is shown in Figure 2.13. It uses an increasing failure rate in the useful life since the increase is caused by usual wear, and can be reduced by periodic maintenance.

Hinow and Mevissen (2011) explained the following failure distribution functions of Hazard rate: I) First Weibull distribution after commissioning, II) Exponential distribution during the operation time, III) Second Weibull distribution during the equipment aging and IV) Additional Weibull distribution for higher failure rates after substation overhaul.

The useful life of an equipment or system in the practical world is normally finite, but for degradable and repairable one the deterioration rate and hence failure rate can be minimize and then restored into the younger one by the preventive maintenance. The preventive maintenance model for failure rate reduction in the finite time period (L) is shown in Figure 2.14 (Cheng et al., 2014; Cheng et al., 2015; Chang and Yang, 2007).

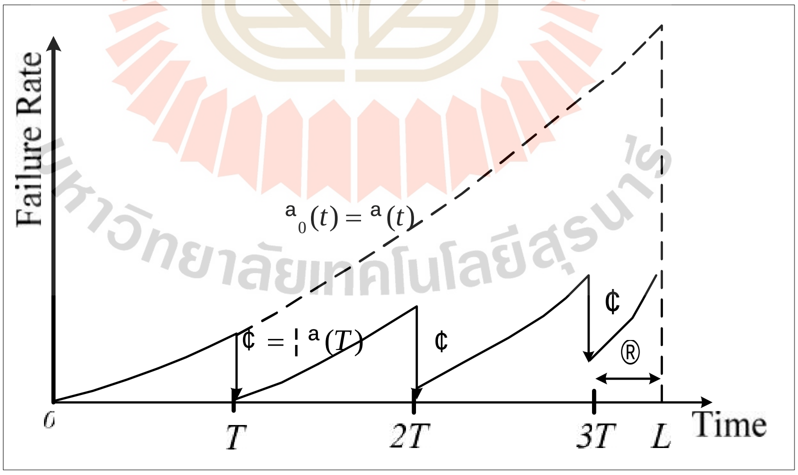


Figure 2.14 Preventive maintenance model

Where:

L is the finite useful lifetime of the component

T is the time interval for every preventive maintenance (*N*)

¢ is the amount of failure rate reduced after every preventive maintenance

N is the number of preventive maintenance undertaken during the finite lifetime *L*

® is the time interval between the N^{th} and *L* preventive maintenance i.e. ®=*L*-*NT*

¦ The restoration factor to measure the amount of restoration after every PM

Assumptions

Firstly, the component is disposed at specified finite working time (*L*) without replacing to a new one while the disposed component is assumed to have no salvage market.

Secondly, the whole interval of preventive maintenance is bounded to the range of (0, *L*).

Thirdly, every preventive maintenance can reduce the failure rate of the respective component to a younger state.

Fourthly, for the given number of preventive maintenance (*N*), the amount of failure rate reduced (¢) after every preventive maintenance is assumed to be constant. The reduced amount is assumed to be measured by the restoration factor (¦). The exponential expression of failure rate is given in (2.20) to (2.23) (Brown, 2009).

Failure rate, $$ª(t) = Ae^{Bt} + C \quad (2.20)$$

$$A = \frac{[\text{ª}(1/2) - \text{ª}(0)]^2}{\text{ª}(1) - 2\text{ª}(1/2) + \text{ª}(0)} \tag{2.21}$$

$$B = 2\ln\left(\frac{\text{ª}(1/2) + A - \text{ª}(0)}{A}\right) \tag{2.22}$$

$$C = \text{ª}(0) - A \tag{2.23}$$

Table 2.1 Failure rate model parameters (failure rate/year) (Brown, 2009).

AIS substation equipment	$\text{ª}(0)$	$\text{ª}(1/2)$	$\text{ª}(1)$	A	B	C
Power transformer <25MVA	0.0075	0.040	0.140	0.01565	2.2478602	-0.008148148
>25MVA	0.0050	0.030	0.120	0.00962	2.5618677	-0.004615385
Circuit breaker	0.0005	0.010	0.060	0.00223	3.3214624	-0.001728395
Disconnect switches	0.0020	0.010	0.320	0.00021	7.3142615	0.001788079
Instrument transformer	0.0000	0.010	0.060	0.00250	3.2188758	-0.002500000
Air insulated bus-bar	0.0005	0.010	0.076	0.00160	3.8767259	-0.001097345

2.5 Literature Survey of Power System Maintenance

Currently, several researchers have demonstrated the importance of maintenance activities in the entire power system or individual power system component. Reliability Centered Maintenance has been among the mostly applied technique for improving the availability, reliability, minimizing failure rate and maintenance costs at all. In this section selected some of the research works performed in the power system and its components are highlighted to give an overview of the maintenance strategies in the performance of the system/components.

Sabouhi, Fotuhi-Firuzabad, and Dehghanian (2016) presented a novel risk based framework for a criticality assessment of the plant components as a mean to conduct more focused maintenance activities. It is a risk-based method that prioritized plant components to ensure the most-effective and techno-economic investment decisions. The study was done in the power generating plants (Combined Cycle Power Plant in Iran, comprising of two gas turbine power plant and one steam turbine power plant) in order to identify critical component that influence the overall system functionality. Identified components were obtained by determining their failure impacts on the system reliability, electric safety, cost and the environment. In the study an *RCM* maintenance strategy was employed.

Ruijters, Guck, Drolenga, and Stoelinga (2016) proposed a novel framework that integrated maintenance activities and fault tree analysis. It supported a wide interval of maintenance activities and dependability measures such as system reliability, availability; mean time to failure, maintenance cost and failure cost over time. The proposed model was divided into different component costs and employed a fault tree analysis (*FTA*) technique which prioritizes and identify the potential failure from up-to-down. *FTA* identifies the conditions for the critical failure but cannot propose for maintenance practice. Fault Maintenance tree (*FMT*) was then connected with *FTA* for identifying and proposing maintenance activities. To train the model, statistical model checking was used. Moreover the model was used in two cases such as insulated joints and train compressors.

Belak, Marusa, Ferlic, and Pihler (2013) illustrated the strategic maintenance of 400-kV switching substations. It described a new way for the maintenance of high-voltage equipment in switching stations based on the Reliability-Centric Maintenance (*RCM*), in addition to periodic maintenance. The system implementation used the program that enabled *RCM* as a strategic maintenance concept that has been developed on the basis of ongoing maintenance monitoring. It takes time to consider the index for risk and environment. This new method illustrated an example of using the 400 kV sub-log of the switch stations before and after inspection. The new maintenance approach for high voltage devices in switching substations was based on *RCM* strategy in Slovenian Transmission Operator ELES.

Asgarpoor and Mohamad (1999) performed a research on optimal value-added programs for the maintenance of transmission and distribution systems. Maintenance was considered as a preferred tool for reducing maintenance costs. It was the first consideration for engineers who use it as the main tool as it extends the life of the device. Currently there are increasingly devices malfunction and downtimes. What is needed is the effectiveness of maintenance, which is an important element in the protection and reliability of the electrical system and the economic benefits of electricity users. The purpose of this article is to prepare the working model. Initial anticipation and plan the proper cost of the transmission and distribution system.

Balzer and Schorn (2015) illustrated strategies for optimizing the use of substation assets. They developed a life-cycle cost based approach to optimize the service strategy of the substation and the succeeding renovation based on Fuzzy logic. It involved the finding of the optimal technology, configuration or operational strategy. Their maintenance strategy included the use of *RCM* in the 123 kV Gas

Insulated substation (*GIS*) in the main building and air-insulated substation (*AIS*) and *HIS* in the control building for assessing their technical conditions. Reliability of equipment were the key parameter in the assessment of their life cycle cost. Obtained findings showed that – the more reliable equipment the more suitable is the reduction of maintenance. Also, the less reliable equipment the more suitable is the investment cost in monitoring devices for performing *CBM*.

Sebo et al. (2001) presented a technique for measuring the density of magnetic fields in order to analyze the maintenance of a 345 kV circuit breaker and size comparison. With magnetic field density measurement during SF_6 gas maintenance, the 345 kV breaker at the power station.

Schlabbach and Berka (2001) presented a maintenance-based, reliability-centric for circuit breaker. The article discusses the needs and advantages of maintenance based on reliability as the center compared to the strategies. Other circuit breaker maintenance indicators for maintenance schedules are the technical condition index and the power supply priority indices. This different criteria is set for two individual indicators, which are required for being evaluated. There were factors with different conditions, different uses although it is easy compared to the collection of different conditions, the selection of inputs has the factor to adapt to meet specific needs. Specific maintenance applies to the 30 kV test system over a period of two years. The research found that the RCM maintenance was the appropriate strategy, and proposed to be used in the future.

Xu, Kezunovic, and Wong (2002) proposed an algorithmic approach to manage circuit diagrams to meet the changing environment by integrating the circuit breaker maintenance to provide flexibility.

Frimpong and Taylor (2003) presented the development of conditional maintenance programs for existing power station equipment. Because maintenance work is ongoing, there are some ways to reduce maintenance costs. Also, worker retention issues were not systematically archived. Therefore the importance of managing the maintenance system to be reliable was also seen. Tidy to assist the task force, instead of using a paper note like in the past. An effective maintenance strategy should use all possible audits by diagnosing and using test data from previous maintenance records. Employees should record and design timely decision-making information, operation and maintenance. To achieve the set goals the structure of data storage is essential by retrieving data stored in electronic form from all sources of data collected into data collection centers. Collection of data in each sector of equipment can be brought into the database for processing to provide information for asset managers or those involved in maintenance to create a strategic plan for making decisions in the maintenance process. This system will help to make history and ready to update the data for future use in the future. The maintenance program is based on the data collected on each of the devices in the power station with both mechanical components, electric and hydraulic by checking these devices through system monitoring or testing from the tester, what are the defects and maintenance requirements. The program offered in the research will rely on the principles of data management. It consists of four steps: data collection, integration and analysis, decision making and work execution.

Noor and Junaizee (2004) presented an application of a specialized system for the maintenance of high power transmission lines using the MATLAB program. Using the Fuzzy Logic system, the data that fed into the Fuzzy system comes from the records of the personnel involved in the maintenance of the transmission line. The output section shows the status and overall condition of the transmission system. This specialized system is used to monitor various types of high-strength insulators. It is useful for engineers involved in the management and management of assets in the transmission system to enable them to evaluate and use strategies to decide which to choose whether Emergency Maintenance, Condition Based Maintenance, or Maintenance Needs (Do Nothing).

Bi et al., (2005) presented a maintenance strategy based on the condition of the equipment in the power supply at the power station. Protection of electrical equipment before power failure was aimed to reduce the budget for repairs. Also improved to increase the reliability of power supply and device operation. This is a widely used method of electricity. However, the development of maintenance is not yet a map, of course, and difficult to understand. So the article in the first part will presented the definition and meaning of conditional maintenance, and then presented the development of maintenance based on the state of the power supply equipment and conduct analysis for the domestic development. The researcher himself by combining all the tests together, lastly, practical strategy is an advanced tool for maintenance that is mind-focused.

Pharmatrisanti, Meijer, and Smit (2006) presented the application of conditional maintenance to high and high pressure gas stations under control in Damp conditions and different power systems. It was commented that, before the year 2004, the PLN P3B system should be used for maintenance work under high pressure conditions. There were 3 reasons why PLN was used:

1. The PLN organization operates all high-voltage equipment under and in certain tropical environments, as well as areas with high levels of pollutants.

2. Applicable to different electrical systems.

3. Java Bali's electrical system uses three different grounding systems.

Natti, and Kezunovic (2007) presented a model for determining the maintenance effect of a circuit breaker using conditional measurement data. New maintenance optimization and the frequency or frequency of inspections and repairs are subject to the condition of the equipment being maintained. Conditional maintenance was offered in device monitoring and system analysis. This method was only acceptable if the cost of maintenance is included with the tool and software costs. The lower cost of the monitor circuit breaker. Along with the signal processing module and its expertise, the system module will monitor the control circuits. This article offered a model for the maintenance effects of Circuit Breaker using online data, maintain and upgrade the maintenance system.

Hilber et al., (2007) offered a multiobjective optimization applied to policy-based maintenance for power networks. Key targets for the management of the power grid were: Maximum device performance, Long service life, low cost and maintenance. This goal of maintenance focuses on finding the right balance between protection, to get a lower cost and of the balance between preventive maintenance and revision. It is multiobjective and power system optimization.

Ge and Asgarpoor (2008) presented an analytical process for maximizing the maintenance of the substations using the Stochastic Model. Analytical methods were reliable as elements in the work. The information provided were detailed in comparison to traditional modeling. Significant analysis was implemented to support the credibility of individual components of a particular consumer and helped to prioritize the maintenance efficiencies. In addition to the cost analysis presented in this article, they calculated an expected benefit for the suitability and reliability of the system.

Yin et al. (2008) presented conditional maintenance to the power equipment used by Chongqing Electric Power. That became more and more popular and unavoidable for electrical equipment because of the need for reliability and high performance. Conditional assessment is the basis of conditional maintenance and testing of the equipment. The main way to know what the current state of the device is: Is it still working? This article discussed how to evaluate a device. It depended on the test data. Therefore, new principles regarding the maintenance and testing of equipment were needed in order to control the testing and evaluation of electrical equipment. In this article, they used the data management software, MySQL, which is a database system that stores information in the server. The data stored in the server comes from testing data, system fault, bad working state, and finding diagnostic results.

Ling et al. (2009) offered maintenance optimization for production equipment based on top-level maintenance on multi-unit system policies. Market competition causes pressure to be more effective. To maintain a device to increase profitability, as a result, the maintenance of compliance. The conditions are becoming more popular and emphasized by researchers and practitioners in power plants due to the advantages of effective improvement. Maintenance avoids unnecessary maintenance, maintenance policies based on new and used conditions, and the opportunity to offer for multiple units. In this article, reference is made to the maintenance policy of equipment deterioration using Markov chains. The treatment depends on the deterioration of the device along with the plan of policy. Presented activities in electrical equipment maintenance can be optimized for increasing company profits, creating extended scoping intervals by considering price changes, sell and buy coal, electricity and heat. In the future Monte Carlo models are also used for maintenance.

Krontiris and Balzer (2010) presented an assessment of the impact of high voltage maintenance with the reliability of a circuit breaker. Measurement in preventative maintenance of equipment is carried out in a portable device. Critical downsizing on life-critical maintenance depends on maintenance. The Chinese algorithm is used to evaluate the parameters based on the reliability of the circuit breaker. There is also confidence for the parameters to be calculated by means of the Monte Carlo simulation.

Pansrisu, and Premrudeepreechacharn (2010) proposed the optimization of preventive maintenance for the stimulation of the Bhumibol Hydroelectric Power System. The reliability of power plants is highly relevant. With regard to the way the equipment maintenance work in the system is carried out from the operational records of the Bhumibol Electricity Generating Plant during 2002-2006, the emergency stop of the power plant is different. Mostly caused to stimulate the operation of the power plant, therefore, the stimulation maintenance system will need to be improved for the reliability of the power plant. This article presented a preventive maintenance tool called Enhancement Maintenance (PMO). This method intended to improve maintenance in relation to the mode. The degradation of the device since the wiebull distribution will be able to find time means, Mottiness, mismanagement; and mismanagement are minimized due to data limitation. WEIBULL distribution was used for statistical analysis. This research brought PMO to Bhumibol Hydropower Plant generators 1-4. From simulation results it was shown that PMO maintenance plans can improve the reliability of power plants compared to Turn off power plants. In addition, power plants can also reduce unnecessary maintenance. The reliability of the system was also increased. Analytical studies were considered as a guide to EGAT's other stimulus systems.

Mohamed and Dalal (2010) presented their work on strategic planning using noise recorders for prediction and planning maintenance, maintenance of tools and related electrical equipment in order to make the power supplies work well and last as long as possible. This aimed to reduce maintenance costs and minimize power outages that affect households and industry.

Jin (2010) proposed a system to support the design of maintenance based on the condition of the power transformer in the high-voltage substation, where most of the transformers were installed at the station. An online tool system - this system is difficult to access data with the computer. A new system has been developed to assist in the management of data in power systems using a high-voltage data base system. With this system data can easily be collected and analyzed. The system can provide the results of the judgment based on the properties of the experiment, the protection of electrical equipment and the transmission of data to an online archive to the remote terminal.

Wardani et al. (2011) presented the evaluation requirements of 500/150 kV power transformers using conditional maintenance. It was said that the maintenance of power system equipment can be separated into maintenance, preventive maintenance and maintenance to repair. It costs more than maintenance to protect.

Because when the equipment in the system is damaged, it affects users. This is why this research was undertaken with the PLN P3B Jawa and Bili systems as a guideline for studying preventive maintenance practices such as scheduled maintenance and Conditional maintenance has been used in this research. Which maintenance schedules will be considered on the part of Oil replacement stops the measurement and shutdown inspection / measurement, but this will reduce the cost and reduce the reliability of the system. The maintenance period is based on statistical data. Often used with plants that are used and compliant with PLN P3B Jawa Bali standards, and while the maintenance period is based on the deterioration of the parameters of the equipment. Therefore, the knowledge of the deterioration conditions of the equipment is very important in the maintenance of the condition. In this research, maintenance of the transformer was undergone a condition based maintenance process. The FMEA and FMECA methods were used to determine the cause of the transformer maintenance.

Chaidee and Tippachon (2011) presented fault statistics and condition evaluations for transformer maintenance. The transformer has stopped working under normal conditions and abnormal conditions. Maintenance is critical to having the transformer back in ready-to-use condition. Despite the well-known traditional preventive maintenance, operations are often successful. But this method has a high cost, so the purpose of this research was to improve the defect by the systematic recording of statistical data. The faults and analysis to determine the critical components of the transformer at 115/22 kV and 230/115 kV were taken into account based on the technical data recorded. In addition, the defective element was analyzed by Weibull method in order to estimate the available time of the transformer to support the procedure for conditional assessment. By analyzing the historical data tests, the results of the dissolved gas analysis transformer conditions have been especially evaluated. This was a checklist to evaluate the transformer's deterioration.

Carneiro et al. (2012) presented the power transformer power management at the power station to reflect maintenance, reliability, centrality and monitoring. This article is to present the method. Prioritize maintenance Transformer at the power station. It is a very important device in the power system that transmits power from source to load. Reflecting on the fault analysis, the risk management mitigation has the best use of maintenance. Predictive defense To reduce maintenance shutdown Transformer Use statistical concepts. To apply Considering the differences between transformers. (Transmission and distribution of oil) to study the life cycle of See depreciation The reliability, the risk, the delinquency, and the effectiveness of forecasting techniques are based on the basic process of reliability-centric maintenance. Combined with historical data, device diagnostics depend on monitoring and forecasting.

Wibisana, Wibowo and Arifianto (2012) presented a condition for the maintenance of circuit breakers rated voltage of 500 kV in Jawa Bali, Indonesian. The maintenance strategy involved monitoring (inspection) and evaluation assets (assessment). The article discussed how to improve the maintenance of circuit breakers using *FMEA* (failure mode effect analysis).

Morteza and Habib (2013) proposed maintenance planning for existing circuit breakers, power systems. This article offers effective equations for maintenance planning of circuit breaker. The equation presented here is two-fold. In the first part, continuous maintenance depending on the time. The Markov model was used to analyze the random deterioration of equipment in the system and determine the annual breakdown and maintenance costs of Circuit Breaker. The second part studied the impact of circuit breaker breakdown with unacceptable power bills in the system by using IEEE testing system to increase reliability. Comparison of the results between the methods was presented and reported by the circuit breaker network. The results show the effectiveness of the proposed method.

2.6 Chapter summary

This chapter has discussed the various maintenance strategies performed in the power system. It also shows the modeling of reliability, failure rate and configuration of the electric distribution system. Moreover, real world cases involving the application of maintenance strategies in the power system components and their outcomes have been described.

CHAPTER III

OPTIMAL IN RELIABILITY STRUCTURE AND PROCEDURE FOR SIMULATION

This chapter provides the detail of structure for optimization to find out popper time for preventive maintenances of high voltage substation and procedure of algorithm to apply optimization technique in to this thesis.

3.1 General Form of Optimization Formula

The failure rate and reliability problem are nonlinear optimization problem. It consists of a nonlinear objective function defined with nonlinear constraints. The reliability problem requires the solution of nonlinear equations, describing optimal of lowest failure rate or hest reliability depend on cost to maintenance in limitation for budget support. The general optimal problem can be expressed as a constrained as follows.

Minimize $f(x)$

Subject to $g(x) = 0$, equality constraints

$h(x) \leq 0$, inequality constraints

$f(x)$ is objective function, $g(x)$ equality constrain function, $h(x)$ is inequality constrains function. The optimal problem equation can convert both equality and inequality constraints into penalty terms and therefore added to form the penalty function as described in Equation (3.1) and Equation (3.2).

$$P(x) = f(x) + \Omega\ (x) \tag{3.1}$$

$$\Omega\ (x) = \rho\ \{g^2(x) + [\max(0,h(x))]^2\} \tag{3.2}$$

where: $P(x)$ is the penalty function

$\Omega\ (x)$ is the penalty term

° is the penalty factor

By using a concept of the penalty method (Dutta and Sinha, 2006), the constrained optimization problem is transformed into an unconstrained optimization problem in which the penalty function as described above is minimized.

3.2 Design Optimal Reliability Equation

3.2.1 Objective Function

The objective functions in the high voltage substation were simulated through MATLAB software package. An optimal period for performing the preventive maintenance which corresponds to the highest reliability, lowest failure rate and minimum cost was aimed after optimization. In this thesis considers the failure rate and reliability of the simplified arrangement of the high voltage substation system (single bus-single breaker one bay and double bus-double breaker one bay) and apply to the 115/22 kV Nongki substation located 80 km from Nakhon Ratchasima Province.

In this thesis, the value of below are between x-axis (Time in year) and y-axis (reliability value) is applied to the objective function can be expressed as given in Equation (3.3).

$$OBJ = Reliability\ X\ Time\ (PM) - Reliability\ X\ Time\ (non,\ PM) \qquad (3.3)$$

where: $\mathrm{Re}\,liability \cdot Time(pm)$ is the function of area under the graph between reliability and period time with have PM. Maybe can define this equation as

$$Reliability\ X\ Time(PM) = \sum_{i=1}^{T_f} e^{(-\alpha t_i)} + e^{(-\alpha_0 t_i)} \qquad (3.4)$$

α_0 is failure rate at the first year for run system or a new machine ($\alpha(t=1)$).

The *Reliability X Time(non, PM)* is the function of area under the graph between reliability and period time without PM or conventional scenario. This equation can be define by

$$Reliability\ X\ Time(non,\ PM) = \sum_{i=1}^{T_f} (e^{(-\alpha t_i)}) . \qquad (3.5)$$

3.2.2 System Constraints

The controllable system quantities are period time of PM and optimal cost for performing preventive maintenance showed the successful optimization of the maintenance period. These are system constraints to be formed as limitation of both parameter as inequality constraints as shown below in (3.6) to (3.8).

$$t_{i,PM}^{\min} \le t_{i,PM} \le t_{i,PM}^{\max} \tag{3.6}$$

$$cost_{i,PM}^{\min} \le cost_{i,PM} \le cost_{i,PM}^{\max} \tag{3.7}$$

$$cost_{Total,PM}^{\min} \le \sum_{i=1}^{n} cost_{i,PM} \le cost_{Total,PM}^{\max} \tag{3.8}$$

where:

$t_{i,PM}^{\min}$, $t_{i,PM}^{\max}$ are upper and lower limits of period time for PM equipment *i*

$cost_{i,PM}^{\min}$, $cost_{i,PM}^{\max}$ are upper and lower limits of cost for performing preventive maintenance equipment *i*

$cost_{i,PM}$ is cost for performing preventive maintenance equipment *i*

3.2.3 Control Parameters

The BFGS and GA are considered for solving reliability time period of preventive maintenance because it is efficient search methods. It was designed to work on Newton's method, which is often used for finding zeros of a nonlinear function (Hu et al., 2006); (Zhang et al., 2013). Applied to nonlinear programming schemes, one needs to find the zeros of the first derivative $\nabla_x f(x)$ of the objective function. During the searching process, BFGS will collect of the set solution vector. Let *X* be a created possible solutions. The period time for PM equipment ($t_{i,PM}$) and the cost for performing preventive maintenance equipment ($cost_{i,PM}$) can be written as described in Equation (3.9).

$$X = [t_1 \quad t_2 \quad t_3 \quad \cdots t_n \quad \cos t_{Total}] \tag{3.9}$$

$$Cost_{Total} = ValueCost(\sum_{i=1}^{n} \frac{1}{t_i}) \tag{3.10}$$

The total of benefit area under the graph function is computed as the sum of the individual element in the substation objective function. To account for all the system constraints Equation (3.11) to Equation (3.13), the benefit area under the graph function is augmented by non-negative penalty terms to penalize the constraint violations. Thus, the augmented objective function, called the penalty function (Nocedal and Wright, 2000); (Nash and Sofer, 1996), is formed as Equation (3.9).

$$P(x) = OBJ + \Omega_{t,PM} + \Omega_{\cos t,PM} \tag{3.11}$$

where: $\Omega_{t,PM} = \circ \sum_{i=1}^{N_{eq}} \left\{ \max\left(0, t_{i,PM} - t_{i,PM}^{\max}\right) \right\}^2 + \circ \sum_{i=1}^{N_{eq}} \left\{ \max\left(0, t_{i,PM}^{\min} - t_{i,PM}\right) \right\}^2$

(3.12)

$$\Omega_{\cos t,PM} = \circ \sum_{i=1}^{N_{eq}} \left\{ \max\left(0, \cos t_{i,PM} - \cos t_{i,PM}^{\max}\right) \right\}^2 + \circ \sum_{i=1}^{N_{eq}} \left\{ \max\left(0, \cos t_{i,PM}^{\min} - \cos t_{i,PM}\right) \right\}^2 \tag{3.13}$$

N_{eq} is the total number of equipment in substation

3.3 Artificial Intelligence Algorithm to Solver Reliability Problem

3.3.1 Quasi-Newton Method using BFGS

BFGS quasi-Newton method The Broyden Fletcher Goldfarb and Shanno (BFGS) methods are derived from the Newton’s method, which is often used for finding zeros of a nonlinear function (Cheney and Kincaid, 1994). Applied to nonlinear programming schemes, one needs to find the zeros of the first derivative $\nabla_x f(x)$ of the objective function. The detail of BFGS method shows in (Kwannetr et al., 2011) and (Zhang et al., 2013). In this thesis, The BFGS can be an appropriate solving the optimal time period of maintenance. Remarkably, the CPU time to find optimal solutions by using the BFGS is the fast computation. Thus, the BFGS is the choice has been applied for optimization method to solve reliability problem.

In this study, the BFGS method in MATLAB optimization toolbox is employed (Shanno, 1970). The *fminunc* function uses (among other methods) the BFGS Quasi-Newton method. Many of the constrained methods of the optimization toolbox use BFGS and the variant L-BFGS. Many user-contributed quasi-Newton routines are available on MATLAB's file exchange.

3.3.2 Genetic Algorithm

The genetic algorithm (GA) is a search and an optimization technique established on the principles of genetics and natural selection. The GA allows a population constitute of many individuals to emerge underspecified selection rules to a state that maximizes the ‘’fitness’’ (i.e. minimizes the cost function). The genetic algorithm GA uses three main types of controls at each step to build the next generation from the current population. Selection rules select the individuals called parents that contribute to the population to the next generation. Crossover rules couple two parents build children for the later generation. Mutation rules employ random changes to individual parents to create children.

There are many optimization algorithm techniques for solving the optimization problems. Due to the limitation of classical optimization methods in finding global minimum value, the heuristic optimization methods are widely used because of their reliability, flexibility, and robustness in seeking optimum value in recent years (So and Li, 2000). GA was proposed by John Holland in 1975; moreover, it can find the global optimal solution in complex multi-dimensional search space (Pham and Karaboga, 1998), and it is a heuristic search method which mimics the biological process of natural evolution such as mutation, crossover, selection, etc, Like others methods, GA needs the initial value and randomly generates the solutions to find the best fitness value (Leeton et al., 2010).

GA is chosen to build up an algorithm to solve optimal reliability problems (all time period to maintenance the equipment in substation). To reduce programming complication, the Genetic Algorithm (GADS TOOLBOX in MATLAB) is employed to produce a set of initial random parameters. With the searching mechanism, the parameters are modified to give the best result. Flowchart of the GA procedure is shown in Figure 3.1

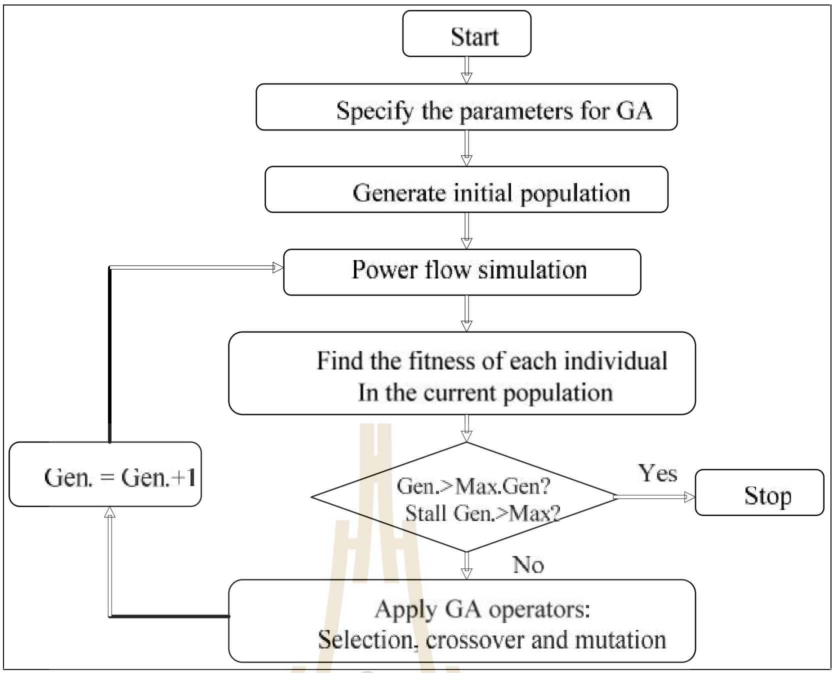


Figure 3.1 Flowchart of the GA procedure (Leeton, 2010).

The GA reach the region of the optimal solutions and its accuracy quickly for two reasons: GAs avoid local minima by searching in several regions (working with population of solutions) to arrive at global minima. No gradient information and the initial population represent an important factor in the program genetic algorithm to arrive at the best fitness function and low time executing the process of the program.

3.4 Simulation Procedure

The simple algorithm was employed to perform simulation as shown below. It aimed to reduce the failure rate compared with the conventional preventive maintenance (PM) in a preventive maintenance period of 1, 2, 3, 5 and 10 years).

1. Define initial values of expected lifetime (T_f) of the equipment (in year) and preventive maintenance period (in year, T_{pm})

2. Define parameters of failure rate constant of each equipment in the power substation (A, B and C) in (2.21) to (2.23). Equipment are incoming system, DS, CB, Bus bar and transformer.

3. Calculate failure rate (*FR*) value from (2.29) before and after maintenance with check criteria of time (T); if it is more than T_{pm} then the system should adopt *PM*. The *PM* reduces *FR* to the minimum level.

4. Collect *FR* values after every stopping criteria of the simulation.

5. Consider the arrangement of busbar in the substation, to compute series and parallel *FR*.

For calculation total FR of substation.

6. Calculate the failure rate in (2.20) for series and reliability in (2.4) for series. Calculate the failure rate in (2.20) for parallel and reliability in (2.16) for parallel.

7. Collect FR values after every stopping criteria of the simulation.

8. The objective function is created by difference value between before PM and without PM for supporting Artificial Intelligence (GA and BFGS).

9. Artificial Intelligence will be obtain optimal period time value base on criteria of limitation time and cost function.

This procedure can be summarized as the flow diagram in Figure 3.2.

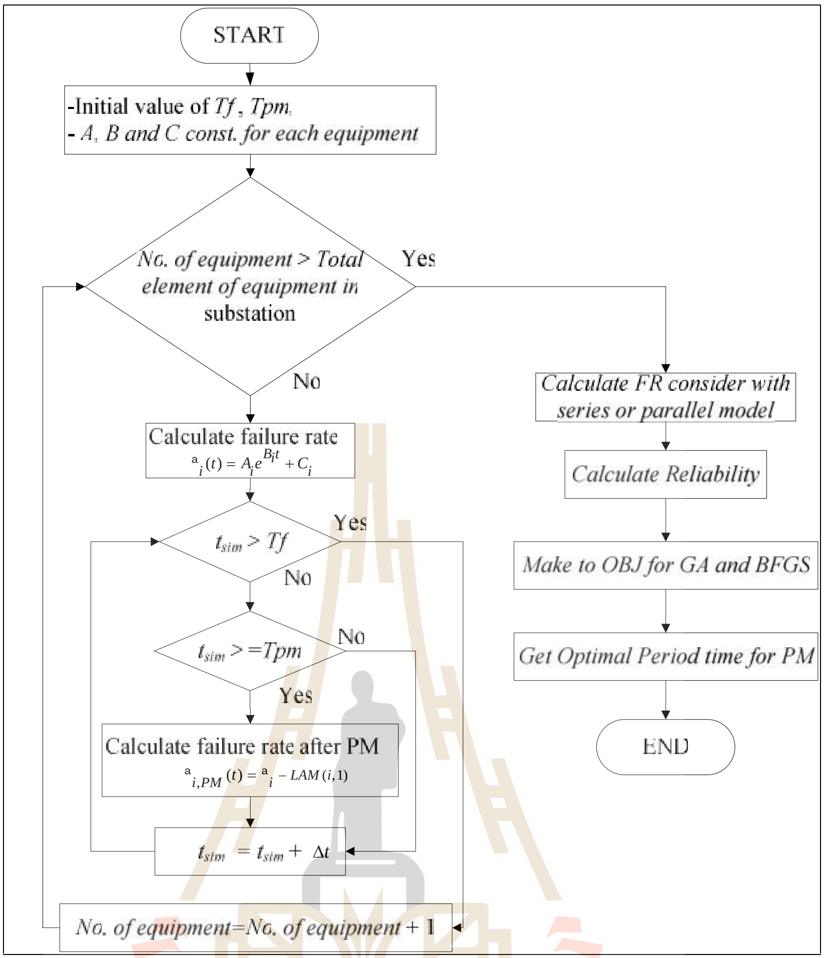


Figure 3.2 The algorithm for simulation failure rate and reliability

3.5 Chapter summary

This chapter has discussed the various maintenance strategies performed in the power system. It also shows the modeling of reliability, failure rate and configuration of the electric distribution system. Moreover, real world cases involving the application of maintenance strategies in the power system components and their outcomes have been described. The intelligence algorithm (GA and BFGS) were applied to find out popper time for preventive maintenances of high voltage substation and procedure of algorithm is illustrated to apply optimization technique in to this thesis.

CHAPTER IV

SIMULATION RESULTS AND DISCUSSION

This chapter provides the result of maintenance in electric power substation systems and their useful utilizations for minimizing maintenance cost and failure rate in the other hand, considering maximize the reliability of equipment in substation. The simulation for test systems were done in the same computer which was an Intel®, Core (TM) i5-6200U, CPU @2.3 GHz, 4.0 GB RAM. The results of reliability and failure rate of the simplified bus configuration in single bus-single breaker one bay, double bus-double breaker one bay and the case study of 115/22 kV Nongki substation are also presented in this chapter.

4.1 Single bus single bay test system

For the substation containing high voltage components as shown in Figure 4.1, the failure rate can be given as in (2.20) whereby *A*, *B* and *C* are constants. In (Brown, 2002). The values of *A*, *B* and *C* have been given based on equipment inspection data and have been summarized in Table 4.1.

Table 4.1 Failure rate modeling of substation components

Parameter	Incoming	DS	CB1	TR	CB2
A	0.01976	0.00021	0.00223	0.01565	0.00223
B	3.42959	7.31426	3.32146	2.24786	3.32146
C	-0.00976	-0.00179	-0.00173	-0.00815	-0.00173

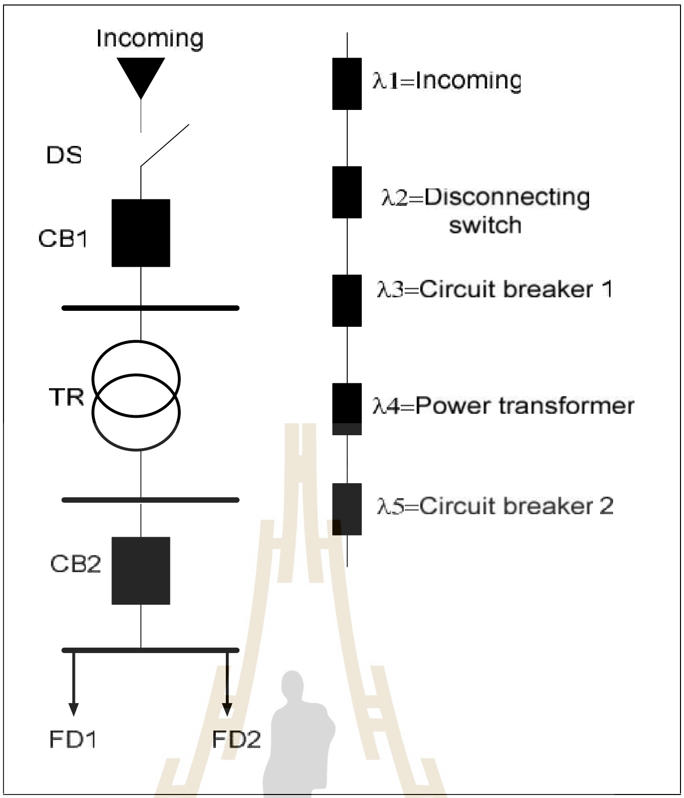
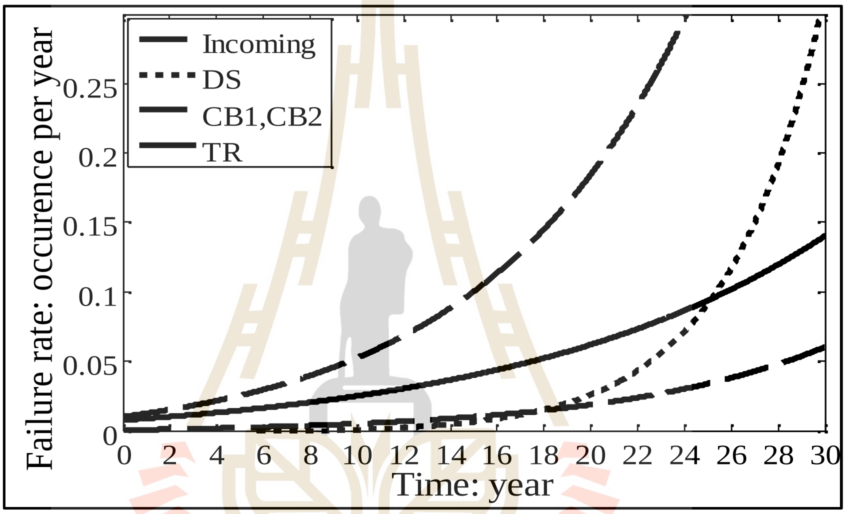
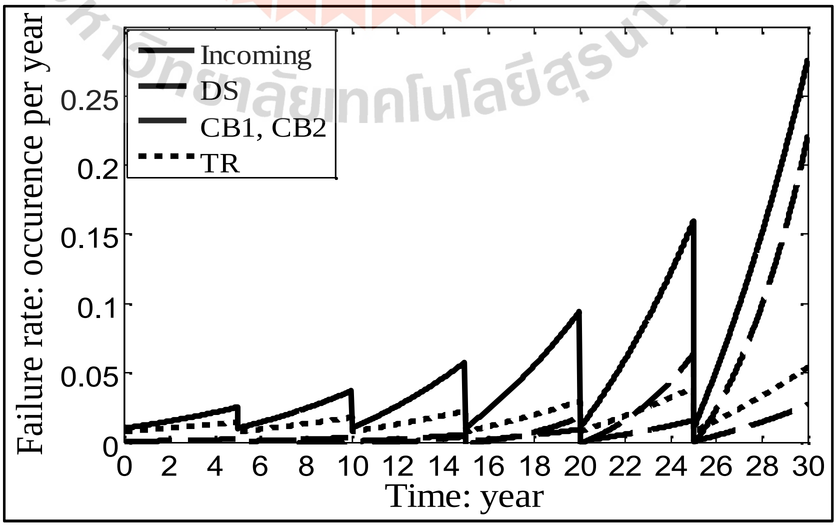
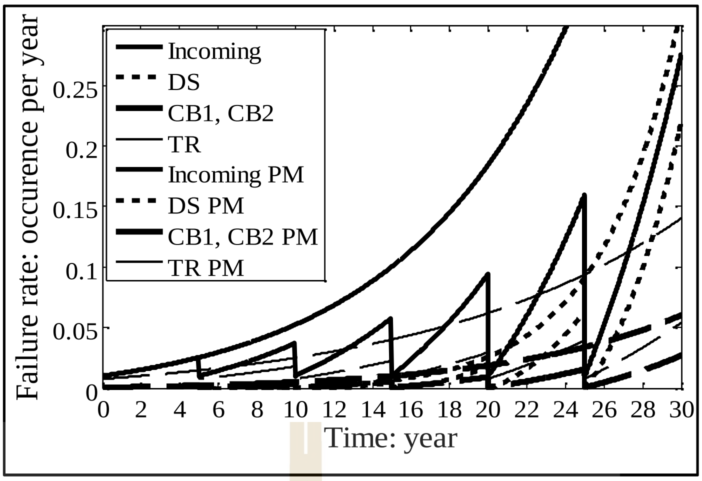


Figure 4.1 single bay single bus

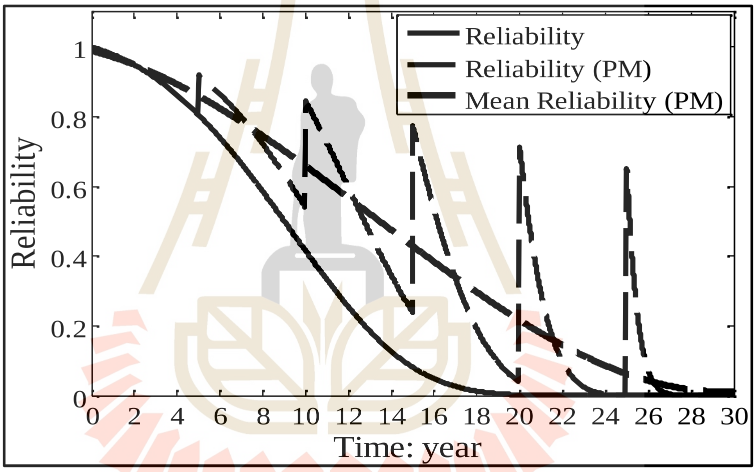
When considering the maintenance period of five years and use constants given in Table 4.1, the failure rates of each substation components are as shown in Figure 4.2. The machine or equipment in substation was used for a long time (1 to 30 year) will be effected for incensement of failure rate. In figure 4.2, failure rate of incoming is highest and failure rate of circuit breaker is lowest. In Figure 4.3 shows result of the failure rate after maintenance period of every five years. For example, maintenance period of every five years will be shown the failure rate is low on the years which have PM activity after that FR will increase for usage machine on every day. Also, failure rate of incoming is highest and failure rate of circuit breaker is lowest. The comparison of failure rate and reliability and without a maintenance


Incoming
DS
CB1,CB2
TR
Failure rate: occurence per year
0.25
0.2
0.15
0.1
0.05
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time: year

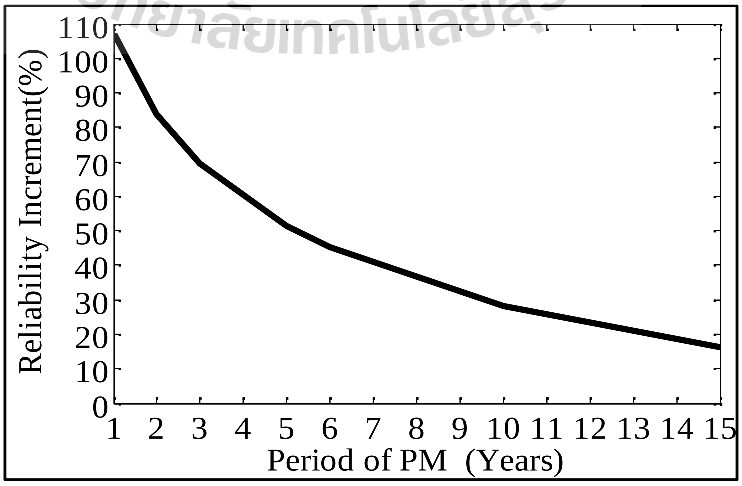

Incoming
DS
CB1, CB2
TR
Failure rate: occurence per year
0.25
0.2
0.15
0.1
0.05
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time: year



Failure rate: occurence per year
Time: year
Incoming
DS
CB1, CB2
TR
Incoming PM
DS PM
CB1, CB2 PM
TR PM



Reliability
Time: year
Reliability
Reliability (PM)
Mean Reliability (PM)



Reliability Increment(%)
Period of PM (Years)

Table 4.2 Reliability comparison of maintenance periods of single bus-single breaker system

	No PM	Period (Years) with PM						
		1	2	3	5	6	10	15
Area	8.9	18.6	16.5	15.2	13.6	13.0	11.5	10.4
Increment (%)	-	107.1	83.8	69.4	51.4	45.1	28.3	16.1

PM*:* Preventive Maintenance

Applying the Genetic Algorithm and BFGS optimization to verify the effectiveness and performance of single bus-single breaker test system was used for test system. The simulations were performed using MATLAB software. The test was carried out by solving the reliability increment percentage objective. Variable limitation given in Table 4.3 was used as system constraints. For comparison purposes, genetic algorithm, BFGS were applied to solve the test system with various cases. Each method was challenged by solving given algorithm reliability increment of 30 trials randomly. Minimum, average, maximum and standard deviation of the 30 trial solutions for bus-single breaker system obtained by each method were evaluated and shown in Table 4.4. Table 4.5 showed the comparison of CPU time spent by each approach. The optimal control variables obtained by each method were shown in Tables 4.6 to 4.7.

Table 4.3 Variable limits used for reliability increment of Single bus-single breaker system

Variable	Limitation	
	Minimize	Maximum
$t_{1,PM}$ to $t_{5,PM}$ (Year)	1.0	10.0
$\cos t_{1,PM}$ to $\cos t_{5,PM}$ (% factor cost reduce from maximum budget)	20	80

Table 4.4 Reliability increment obtained by using GA and BFGA of Single bus-single breaker system

Method	Algorithm Reliability increment (%)			
	Minimum	Average	Maximum	Deviation
GA	79.14	83.42	85.82	1.52
BFGS	24.76	39.80	59.40	8.59

Table 4.5 Computational time to obtain Reliability increment by GA and BFGS for Single bus-single breaker system

Method	Computational Time (s)			
	Minimum	Average	Maximum	Deviation
GA	3.5729	6.5145	11.7094	2.0885
BFGS	0.0140	0.0266	0.2814	0.0482

Table 4.6 Optimal solution by the GA for Single bus-single breaker system

Variable	Statistic (per year)				The cost to maintenance (p.u.) of lift time (30 Y)
	Avg. (Year/time)	STD.	Min. (time/Year)	Max. (time/Year)	
$t_{1,PM}$	1.2250	0.1954	1.0020	1.6451	25
$t_{2,PM}$	1.7445	0.5055	1.0185	2.8958	17
$t_{3,PM}$	2.4361	0.5822	1.1668	3.3488	12
$t_{4,PM}$	2.4361	0.5442	1.0485	3.4575	12
$t_{5,PM}$	2.5893	0.7970	1.6933	5.1340	12

Avg.: Avergae, STD.: standard deviation, Min.: Minimum, Max.: Maximum

Table 4.7 Optimal solution by the BFGS for Single bus-single breaker system

Variable	Statistic (per year)				The cost or budget to maintenance per year (Baht)
	Avg. (Year/time)	STD.	Min. (time/Year)	Max. (time/Year)	
$t_{1,PM}$	6.0917	2.5385	2.0745	9.7509	5
$t_{2,PM}$	5.8412	2.4539	1.4780	9.7751	5
$t_{3,PM}$	5.5741	2.7364	1.4162	9.6821	5
$t_{4,PM}$	5.8817	2.5297	1.2219	9.8380	5
$t_{5,PM}$	6.6786	3.0130	1.0709	9.9690	4

The results showed that the GA and BFGS optimal methods gave the best time period solution when compared with those obtained by the GA and BFGS. For Single bus-single breaker system test system, the average reliability increase solutions were 83.42 and 39.80 for the GA and BFGS methods, respectively. However, when considering the maximum reliability incensement, the GA and BFGS were the two methods that can find the maximum reliability increase of 85.82 and 59.40. The standard deviation of the solutions obtained by the GA and BFGS were 1.52, 8.59, respectively. The CPU times spent by each method to find the optimal solution showed that the BFGS consumed the least computational time effort than GA. As a result, the reliability increase of the test system can be improved with 83% incensement.

The optimal solution by the BFGS and GA for Single bus-single breaker system were shown in Table 4.6 and 4.7. Assume, the lift time is 30 year old for each equipment in substation and average time for maintenance per year in 1.2 for incoming, 1.7 for DS, 2.4 for CB1, 2.4 for transformer and 2.5 for CB2. The total cost each equipment in substation for maintenance consider by lift time divided by average time for maintenance. For example incoming equipment has total cost for maintenance is computed by 30/1.2250 equal 25 p.u., if 1 p.u. equal 10,000 baht so total cost for maintenance is 250,000 baht or total cost for maintenance of transformer is 30/2.4361 equal 12 (120,000 baht) etc.

4.2 Double Bus-Double Breaker Test System

A substation with HV components arranged as shown in Figure 4.7 can be described as a double bus-double breaker system. The failure rate of the system without preventive maintenance and with preventive maintenance of every five years is shown in Figure 4.8. The machine or equipment in substation was used for a long time (1 to 30 year) will be effected for incensement of failure rate. The Figure 4.9 compares the reliability of the whole substation with two incomings, four disconnecting switches, three circuit breakers, and one power transformer without maintenance and with preventive maintenance of every five years.

Table 4.8 Reliability comparison of maintenance periods of Double bus double-breaker system

	No PM	Period (Years)						
		1	2	3	5	6	10	15
Area	9	24	21	19	16	15	13	11
Increment (%)	-	95	82	71	54	48	31	17

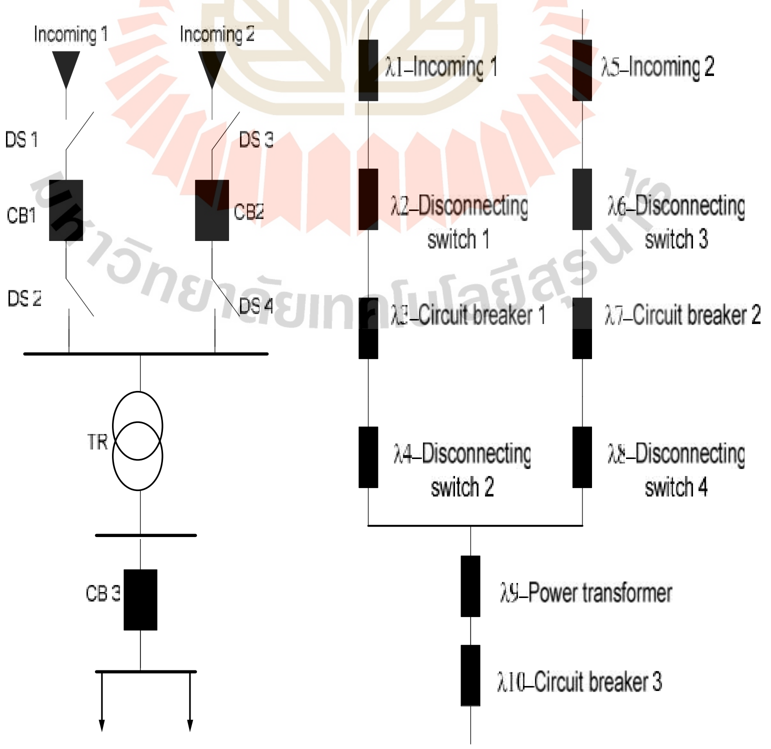
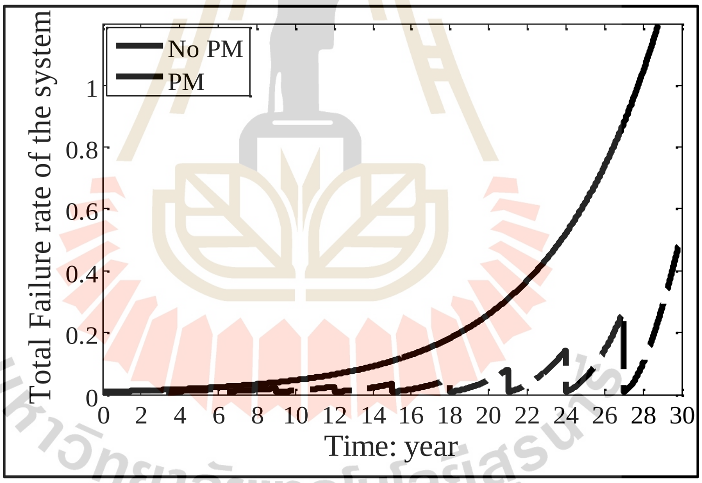
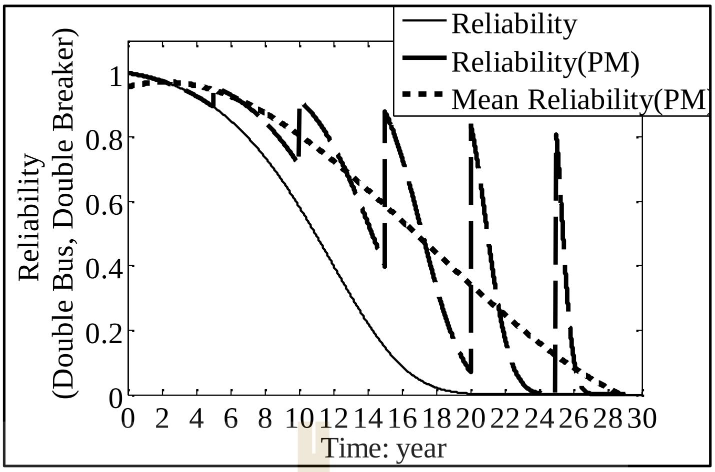
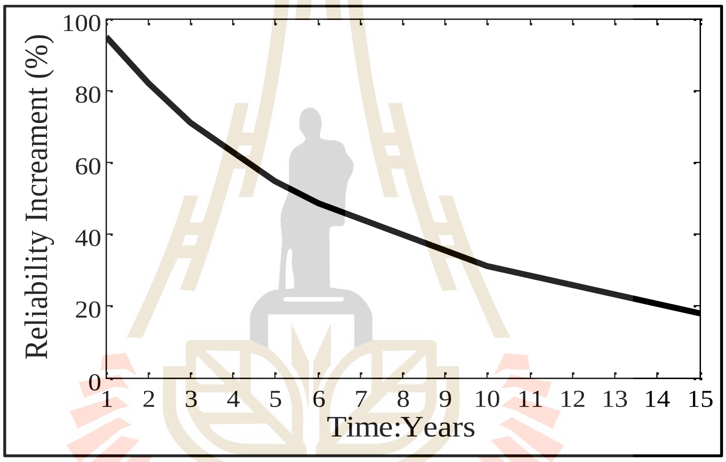


Figure 4.7 Double bus double-breaker system



No PM
PM
Total Failure rate of the system
Time: year
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30





Variable	Limit	
	Minimum	Maximum
$t_{1,PM}$ to $t_{10,PM}$ (Year)	1.0	10.0
$cost_{1,PM}$ to $cost_{10,PM}$ (% factor cost reduce from maximum budget)	20	80

Also, applying the Genetic Algorithm and BFGS optimization to verify the effectiveness and performance of double bus- double breaker test system was used for test system. The test was carried out by solving the reliability increment percentage objective. Variable limitation given in Table 4.9 was used as system constraints. For comparison purposes, genetic algorithm, BFGS were applied to solve the test system with various cases. Each method was challenged by solving given reliability increment of 30 trials randomly. Minimum, average, maximum and standard deviation of the 30 trial solutions for double bus- double breaker test system obtained by each method were evaluated and shown in Table 4.10. For Table 4.11 showed the comparison of CPU time spent by each approach. The optimal control variables obtained by each method were shown in Tables 4.12 to 4.13.

Table 4.10 Reliability increment obtained by using GA and BFGA Double bus double-breaker system

Method	Reliability increment (%)			
	Minimum	Average	Maximum	Deviation
GA	89.3617	93.8903	95.8439	1.5978
BFGS	28.6089	48.0512	71.1424	9.8247

Table 4.11 Computational time to obtain Reliability increment by GA and BFGS for Double bus double-breaker system

Method	Computational Time (s)			
	Minimum	Average	Maximum	Deviation
GA	10.2562	31.5520	59.0775	11.0642
BFGS	0.0358	0.0501	0.2963	0.0468

Table 4.12 Optimal solution by the GA for Double bus-Double Breaker Test System

Variable	Statistic				The cost or budget to maintenance per year (Baht)
	Avg.	STD.	Min.	Max.	
$t_{1,PM}$	1.2192	0.2074	1.0014	1.9900	24
$t_{2,PM}$	1.2990	0.2611	1.0308	2.1954	23
$t_{3,PM}$	1.4111	0.3381	1.0203	2.2738	21
$t_{4,PM}$	1.4060	0.3851	1.0085	2.6634	21
$t_{5,PM}$	1.1898	0.1837	1.0140	1.8625	25
$t_{6,PM}$	1.2922	0.2562	1.0023	2.1290	25
$t_{7,PM}$	1.4557	0.4213	1.0010	2.5109	23
$t_{8,PM}$	1.3788	0.2965	1.0131	2.0523	21
$t_{9,PM}$	1.2372	0.2143	1.0108	1.9102	24
$t_{10,PM}$	1.3836	0.3261	1.0034	2.2106	21

Table 4.13 Optimal solution by the BFGS for Double bus-Double breaker test system

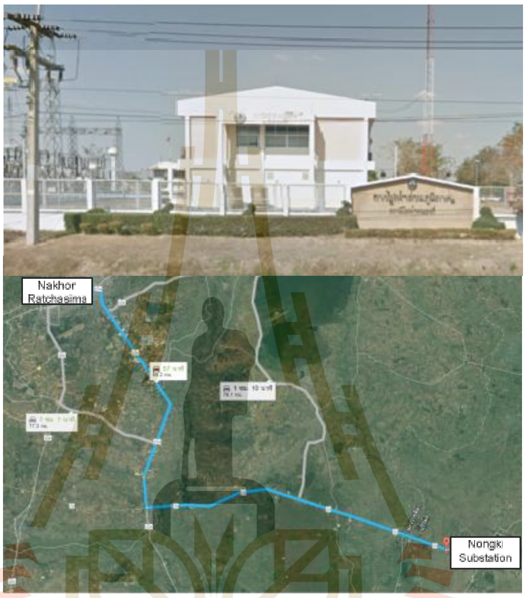
Variable	Statistic				The cost or budget to maintenance per year (Baht)
	Avg.	STD.	Min.	Max.	
$t_{1,PM}$	5.1709	2.8369	1.0041	9.9192	5
$t_{2,PM}$	4.8697	2.5379	1.2861	9.7249	6
$t_{3,PM}$	5.9936	2.5349	1.2033	9.8908	5
$t_{4,PM}$	6.1432	2.4253	1.0614	9.9816	4
$t_{5,PM}$	5.2578	2.2901	2.0477	9.9626	5
$t_{6,PM}$	5.0693	2.4847	1.0311	8.2758	6
$t_{7,PM}$	5.0090	2.3500	1.3501	9.3914	6
$t_{8,PM}$	6.4347	2.3509	1.9770	9.7566	4
$t_{9,PM}$	5.5805	2.7094	1.5069	9.9246	5
$t_{10,PM}$	6.0437	2.5913	1.5381	9.9557	5

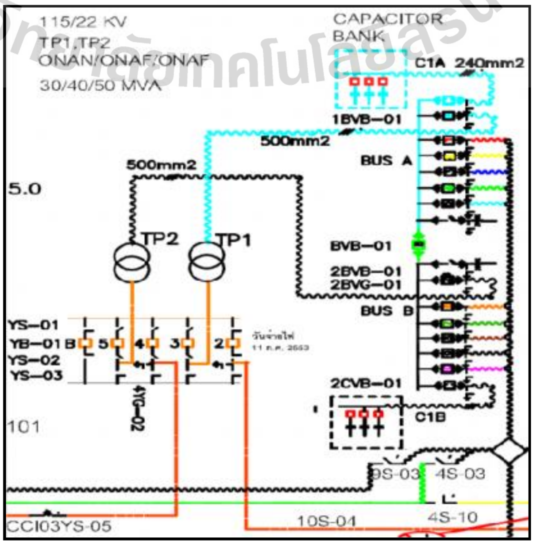
The results showed that the GA and BFGS optimal methods gave the best time period solution when compared with those obtained by the GA and BFGS. For double bus- double breaker system test system, the average reliability incensement solutions were 93.89 and 48.05 for the GA and BFGS methods, respectively. However, when considering the maximum reliability incensement, the GA and BFGS were the two methods that can find the maximum reliability incensement of 95.84 and 71.14. The standard deviation of the solutions obtained by the GA and BFGS were 11.0642, 0.0468, respectively. The CPU times spent by each method to find the optimal solution showed that the BFGS consumed the least computational time effort than GA. As a result, the reliability incensement of the test system can be improved with 95% incensement.

The optimal solution by the BFGS and GA for Double bus-Double breaker test system were shown in Table 4.12 and 4.13. Assume, the lift time is 30 year old for each equipment in substation and average time for maintenance per year in 1.2192 for incoming, 11.2990 for DS1-3, 1.4111 for CB1-2, 1.4060 for DS2-4, 1.2372 for transformer and 1.3836 for CB3. The total cost each equipment in substation for maintenance consider by lift time divided by average time for maintenance. For example incoming equipment has total cost for maintenance is computed by 30/1.2192 equal 24 p.u., if 1 p.u. equal 10,000 baht so total cost for maintenance is 240,000 baht or total cost for maintenance of transformer is 30/1.2372 equal 24 (240,000 baht) etc.

4.3 A case study of Nongki substation

A 115/22 kV Nongki substation was used as a case study for evaluating the failure rate and reliability of substation. This substation is 80 km from Nakhon Ratchasima Provice and around 95 km from buriram provinve; and is controlled and monitored by Dispatching Center (North-East) NakhonRatchasima area 3 (see Figure 4.11). Nongki-substation was employed as a special case to study the effectiveness and performance of the system. It steps down voltage from 115 kV to 22 kV and has bus alignment "*main and transfer bus system*". It has two incoming, two power transformer, two medium voltage bus bars each bus bar have seven feeder lines to distribution load. The single line diagram of Nongki-substation is shown in Figure


Nakhor Ratchasima
Nongki Substation


115/22 KV
TP1,TP2
ONAN/ONAF/ONAF
30/40/50 MVA
CAPACITOR BANK
C1A 240mm2
1BVB–01
500mm2
BUS A
500mm2
5.0
TP2
TP1
BVB–01
2BVB–01
2BVG–01
BUS B
YS–01
YB–01
YS–02
YS–03
2CVB–01
C1B
101
9S-03
4S-03
10S-01
4S-10
CCI03YS-05

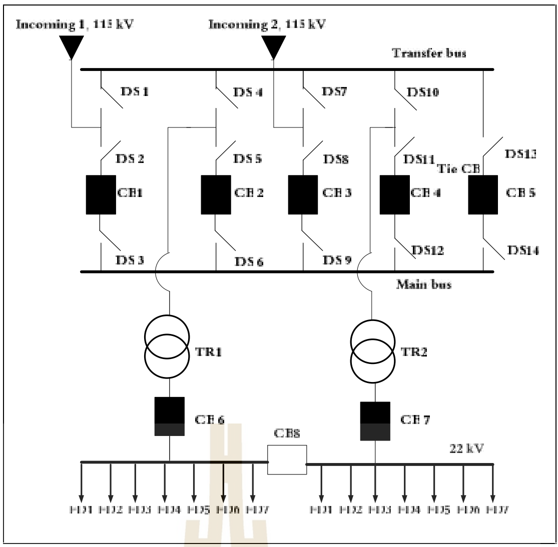


Figure 4.12 Single line diagram of the Nongki substation

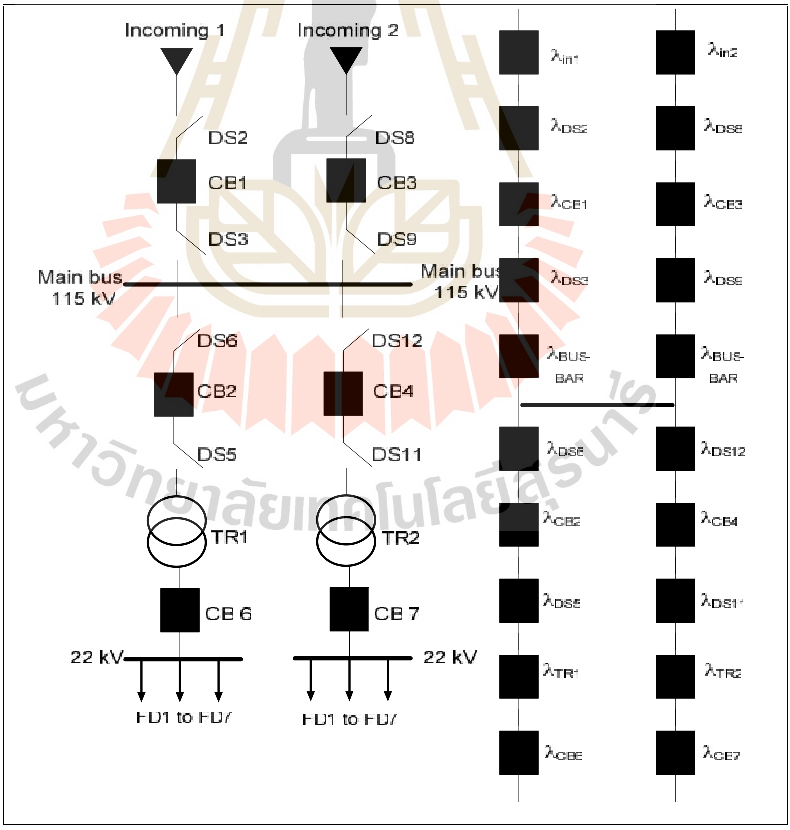


Figure 4.13 The simplified single line diagram of Nongki substation

Figure 4.14 shows the total failure rate of the system (Nongki substation). It compares the total failure rates of the system without preventive maintenance and with preventive maintenance of every 1, 2, 3, 5 and 10 years. It is observed that, generally, the inclusion of preventive maintenance reduces the total system failure rate. By performing the preventive maintenance in the period of 1 year the failure rate of the system is highly reduced compared to when the preventive maintenance period is extended (2, 3, 5, 10 years). Unlikely, when the preventive maintenance period is highly extended i.e. for 10 years in Figure 4.14, small difference of total failure rate is resulted from no maintenance. This means that, when the substation has critically extended preventive maintenance schedule it sometimes becomes close to no maintenance substation with high failure rate. In (Cheng et al., 2014) preventive maintenance was stated to minimize the deterioration or failure rate of the system. On the other side, the higher failure rate can lead to costly operations (Brown, 2004). Although the substation is well maintained it has the possibility to have the same failure rate as the system with no maintenance over a long period of maintenance (see Figure 4.14 beyond 30 abscissa).

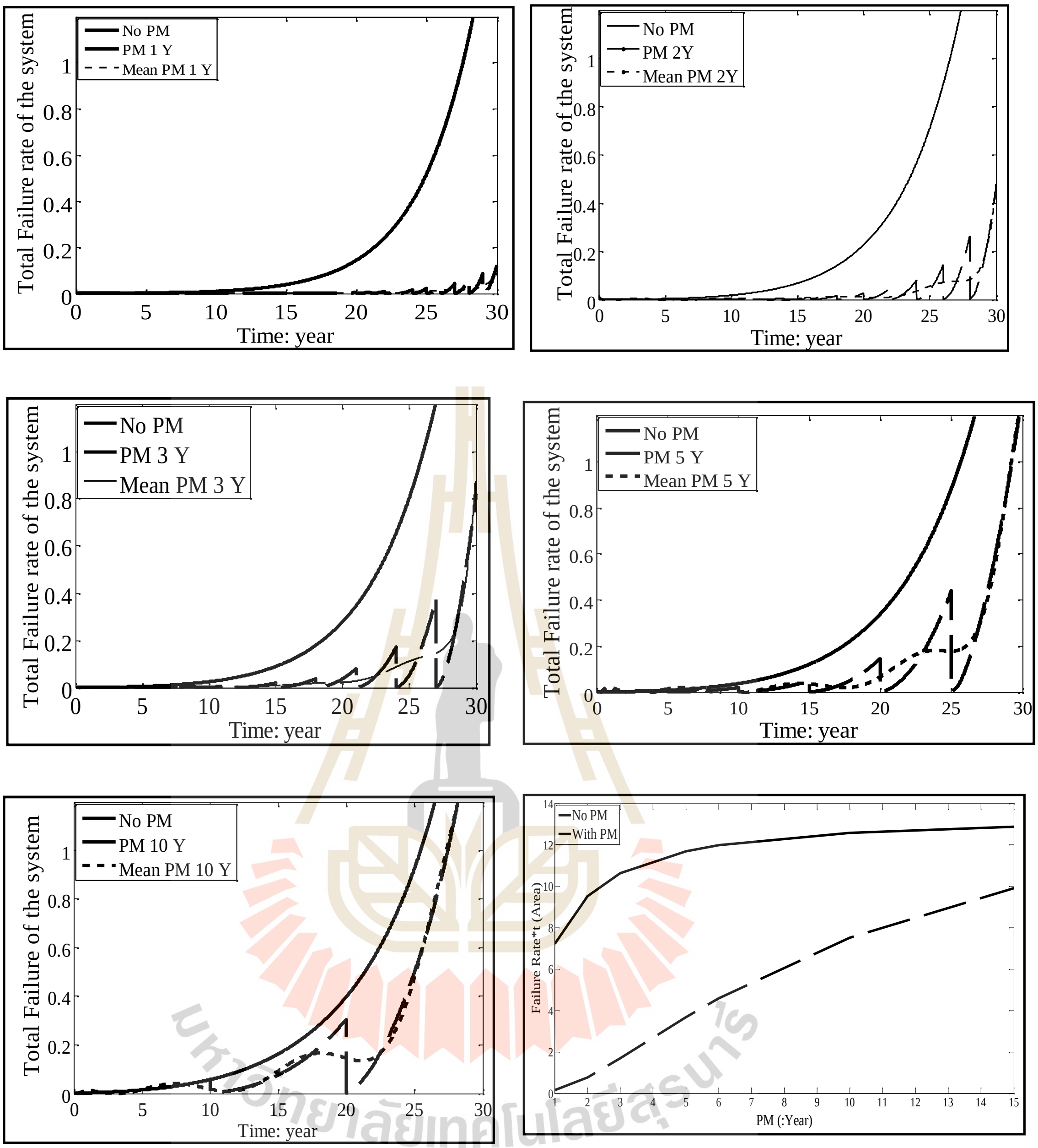


Figure 4.14 Total failure rate of the Nongki substation for every 1, 2, 3, 5, and 10 years of preventive maintenances

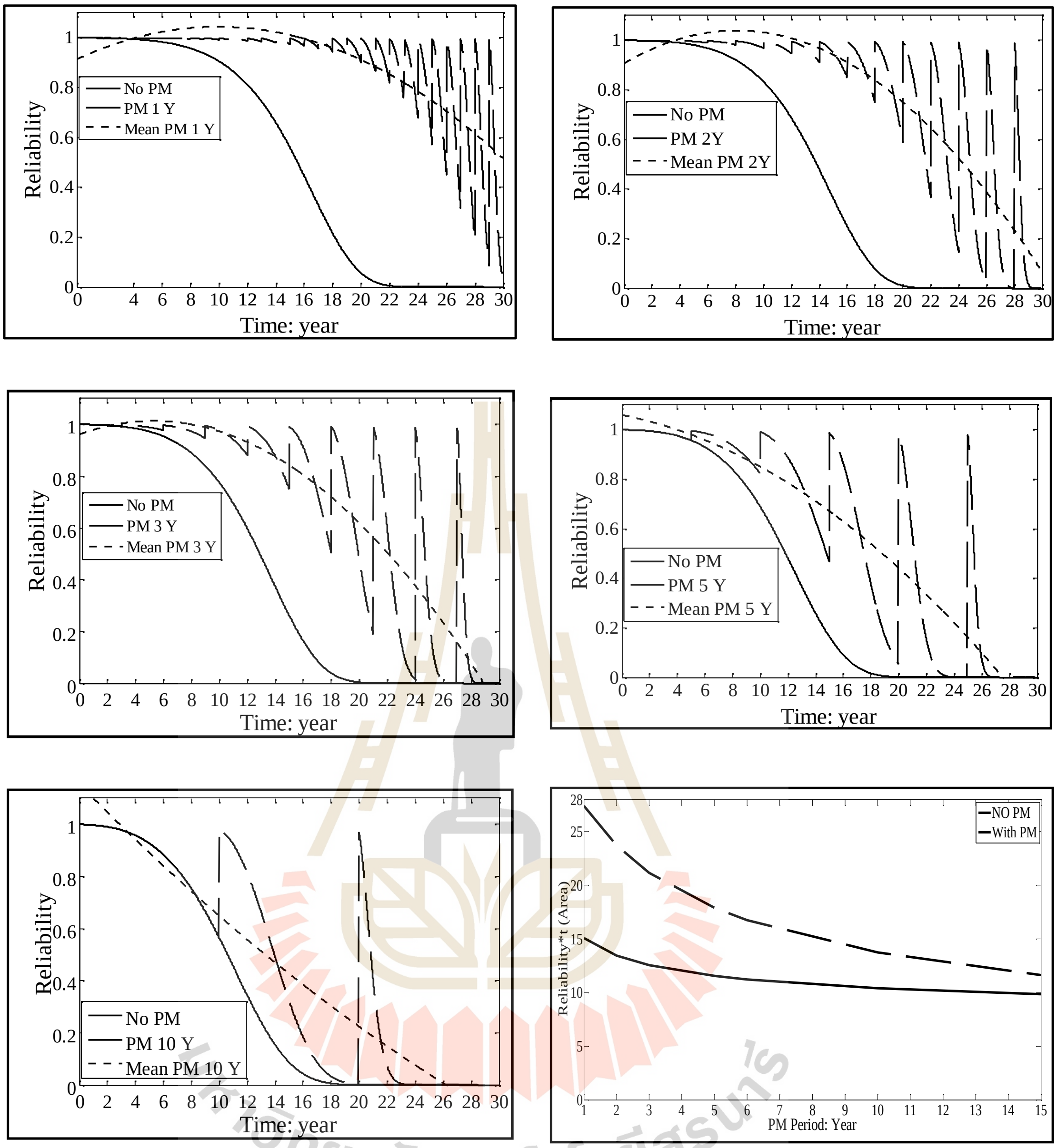


Figure 4.15 Total system reliability of the Nongki substation for every 1, 2, 3, 5, and 10 years of preventive maintenance

reliability of the system. Observation shows that, preventive maintenance in the period of 1 year improves much the reliability of the system compared to when the preventive maintenance period is extended (2, 3, 5, 10 years). This can be seen clearly in Fig 22. When the preventive maintenance period is highly extended i.e. for 10 years in Figure 4.15, small difference of reliability is resulted from no maintenance. In generally, lower system failure rate was achieved by implementation of preventive maintenance in the shorter period (say 1 year for this case). However, the higher reliability was also obtained by implementation of preventive maintenance in the shorter period. This shows that, lowest failure rate and the highest reliability of the system may be obtained together in shorter preventive maintenance.

Also, applying the Genetic Algorithm and BFGS optimization to verify the effectiveness and performance of Nongki substation test system was used for test system. The test was carried out by solving the reliability increment percentage objective. Variable limitation given in Table 4.14 was used as system constraints. For comparison purposes, genetic algorithm, BFGS were applied to solve the test system with various cases. Each method was challenged by solving given reliability increment of 30 trials randomly. Minimum, average, maximum and standard deviation of the 30 trial solutions for Nongki substation test system obtained by each method were evaluated and shown in Table 4.15. For Table 4.16 showed the comparison of CPU time spent by each approach. The optimal control variables obtained by each method were shown in Tables 4.17 to 4.18.

Table 4.14 Variable limits used for reliability increment for Nongki substation

Variable	Limit	
	Min.	Max.
$t_{1,PM}$ to $t_{5,PM}$ (Year)	1.0	10.0
$\cos t_{1,PM}$ to $\cos t_{5,PM}$ (% factor cost reduce from maximum budget)	20	80

Table 4.15 Reliability increment obtained by using GA and BFGA Nongki substation test system

Method	Reliability increment (%)			
	Minimum	Average	Maximum	Deviation
GA	47.4712	51.5919	55.0330	2.0021
BFGS	61.1406	69.0332	74.5752	3.1105

Table 4.16 Computational time to obtain Reliability increment by GA and BFGS for Nongki substation test system

Method	Computational Time (s)			
	Minimum	Average	Maximum	Deviation
GA	23.6464	25.4529	26.5589	0.4866
BFGS	0.1563	0.2929	0.4830	0.0914

The results showed that the GA and BFGS optimal methods gave the best time period solution when compared with those obtained by the GA and BFGS. For Nongki substation test system, the average reliability incensement solutions were 51.59 and 69.03 for the GA and BFGS methods, respectively. BFGS can provide solution is better than GA about 18%. However, when considering the maximum reliability incensement, the GA and BFGS were the two methods that can find the maximum reliability incensement of 55.0330 and 74.5752. The standard deviation of the solutions obtained by the GA and BFGS were 2.0021, 3.1105, respectively. The CPU times spent by each method to find the optimal solution showed that the BFGS consumed the least computational time effort than GA. As a result, the reliability incensement of the test system can be improved with 70% incensement.

Table 4.17 Optimal solution by the BFGS for Nongki substation test system

Variable	Statistic				The cost or budget to maintenance per year (Baht)
	Avg.	STD.	Min.	Max.	
$t_{1,PM}$	5.04	2.69	1.25	9.18	6
$t_{2,PM}$	5.48	2.63	1.17	9.82	5
$t_{3,PM}$	4.62	2.71	1.09	9.46	6
$t_{4,PM}$	6.01	2.24	2.31	9.03	5
$t_{5,PM}$	5.97	2.23	1.49	9.32	3
$t_{6,PM}$	5.97	2.36	1.10	9.71	5
$t_{7,PM}$	6.97	2.42	1.81	9.96	4
$t_{8,PM}$	5.65	2.49	1.15	9.79	5
$t_{9,PM}$	4.75	2.21	1.13	8.03	6
$t_{10,PM}$	5.88	2.55	1.18	9.43	5
$t_{11,PM}$	6.07	2.54	1.16	9.85	5
$t_{12,PM}$	5.37	2.76	1.22	9.75	5
$t_{13,PM}$	5.01	2.93	1.02	9.89	6
$t_{14,PM}$	5.13	2.71	1.06	9.78	5
$t_{15,PM}$	5.96	2.54	1.32	9.87	5
$t_{16,PM}$	5.12	2.93	1.11	9.88	5
$t_{17,PM}$	6.30	2.65	1.57	9.99	4
$t_{18,PM}$	5.98	2.26	1.61	9.61	5
$t_{19,PM}$	5.93	2.44	1.05	9.94	5
$t_{20,PM}$	6.23	2.41	1.97	9.88	4

Table 4.18 Optimal solution by the GA for Nongki substation test system

Variable	Statistic				The cost or budget to maintenance per year (Baht)
	Avg.	STD.	Min.	Max.	
$t_{1,PM}$	8.76	1.14	5.91	9.99	3
$t_{2,PM}$	7.85	1.36	4.42	9.98	3
$t_{3,PM}$	7.96	1.46	4.42	9.96	3
$t_{4,PM}$	8.24	1.55	3.77	9.98	3
$t_{5,PM}$	8.05	1.73	3.51	9.97	3
$t_{6,PM}$	8.26	1.59	4.40	9.99	3
$t_{7,PM}$	7.87	1.70	3.82	9.96	3
$t_{8,PM}$	8.24	1.33	4.98	9.97	3
$t_{9,PM}$	7.93	1.71	3.96	9.98	3
$t_{10,PM}$	7.26	1.78	2.85	9.93	4
$t_{11,PM}$	8.91	1.01	7.44	9.99	3
$t_{12,PM}$	7.80	1.51	5.28	10.0	3
$t_{13,PM}$	7.35	2.22	3.29	9.98	4
$t_{14,PM}$	8.08	1.63	4.27	9.99	3
$t_{15,PM}$	6.88	2.47	1.18	9.99	4
$t_{16,PM}$	8.17	1.45	3.74	9.97	3
$t_{17,PM}$	7.91	2.12	2.37	9.91	3
$t_{18,PM}$	8.26	1.54	4.95	9.99	3
$t_{19,PM}$	8.35	1.28	5.14	9.98	3
$t_{20,PM}$	7.56	1.90	2.33	9.90	3

The optimal solution by the BFGS and GA for Double bus-Double breaker test system were shown in Table 4.17 and 4.18. Assume, the lift time is 30 year old for each equipment in substation and average time for maintenance per year in 5.04 for incoming1-2, 5.48 for DS2-8, 4.62 for CB1-3, 6.01 for DS3-9, 5.97 for BusBar, 6.97

for DS6-12, 5.65 for CB2-4, 4.75 for DS5-11, 5.88 for transformer and 6.07 for CB6-7. The total cost each equipment in substation for maintenance consider by lift time divided by average time for maintenance. For example incoming equipment has total cost for maintenance is computed by 30/5.04 equal 6 p.u., if 1 p.u. equal 10,000 baht so total cost for maintenance is 60,000 baht or total cost for maintenance of transformer is 30/5.88 equal 5 (50,000 baht) etc.

4.4 Chapter summary

This chapter illustrates the result of reliability maintenance in electric power substation systems for each case study and their useful utilizations for considering maximize the reliability of equipment in substation. The results of reliability and failure rate of the simplified bus configuration in single bus-single breaker one bay, double bus-double breaker one bay and the case study of 115/22 kV Nongki substation are also presented in this chapter. The percentage of increment reliability more than 95% of all case study for one year of PM, and more than 50% for five years of PM. Similarly, improved reliability was also obtained in a shorter preventive maintenance. It was concluded that, performing preventive maintenance especially in a shorter period may improve both reliability as well as failure rate of the substation.

Solution methods for solving reliability problems with the increment of reliability area under time objective are described in this thesis. Some efficient search methods in forms of intelligences (e.g. genetic algorithm and BFGS) were employed. The results showed that a set of optimal solutions with respect to the increment of reliability objective can be efficiently solved by using the artificial intelligence. As a result, the GA and BFGS methods showed satisfactory performances of finding the optimal time period maintenance solutions for efficiently operator system.

CHAPTER V

CONCLUSION AND FUTURE WORKS

5.1 Summary of the Thesis

This thesis presents the application of reliability centered maintenance to optimize preventive maintenance period of an electric power substation in which the periods in total failure rate and system reliability were used as the problem objectives. In this work, high voltage substation integrating disconnecting switch, circuit breaker, mains bus bars, transformer was studied for the preventive maintenance of every 1, 2, 3, 5, and 10 years. Other conditions such as substation sensors, grounding, etc. were not considered in the study. The objective functions in the HV substation were simulated through MATLAB software package. An optimal period for performing the preventive maintenance which corresponds to the highest reliability, lowest failure rate and minimum cost was aimed after optimization. In this thesis considers the failure rate and reliability of the simplified arrangement of the HV substation system (single bus-single breaker one bay and double bus-double breaker one bay) and apply to the 115/22 kV Nongki substation located 80 km from Nakhon Ratchasima Province which is controlled and monitored by Dispatching Center (North-East) Nakhon Ratchasima area 3 was used as a case study. It steps down voltage from 115 kV to 22 kV and has bus alignment "main and transfer bus system". Moreover, it has two 115 kV incomings, two power transformer, two medium voltage bus bars (22 kV) each bus bar have seven feeder lines to distribution load. Results showed that lowest system failure rate can easily obtained by performing preventive maintenance in the shortest period (say 1 year for this case). However, the highest reliability was also obtained in the shortest period of preventive maintenance. Therefore, lowest failure rate and the highest reliability of the system were both seen to be obtained in the shorter period of preventive maintenance. Furthermore, the study of optimal cost for performing preventive maintenance showed the successful optimization of the maintenance period. The percentage of increment reliability more than 95% of all case study for one year of PM, and more than 50% for five years of PM. Similarly, improved reliability was also obtained in a shorter preventive maintenance. It was concluded that, performing preventive maintenance especially in a shorter period may improve both reliability as well as failure rate of the substation.

5.2 Suggestion for Future Work

The algorithm in this thesis can support every bus alignment for example, Double -main and single-transfer bus system, Double -bus single-breaker system, Ring - bus system, Breaker and a half system etc. Also, another artificial Intelligent can search parameter for time period maintenance such as differential evolution, particle swarm optimization, artificial bee colony, etc.

REFERENCES

Asgarpoor, S. and Mohamad, D. (1999). A Maintenance Optimization Program for Utilities' Transmission and Distribution Systems. **Proceedings of the 1999 North American Power Symposium**. (pp.454-459)

Balzer, G. (2005). Condition Assessment and Reliability Centered Maintenance of High Voltage Equipment. **Proceedings of 2005 Internatonal Symposium on Electrical Insulating Materials**. B4-1, 259-264.

Balzer, G. and Schorn, C. (2015). Asset Management for Infrastructure Systems: Energy and Water. **Springer: NY**. (pp. 17 – 18).

Balzer, G., Degen, W., Laskowski, K., Halfmann, K., Hartkopf, T., and Neumann, C. (2004). Strategies for Optimizing the Use of Substation Assets. **CIGRE**. B3-101.

Belak, L. Marusa, R., Ferlic, R., and Pihler, J. (2013). Strategic Maintenance of 400-kV Switching Substation. **IEEE Transactions on Power Systems**. Vol. 28(1). pp. 394 – 401. IEEE Publisher.

Bi, P., Xue, J., Ni, J., Zhang, H., Feng, T. and Li, M. (2005). Practice And Strategy For Condition Based Maintenance of Power Supply Equipment, **Conference and Exhibition on Transmission and Distribution: Asia and Pacific**. (1 – 5)

Brown, R. E. (2004). Failure Rate Modeling Using Equipment Inspection Data. **IEEE Transactions on Power Systems**. Vol. 19(2). pp. 782 – 787. IEEE Publisher.

Brown, R. E. (2009). Electric Power Distribution Reliability. 2nd Ed, **Taylor & Francis Group: USA**. (pp. 361 – 370).

Brown, R. E.. (2002). Failure Rate Modeling. **DEStech Publications, Inc: USA**, Vol.2.

Buhler, J., and Balzer, G. (2011). Long-Term Impact Evaluation of Maintenance Activities on MV/LV Substations. **IEEE Trondheim on Power Technology**. pp. 1 – 8. IEEE Publisher.

Carneiro, J. C. (2013). Substation Power Transformer Risk Management: Predictive Methodology Based Reliability Centered Maintenance Data. **4th International Conference on Power Engineering, Energy and Electrical Drives**. 259-264. Instanbul, Turkey: IEEE Publisher.

Carneiro, J. C., Jardini, J. A., and Brittes, J.L.P. (2012). Substation Power Transformer Risk Management: Reflecting on Reliability Centered Maintenance and Monitoring. 6th **IEEE/PES Transmission and Distribution: Latin America Conference and Exposition (T&D-LA)**. 1-8: IEEE Publisher.

Chaidee, E. and Tippachon, W. (2011). Failure Statistics and Condition Evaluation for Power Transformer Maintenance. **Asia-Pacific Power and Energy Engineering Conference (APPEEC)**. (pp. 1 – 4).

Chan, T., Liu, C. C. and Choe, J. W. (2005). Implementation of reliability-centered maintenance for circuit breakers, **Power Engineering Society General Meeting**, Vol. 1, pp. 684 – 690.

Chang, C. S. and Yang, F. (2007). Evolutionary Multi-objective Optimization of Substation Maintenance using Markov Model. **International Conference on Intelligent Systems Applications to Power Systems, 2007. ISAP 2007.** (1-6). Toki Messe, Niigata, Japan: IEEE Publisher.

Cheney, W. and Kincaid, D. (1994). **Numerical mathematics and computing**. Brooks/Cole, Pacific Grove.

Cheng, C., Chen, J., Sun, T. and Liu, M. (2015). A Modified Preventive Model with Failure-rate-reduction under Warranty Consideration. **Scientific Cooperations Workshops on Engineering Branches,** 168-172.

Cheng, C., Zhao, X., Chen, M., and Sun, T. (2014). A Failure-rate-reduction Periodic Preventive Maintenance Model with Delayed Initial Time in a Finite Time Period. **Quality Technology & Quantitative Management**. 11(3): 245-254.

Dutta, P. and Sinha, A. K. (2006). Voltage Stability Constrained Multi-objective Optimal Power Flow using Particle Swarm Optimization. **First International Conference on Industrial and Information Systems**. (pp. 161 – 166). Peradeniya: IEEE Publisher.

Frimpong G. and Taylor, T. (2003). Developing an effective condition based maintenance program for substation equipment", **Rural Electric Power Conference**, pp. C6-1 - C6-9.

Ge, H. and Asgarpoor, S. (2008). An analytical method for optimum maintenance of substations, **Transmission and Distribution Conference and Exposition**, (pp. 1 – 6)

Gill, P. (2009). Electrical Power Equipment Maintenance and Testing. 2nd Ed, **CRC Press: NY**. (pp. 1 – 5).

Hilber, P., Miranda, V., Matos, M. A. and Bertling, (2007). Multiobjective Optimization Applied to Maintenance Policy for Electrical Networks, **IEEE Transactions on Power Systems**, Vol. 22, pp.1675 – 1682.

Hinow, M., and Mevissen, M. (2011). Substation Maintenance Strategy Adaption for Life-Cycle Cost Reduction Using Genetic Algirithm. **IEEE Transaction on Power Delivery**. 26(1): 197-204.

Hu, J.L., Wu, Z., McCann, H., Davis, L.E., and Xie, C.G. (2006). BFGS quasi-Newton method for solving electromagnetic inverse problems. **IEEE Proceedings Microwaves, Antennas and Propagation**. 153(2): 199-204.

IEEE Std. 493-1997. Recommended Practice for the Design of Reliable Indusrtial and Commercial Power Systems. **Power System Reliabiliy Subcommittee of the Power System Engineering Committee of the IEEE Industry Applications Society**. (pp. 4 – 6). New York, USA: IEEE Publisher

Jin, H. (2010). Support System Design for High Voltage Electric Equipment Condition-based Maintenance of Transformer Substation. **Power and Energy Engineering Conference** (**APPEEC**). pp. 1 – 3

Khamphanchai, W., Pisanupoj, S., Ongsakul W., and Pipattanasomporn, M. (2011). A multi-agent based power system restoration approach in distributed smart grid. **International Conference and Utility Exhibition on Power and Energy Systems: Issues and Prospects for Asia (ICUE)**. (pp. 1 – 7). Pattaya City, Thailad: IEEE Publisher.

Krontiris, T. and Balzer, G. (2010). Assessing the effect of maintenance on high-voltage circuit breaker reliability, **International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)**. (pp. 761 – 766).

Ledezma, J., Dortolina, C., Hakelberg, H., and Furuno, K. (2010). Condition Assessment and Asset Management in Electric Power T&D Networks. **CIRED Workshop**. (pp. 1-4): Lyon

Leeton, U., Uthitsunthorn D., Kwannetr ,U., Sisuphun, N., and Kulworawanichpong, T. (2010) Power Loss Minimization Using Optimal Power Flow Based on Partical Swarm Optimization, **International Conference on Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON)**, Chiang Mai, Thailand, pp. 1-5.

Leeton, U., Uthitsunthorn, D., Kwannetr, U., Sinsuphun, N. and Kulworawanichpong, T. (2010) Power Loss Minimization Using Optimal Power Flow Based on Particle Swarm Optimization, **IEEE Xplore**, I July 28,2010.

MLA, (2017). What Is the Genetic Algorithm? - MATLAB & Simulink, https://www.mathworks.com/help/gads/what-is-the-genetic-algorithm.html (accessed June 10, 2017).

Mohamed A. E. and Dalal, H. H. (2010). Predictive Maintenance Strategy Based on Disturbance Recorders. **The Online Journal on Power and Energy Engineering** (**OJPEE**), Vol. 1(3). pp.99-105.

Morteza, A. and Habib, R.M. (2013). Circuit breakers maintenance planning for composite power systems. **IET Generation Transmission & Distribution**, Vol. 7. pp.1135 - 1143

Natti, S. and Kezunovic, M. (2007). Model for Quantifying the Effect of Circuit Breaker Maintenance Using Condition-Based Data, **Power Tech**, pp. 1605 – 1610.

Noor, M., and Junaizee, M. (2004). Application of a Knowledge-based Expert System to High-voltage Transmission Line Maintenance, **International Energy Transmission and Distribution Conference & Exhibition**, pp. 862.

Pansrisu, S. and Premrudeepreechacharn, S. (2010). Preventive maintenance optimization for excitation system of bhumibol hydro power plant. **Proceedings of the International Conference on Energy and Sustainable Development**. (pp. 1 – 6)

Pham, D.T., and Karaboga D., "Intelligent Optimization Techniques", 1998.

Pharmatrisanti, A., Meijer, S. and Smit, JJ. (2006). Applying Condition-Based Maintenance on HV and EHV GIS Operated under Tropical Condition and Heterogeneous Power System, **International Conference on Properties and applications of Dielectric Materials**, pp.673 – 676

Pourahmandi, F., Fotuhi-Firuzabad, M., and Dehghanian, P. (2017). Application of Game Theory in Reliability Centered Maintenance of Electric Power Systems. **IEEE Transaction on Industry Applications**. 53(2): 936-946.

Romeu,J. L. (2004). Understanding Series and Parallel Systems Reliability**, START 2004-5 S&P SYSREL,** Vol. 11, No. 5, (pp. 1-8).

Ruijters, E., Guck, D., Drolenga, P. and Stoelinga, M. (2016). Fault Maintenance Trees: Reliability Centered Maintenance via Statistical Model Checking. **IEEE Transaction on Industry Applications**. 53(2): 936-946.

Sabouhi, H., Fotuhi-Firuzabad, M., and Dehghanian, P. (2016). Identifying Critical Components of Combined Cycle Power Plants for Implementation of Reliability-Centered Maintenance. **CSEE Journal of Power and Energy Systems**. 2(2): 87-97.

Sang, H., Wang, G. and Zhou, Z. (2007). Evolutionary multi-objective optimization of inspection frequencies for substation condition-based maintenance. **International Forum on Strategic Technology** (**IFOST**). Vol. 1, pp. 480 – 486.

Schlabbach, J. and Berka, T. (2001). Reliability-centred maintenance of MV circuit-breakers, **IEEE Porto Power Tech Proceedings**,Vol. 4

Sebo, S.A., Caldecott, R., Kasten, D.G., Wang, S.,. Leach, J.A and Vinh, T. (2001). Magnetic flux density measurement techniques to analyze 345kV circuit breaker maintenance operations", **IEEE Porto Power Tech Proceedings**, Vol.4

Shanno, D.F. (1970). Conditioning of quasi-Newton methods for function minimization. **Mathematic Computation**. Vol. 24, (pp. 647–656).

Smith, A. M., and Hinchcliffe, G. R. (2004). RCM- Gateway to World Class Maintenance. **Oxford, MA, USA: Butterworth-Heinemann**.

Smith, R. and Mobley, R. K. (2011). Rule of Thumb for Maintenance and Reliability Engineers. **Butterworth-Heinemann**, (pp. 336)

Smithy, R., and Mobley, K. R. (2012). Rules of Thumb for Maintenance and Reliability Engineers. **GPP**. (pp. 5 – 6).

So, C. W. and Li, K. K. (2000). Overcurrent relay coordination by evolutionary programming, **Electric Power System Research**, vol.53, pp. 83–90.

Wang, L., Zheng, E., Li, Y., Wang, B. and Wu, J. (2009). Maintenance optimization of generating equipment based on a condition-based maintenance policy for multi-unit systems, **Control and Decision Conference**, (pp. 2440 – 2445).

Wardani, N.U.A., Purnomoadi, A.P., Septiani, H.I., Arifianto, I., Cahyono, B. (2011). Condition assessment of 500/150 kV power transformer based on condition based maintenance, **International Conference on Electrical Engineering and Informatics (ICEEI)**. (pp. 1 – 4).

Wibisana, Y., Wibowo, R.S. and Arifianto, I. (2012). The condition-based maintenance concept for 500 kV circuit breakers in PLN P3B Jawa Bali — Indonesia. **International Conference on Condition Monitoring and Diagnosis (CMD)**. (pp. 529 – 532).

Wu, Y. R. and Zhao, H. S. (2010). Optimization maintenance of wind turbines using Markov decision processes. **International Conference on Power System Technology (POWERCON)**. (pp. 1 – 6).

Xu, X., Kezunovic, M. and Wong, D. (2002). Agent-oriented approach to work order management for circuit breaker maintenance", **Power Engineering Society Summer Meeting**, Vol. 1, pp. 553 – 558.

Yin, H., Wang, Y., Wu, G. and Liu, Y. (2008). Discussion on Condition-based Maintenance for Electric Equipments in Chongqing Electric Power Corporation, **International Conference on High Voltage Engineering and Application**, (pp. 613 – 615).

Zhang, Y., Mu, B., and Zheng, H. (2013). Link Between and Comparison and Combination of Zhang Neural Network and Quasi-Newton BFGS Method for Time- Varying Quadratic Minimization. **IEEE Transactions on Cybernetics**. 43(2): 490-503.

APPENDIX A

SOURCE CODE PROGRAMING OF OPTIMAL RELIABILITY STRATEGY MAINTENANCE

The source code program in this thesis used MATLAB program version 2014 installed in the computer specification by Intel®, Core (TM) i5-6200U, CPU @2.3 GHz, 4.0 GB RAM.. The BFGS method in MATLAB optimization toolbox is employed. The *fminunc* function uses (among other methods) the BFGS Quasi-Newton method. Also, the GA is chosen to build up an algorithm to solve optimal reliability problems, the Genetic Algorithm (GADS TOOLBOX in MATLAB) is employed to produce a set of initial random parameters.

A.1 Objective function for Single bus single bay test system

```
function [f]=obj_reliability(TOPM)
global rho CC
CC=3;
Amax =[10       10       10       10       10      CC*(1/1)];
Amin =[1        1        1        1        1       CC*(1/10)];
%Define parameter of equipment in substation included
%Tpm is Time of preventive maintenance (year)
%Tf is Expected lifetime (year)
%=====Defining Parameter ==============================
%  [A          B          C               Tf            Tpm]
emt =[0.01976    3.4295969   -0.009756098    30            TOPM(1);%Inc
     0.00021     7.3142615  -0.001788079    30            TOPM(2);%DS
     0.00223     3.3214624  -0.001728395    30            TOPM(3);%CB1
     0.01565     2.2478602  -0.008148148    30            TOPM(4);%TR
     0.00223     3.3214624  -0.001728395    30            TOPM(5)];%CB2
%=========END Of Defining Parameter ======================
Tf =max(emt(:,4));  %Expected lifetime (year)
x =0:0.01:1;
t =x*Tf;
Tpm =emt(:,5);  %PM cycle (year)
Tch =Tpm;
LAM0 =zeros(1,length(Tch));
for h=1:length(Tpm)
    for k=1:length(t)
        lam(h,k)=emt(h,1)*exp(emt(h,2)*x(k))+emt(h,3);
        LAMP(h,k)=lam(h,k)-LAM0(h);
        if t(k)>=Tch(h)
            LAM0(h)=lam(h,k)-lam(h,1);
            Tch(h)=Tch(h)+Tpm(h);
        end
    end
end
```

```
%Series of Failure Rate
for u=1:length(t)
    lamT(u) = sum(lam(:,u));
    LAMPT(u) = sum(LAMP(:,u));
end
%F1 and F2 are Reliability R(t)=exp(-FR*t)
F1 =exp(-lamT.*t);
F2 =exp(-LAMPT.*t);
%Mean Reliability after PM
a =polyfit(t,F2,3);
MF2 =polyval(a,t);

F1_area =0;
F2_area =0;
MF2_area =0;
for u=1:length(t)
 if u>1
        F1_area =F1_area +F1(u)*(t(u)-t(u-1));
        F2_area =F2_area +F2(u)*(t(u)-t(u-1));
        MF2_area =MF2_area +MF2(u)*(t(u)-t(u-1));
    else
        F1_area =F1_area +F1(u)*t(u);
        F2_area =F2_area +F2(u)*t(u);
        MF2_area =MF2_area +MF2(u)*t(u);
    end

end

Inc_per =((F2_area-F1_area)/F1_area)*100;

%Cost of PM refer to FR
CS =1/TOPM(1)+1/TOPM(2)+1/TOPM(3)+1/TOPM(4)+1/TOPM(5);

objective_function=-Inc_per;

%=======make Penalty Function================
Var =[TOPM CS];
PT =0; %panelty Term
for k=1:length(Var)
    up(k)=0;
    down(k)=0;
    if Var(k)>Amax(k)
        up(k)=rho*(Var(k)-Amax(k))^2;
    elseif Amin(k)>Var(k)
        down(k)=rho*(Amin(k)-Var(k))^2;
    end
    PT=PT+up(k)+down(k);
end
f=objective_function+PT;
return
```

A.2 Main Run by GA for Single bus single bay test system

```
clc;
clear all;
close all;
global rho
rho=1e6;
Amax =[10      10      10      10      10];
Amin =[1       1       1       1       1];

for kk=1:30
    fprintf('iter %d\n',kk);
    tic
    rand('state',sum(100*clock))
    numberOfVariables=length(Amax);
    fobj001 =@obj_reliability;
    optionsGA =gaoptimset('PopulationType','doubleVector',...
        'PopInitRange',[Amin;Amax],...
        'PopulationSize',50,...
        'CrossoverFraction', 0.8000,...
        'Generations',1000);
 [xopt,fval,EXITFLAG,OUTPUT]=
ga(fobj001,numberOfVariables,[],[],[],[],[],[],[],optionsGA);

    tcpc(kk)=toc;
    tpm1(kk)=xopt(1);
    tpm2(kk)=xopt(2);
    tpm3(kk)=xopt(3);
    tpm4(kk)=xopt(4);
    tpm5(kk)=xopt(5);
    fRilia(kk)=fval;
end

%=======mean============
mean_tcpc=mean(tcpc)
mean_tpm1=mean(tpm1)
mean_tpm2=mean(tpm2)
mean_tpm3=mean(tpm3)
mean_tpm4=mean(tpm4)
mean_tpm5=mean(tpm5)
mean_fRilia=mean(fRilia)

%=======std==============
std_tcpc=std(tcpc)
std_tpm1=std(tpm1)
std_tpm2=std(tpm2)
std_tpm3=std(tpm3)
std_tpm4=std(tpm4)
std_tpm5=std(tpm5)
std_fRilia=std(fRilia)
```

```
%========max===============
max_tcpc=max(tcpc)
max_tpm1=max(tpm1)
max_tpm2=max(tpm2)
max_tpm3=max(tpm3)
max_tpm4=max(tpm4)
max_tpm5=max(tpm5)
max_fRilia=max(fRilia)

%========min===============
min_tcpc=min(tcpc)
min_tpm1=min(tpm1)
min_tpm2=min(tpm2)
min_tpm3=min(tpm3)
min_tpm4=min(tpm4)
min_tpm5=min(tpm5)
min_fRilia=min(fRilia)
```

A.3 Main Run by BFGS for Single bus single bay test system

```
clc;
clear all;
close all;
global rho
rho=1e6;
Amax =[10      10      10      10      10];
Amin =[1       1       1       1       1];
for kk=1:30
    fprintf('iter %d\n',kk);
    tic
    rand('state',sum(100*clock))
    options=
optimset('MaxFunEvals',1000000000,'MaxIter',100000000,'TolX',1e-10);
    for n=1:length(Amax)
        x0(n)=Amin(n)+(Amax(n)-Amin(n))*rand;
    end
 [xopt, fopt, exitflag, output]=fminunc('obj_reliability',x0,options);
    xopt=xopt;
    fval=fopt;
    tcpc(kk)=toc;
    tpm1(kk)=xopt(1);
    tpm2(kk)=xopt(2);
    tpm3(kk)=xopt(3);
    tpm4(kk)=xopt(4);
    tpm5(kk)=xopt(5);
    fRilia(kk)=fval;
end
```

```
%=======mean==============
mean_tcpc=mean(tcpc)
mean_tpm1=mean(tpm1)
mean_tpm2=mean(tpm2)
mean_tpm3=mean(tpm3)
mean_tpm4=mean(tpm4)
mean_tpm5=mean(tpm5)
mean_fRilia=mean(fRilia)
%=======std==============
std_tcpc=std(tcpc)
std_tpm1=std(tpm1)
std_tpm2=std(tpm2)
std_tpm3=std(tpm3)
std_tpm4=std(tpm4)
std_tpm5=std(tpm5)
std_fRilia=std(fRilia)
%=======max==============
max_tcpc=max(tcpc)
max_tpm1=max(tpm1)
max_tpm2=max(tpm2)
max_tpm3=max(tpm3)
max_tpm4=max(tpm4)
max_tpm5=max(tpm5)
max_fRilia=max(fRilia)
%=======min==============
min_tcpc=min(tcpc)
min_tpm1=min(tpm1)
min_tpm2=min(tpm2)
min_tpm3=min(tpm3)
min_tpm4=min(tpm4)
min_tpm5=min(tpm5)
min_fRilia=min(fRilia)
```

A.4 Objective function for Double bus Double bay test system

```
clc;
clear all;
close all;
global rho
rho=1e6;
Amax =[10      10      10      10      10];

function [f]=obj_reliability(TOPM)
global rho CC
CC=8;
Amax =[10       10       10       10       10     10       10       10
10      10     CC*(1/1)];
Amin =[1       1       1       1       1     1       1       1       1
1      CC*(1/10)];
```

```
%Define parameter of equipment in substation included
%Tpm is Time of preventive maintenance (year)
%Tf is Expected lifetime (year)
%================Defining Parameter ========================
% [A          B          C                Tf            Tpm]
emt =[0.01976   3.4295969  -0.009756098   30            TOPM(1);%Inc1
     0.00021    7.3142615  -0.001788079   30            TOPM(2);%DS1
     0.00223    3.3214624  -0.001728395   30            TOPM(3);%CB1
     0.00021    7.3142615  -0.001788079   30            TOPM(4);%DS2
     0.01976    3.4295969  -0.009756098   30            TOPM(5);%Inc2
     0.00021    7.3142615  -0.001788079   30            TOPM(6);%DS3
     0.00223    3.3214624  -0.001728395   30            TOPM(7);%CB2
     0.00021    7.3142615  -0.001788079   30            TOPM(8);%DS4
     0.01565    2.2478602  -0.008148148   30            TOPM(9);%TR
     0.00223    3.3214624  -0.001728395   30            TOPM(10)];%CB3
%===========END Of Defining Parameter ========================

Tf =max(emt(:,4));  %Expected lifetime (year)
x =0:0.01:1;
t =x*Tf;
Tpm =emt(:,5);  %PM cycle (year)
Tch =Tpm;
LAM0 =zeros(1,length(Tch));

for h=1:length(Tpm)
    for k=1:length(t)
        lam(h,k)=emt(h,1)*exp(emt(h,2)*x(k))+emt(h,3);
        LAMP(h,k)=lam(h,k)-LAM0(h);
        if t(k)>=Tch(h)
            LAM0(h)=lam(h,k)-lam(h,1);
            Tch(h)=Tch(h)+Tpm(h);
        end
    end
end

%Series Conponent:Double-bus, Double-breaker system
for u=1:length(t)
    lam14(u)=sum(lam(1:4,u));
    LAMP14(u)=sum(LAMP(1:4,u));
end

for u=1:length(t)
    lam58(u)=sum(lam(5:8,u));
    LAMP58(u)=sum(LAMP(5:8,u));
end

for u=1:length(t)
    lam910(u)=sum(lam(9:10,u));
    LAMP910(u)=sum(LAMP(9:10,u));
end

lam1 =lam14;
```

```
lam2 = lam58;

T = 30; % survive mission tim (year)
for kk=1:length(t)
    lam_Paral(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
end

lam1 = LAMP14;
lam2 = LAMP58;
for kk=1:length(t)
    LAM_Paral(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
end

lamT = lam910 + lam_Paral;
LAMPT = LAMP910 + LAM_Paral;

%F1 and F2 are Reliability R(t)=exp(-FR*t)
F1 = exp(-lamT.*t);
F2 = exp(-LAMPT.*t);

%Mean Reliability after PM
a = polyfit(t,F2,3);
MF2 = polyval(a,t);

F1_area = 0;
F2_area = 0;
MF2_area = 0;
for u=1:length(t)
    if u>1
        F1_area = F1_area + F1(u)*(t(u)-t(u-1));
        F2_area = F2_area + F2(u)*(t(u)-t(u-1));
        MF2_area = MF2_area + MF2(u)*(t(u)-t(u-1));
    else
    F1_area = F1_area + F1(u)*t(u);
        F2_area = F2_area + F2(u)*t(u);
        MF2_area = MF2_area + MF2(u)*t(u);
    end

end

Inc_per = ((F2_area-F1_area)/F1_area)*100;

%Cost of PM refer to FR
CS=
1/TOPM(1)+1/TOPM(2)+1/TOPM(3)+1/TOPM(4)+1/TOPM(5)+1/TOPM(6)+1/TOPM(7)+1/TOPM(8)+1/TOPM(9)+
1/TOPM(10);

objective_function=-Inc_per;
```

```
%=======make Penalty Function==================
Var =[TOPM CS];
PT =0; %panelty Term
for k=1:length(Var)
    up(k)=0;
    down(k)=0;
    if Var(k)>Amax(k)
        up(k)=rho*(Var(k)-Amax(k))^2;
    elseif Amin(k)>Var(k)
        down(k)=rho*(Amin(k)-Var(k))^2;
    end
    PT=PT+up(k)+down(k);
end
f=objective_function+PT;
return
```

A.5 Main Run by GA for Double bus Double bay test system

```
clc;clear all;close all;
global rho
rho=1e6;
Amax =[10       10       10       10       10       10       10       10
10       10];
Amin =[1        1        1        1        1        1        1        1
1        1];
for kk=1:30
    fprintf('iter %d\n',kk);
    tic
    rand('state',sum(100*clock))
    numberOfVariables=length(Amax);
    fobj001 =@obj_reliability;
    optionsGA =gaoptimset('PopulationType','doubleVector',...
        'PopInitRange',[Amin;Amax],...
        'PopulationSize',50,...
        'CrossoverFraction', 0.8000,...
        'Generations',1000);
 [xopt,fval,EXITFLAG,OUTPUT]                                          =
ga(fobj001,numberOfVariables,[],[],[],[],[],[],[],optionsGA);
    tcpc(kk)=toc;
    tpm1(kk)=xopt(1);
    tpm2(kk)=xopt(2);
    tpm3(kk)=xopt(3);
    tpm4(kk)=xopt(4);
    tpm5(kk)=xopt(5);
    tpm6(kk)=xopt(6);
    tpm7(kk)=xopt(7);
    tpm8(kk)=xopt(8);
    tpm9(kk)=xopt(9);
    tpm10(kk)=xopt(10);
```

```
    fRilia(kk)=fval;
end
%=======mean=============
mean_tcpc=mean(tcpc)
mean_tpm1=mean(tpm1)
mean_tpm2=mean(tpm2)
mean_tpm3=mean(tpm3)
mean_tpm4=mean(tpm4)
mean_tpm5=mean(tpm5)
mean_tpm6=mean(tpm6)
mean_tpm7=mean(tpm7)
mean_tpm8=mean(tpm8)
mean_tpm9=mean(tpm9)
mean_tpm10=mean(tpm10)
mean_fRilia=mean(fRilia)
%=======std=============
std_tcpc=std(tcpc)
std_tpm1=std(tpm1)
std_tpm2=std(tpm2)
std_tpm3=std(tpm3)
std_tpm4=std(tpm4)
std_tpm5=std(tpm5)
std_tpm6=std(tpm6)
std_tpm7=std(tpm7)
std_tpm8=std(tpm8)
std_tpm9=std(tpm9)
std_tpm10=std(tpm10)
std_fRilia=std(fRilia)
%=======max=============
max_tcpc=max(tcpc)
max_tpm1=max(tpm1)
max_tpm2=max(tpm2)
max_tpm3=max(tpm3)
max_tpm4=max(tpm4)
max_tpm5=max(tpm5)
max_tpm6=max(tpm6)
max_tpm7=max(tpm7)
max_tpm8=max(tpm8)
max_tpm9=max(tpm9)
max_tpm10=max(tpm10)
max_fRilia=max(fRilia)
%=======min=============
min_tcpc=min(tcpc)
min_tpm1=min(tpm1)
min_tpm2=min(tpm2)
min_tpm3=min(tpm3)
min_tpm4=min(tpm4)
min_tpm5=min(tpm5)
min_tpm6=min(tpm6)
min_tpm7=min(tpm7)
```

```
min_tpm8=min(tpm8)
min_tpm9=min(tpm9)
min_tpm10=min(tpm10)
min_fRilia=min(fRilia)
```

A.6 Main Run by BFGS for Double bus Double bay test system

```
clc;clear all;close all;
global rho
rho=1e6;
Amax =[10        10        10        10        10        10        10        10
10        10        10        10        10        10        10        10        10
10        10        10];
Amin =[1         1         1         1         1         1         1         1
1         1         1         1         1         1         1         1         1
1         1         1];
for kk=1:1
    fprintf('iter %d\n',kk);
    tic
 %***********start OPT by BFGS************************
    rand('state',sum(100*clock))
    options                                                                  =
optimset('MaxFunEvals',1000000000,'MaxIter',100000000,'TolX',1e-10);
    for n=1:length(Amax)
        x0(n)=Amin(n)+(Amax(n)-Amin(n))*rand;
    end
 [xopt, fopt, exitflag, output]=fminunc('obj_reliability',x0,options);
    tcpc(kk)=toc;
    tpm1(kk)=xopt(1);
    tpm2(kk)=xopt(2);
    tpm3(kk)=xopt(3);
    tpm4(kk)=xopt(4);
    tpm5(kk)=xopt(5);
    tpm6(kk)=xopt(6);
    tpm7(kk)=xopt(7);
    tpm8(kk)=xopt(8);
    tpm9(kk)=xopt(9);
    tpm10(kk)=xopt(10);
    tpm11(kk)=xopt(11);
    tpm12(kk)=xopt(12);
    tpm13(kk)=xopt(13);
    tpm14(kk)=xopt(14);
    tpm15(kk)=xopt(15);
    tpm16(kk)=xopt(16);
    tpm17(kk)=xopt(17);
    tpm18(kk)=xopt(18);
    tpm19(kk)=xopt(19);
    tpm20(kk)=xopt(20);
    fRilia(kk)=fval;
end
%=======mean==============
```

```
mean_tcpc=mean(tcpc)
mean_tpm1=mean(tpm1)
mean_tpm2=mean(tpm2)
mean_tpm3=mean(tpm3)
mean_tpm4=mean(tpm4)
mean_tpm5=mean(tpm5)
mean_tpm6=mean(tpm6)
mean_tpm7=mean(tpm7)
mean_tpm8=mean(tpm8)
mean_tpm9=mean(tpm9)
mean_tpm10=mean(tpm10)
mean_tpm11=mean(tpm11)
mean_tpm12=mean(tpm12)
mean_tpm13=mean(tpm13)
mean_tpm14=mean(tpm14)
mean_tpm15=mean(tpm15)
mean_tpm16=mean(tpm16)
mean_tpm17=mean(tpm17)
mean_tpm18=mean(tpm18)
mean_tpm19=mean(tpm19)
mean_tpm20=mean(tpm20)
mean_fRilia=mean(fRilia)
%=======std==============
std_tcpc=std(tcpc)
std_tpm1=std(tpm1)
std_tpm2=std(tpm2)
std_tpm3=std(tpm3)
std_tpm4=std(tpm4)
std_tpm5=std(tpm5)
std_tpm6=std(tpm6)
std_tpm7=std(tpm7)
std_tpm8=std(tpm8)
std_tpm9=std(tpm9)
std_tpm10=std(tpm10)
std_tpm11=std(tpm11)
std_tpm12=std(tpm12)
std_tpm13=std(tpm13)
std_tpm14=std(tpm14)
std_tpm15=std(tpm15)
std_tpm16=std(tpm16)
std_tpm17=std(tpm17)
std_tpm18=std(tpm18)
std_tpm19=std(tpm19)
std_tpm20=std(tpm20)
std_fRilia=std(fRilia)
%=======max==============
max_tcpc=max(tcpc)
max_tpm1=max(tpm1)
max_tpm2=max(tpm2)
max_tpm3=max(tpm3)
```

```
max_tpm4=max(tpm4)
max_tpm5=max(tpm5)
max_tpm6=max(tpm6)
max_tpm7=max(tpm7)
max_tpm8=max(tpm8)
max_tpm9=max(tpm9)
max_tpm10=max(tpm10)
max_tpm11=max(tpm11)
max_tpm12=max(tpm12)
max_tpm13=max(tpm13)
max_tpm14=max(tpm14)
max_tpm15=max(tpm15)
max_tpm16=max(tpm16)
max_tpm17=max(tpm17)
max_tpm18=max(tpm18)
max_tpm19=max(tpm19)
max_tpm20=max(tpm20)
max_fRilia=max(fRilia)
%=======min==============
min_tcpc=min(tcpc)
min_tpm1=min(tpm1)
min_tpm2=min(tpm2)
min_tpm3=min(tpm3)
min_tpm4=min(tpm4)
min_tpm5=min(tpm5)
min_tpm6=min(tpm6)
min_tpm7=min(tpm7)
min_tpm8=min(tpm8)
min_tpm9=min(tpm9)
min_tpm10=min(tpm10)
min_tpm11=min(tpm11)
min_tpm12=min(tpm12)
min_tpm13=min(tpm13)
min_tpm14=min(tpm14)
min_tpm15=min(tpm15)
min_tpm16=min(tpm16)
min_tpm17=min(tpm17)
min_tpm18=min(tpm18)
min_tpm19=min(tpm19)
min_tpm20=min(tpm20)
min_fRilia=min(fRilia)
```

A.7 Objective function for Nongki substation Test Study

```
clc;clear all;close all;
function [f]=obj_reliability(TOPM)
global rho CC
CC=16;
```

```
Amax  =[10         10         10         10         10      10         10         10
10         10      10         10         10         10         10      10         10
10       10       10       CC*(1/1)];
Amin  =[1         1         1         1         1      1         1         1         1
1        1         1         1         1         1      1         1         1
1        1      CC*(1/10)];
%Define parameter of equipment in substation included
%Tpm is Time of preventive maintenance (year)
%Tf is Expected lifetime (year)
%===============Defining Parameter ==============================
%  [A           B           C               Tf            Tpm]
emt =[0.01976    3.4295969   -0.009756098    30           TOPM(1);%Inc1
     0.00021     7.3142615   -0.001788079    30           TOPM(2);%DS2,8
     0.00223     3.3214624   -0.001728395    30           TOPM(3);%CB1,3
     0.00021     7.3142615   -0.001788079    30           TOPM(4);%DS3,9
     0.00160     3.8767259   -0.00109734530            TOPM(5);%BusBar12
     0.00021     7.3142615   -0.001788079    30           TOPM(6);%DS6,12
     0.00223     3.3214624   -0.001728395    30           TOPM(7);%CB2,4
     0.00021     7.3142615   -0.001788079    30           TOPM(8);%DS4   5
  0.01565     2.2478602  -0.008148148    30            TOPM(9);%TR1,2
     0.00223     3.3214624   -0.001728395    30           TOPM(10);
     0.01976     3.4295969   -0.009756098    30          TOPM(11);%Inc1
     0.00021     7.3142615   -0.001788079    30           TOPM(12);%DS2,8
     0.00223     3.3214624   -0.001728395    30           TOPM(13);%CB1,3
     0.00021     7.3142615   -0.001788079    30           TOPM(14);%DS3,9
     0.00160     3.8767259   -0.001097345 30             TOPM(15);%BusBar
     0.00021     7.3142615   -0.001788079    30           TOPM(16);%DS6
     0.00223     3.3214624   -0.001728395    30           TOPM(17);%CB2,4
     0.00021     7.3142615   -0.001788079    30           TOPM(18);%DS4   5,11
     0.01565     2.2478602   -0.008148148    30           TOPM(19);%TR1,2
     0.00223     3.3214624   -0.001728395    30           TOPM(20)];%CB6,7
%=============END Of Defining Parameter ================
Tf =max(emt(:,4));  %Expected lifetime (year)
x =0:0.01:1;
t =x*Tf;
Tpm =emt(:,5);  %PM cycle (year)
Tch =Tpm;
LAM0 =zeros(1,length(Tch));
for h=1:length(Tpm)
    for k=1:length(t)
        lam(h,k)=emt(h,1)*exp(emt(h,2)*x(k))+emt(h,3);
        LAMP(h,k)= lam(h,k)-LAM0(h);
        if t(k)>=Tch(h)
            LAM0(h)= lam(h,k)-lam(h,1);
            Tch(h)=Tch(h)+Tpm(h);
        end
    end
end
%Series Conponent:Main and Transfer
for u=1:length(t)
    lam15(u)=sum(lam(1:5,u));
```

```
    LAMP15(u) = sum(LAMP(1:5,u));
end

for u=1:length(t)
    lam610(u) = sum(lam(6:10,u));
    LAMP610(u) = sum(LAMP(6:10,u));
end

for u=1:length(t)
    lam1115(u) = sum(lam(11:15,u));
    LAMP1115(u) = sum(LAMP(11:15,u));
end

for u=1:length(t)
    lam1620(u) = sum(lam(16:20,u));
    LAMP1620(u) = sum(LAMP(16:20,u));
end
%Parallel Component:Before Bus
lam1 = lam15;
lam2 = lam1115;
T = 30; %survive mission tim (year)
for kk=1:length(t)
    lam_Paral_up(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
End
lam1 = LAMP15;
lam2 = LAMP1115;
for kk=1:length(t)
    LAM_Paral_up(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
end
%Parallel Component:After Bus
lam1 = lam610;
lam2 = lam1620;
T =30; %survive mission tim (year)
for kk=1:length(t)
    lam_Paral_dn(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
end
lam1 = LAMP610;
lam2 = LAMP1620;
for kk=1:length(t)
    LAM_Paral_dn(kk) = (lam1(kk)*exp(-lam1(kk)*T) + lam2(kk)*exp(-lam2(kk)*T)-(lam1(kk)+lam2(kk))*exp(-(lam1(kk)+lam2(kk))*T))/...
  (exp(-lam1(kk)*T) + exp(-lam2(kk)*T)- exp(-(lam1(kk)+lam2(kk))*T));
end
lamT = lam_Paral_up + lam_Paral_dn;
LAMPT = LAM_Paral_up + LAM_Paral_dn;
FR1 = lamT;
```

```
FR2 =LAMPT;
a =polyfit(t,LAMPT,10);
MFR2 =polyval(a,t);
FR1_area =0;
FR2_area =0;
MFR2_area =0;
for u=1:length(t)
    if u>1
        FR1_area =FR1_area +FR1(u)*(t(u)-t(u-1));
        FR2_area =FR2_area +FR2(u)*(t(u)-t(u-1));
        MFR2_area =MFR2_area +MFR2(u)*(t(u)-t(u-1));
    else
        FR1_area =FR1_area +FR1(u)*t(u);
        FR2_area =FR2_area +FR2(u)*t(u);
        MFR2_area =MFR2_area +MFR2(u)*t(u);
    end

end
Inc_per =((FR2_area-FR1_area)/FR1_area)*100;
objective_function=-Inc_per;
%=======make Penalty Function================
Var =[TOPM CS];
PT =0; %panelty Term
for k=1:length(Var)
    up(k)=0;
    down(k)=0;
    if Var(k)>Amax(k)
        up(k)=rho*(Var(k)-Amax(k))^2;
    elseif Amin(k)>Var(k)
        down(k)=rho*(Amin(k)-Var(k))^2;
    end
    PT=PT+up(k)+down(k);
end
f=objective_function+PT;
return
```

APPENDIX B

PUBLICATIONS

List of Publications

ARTICLES IN JOURNALS

Thongchai, P., Leeton, U. and Kulworawanichpong, T. (2017). **Substation Reliability Improvement Based on Preventive Maintenance**, Accepted to be published by *SYLWAN Journal*, Vol. 161, Issue. 10, pp. 315-341.

ARTICLES IN INTERNATIONAL CONFERENCE PROCEEDINGS

Thongchai, P., Pao-La-Or, P. and Kulworawanichpong, T. (2013). **Condition-based health index for overhead transmission line maintenance.** *In Proceedings of the International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI 2013).* Krabi, Thailand, May 5-17 2013, pp. 1-4.

Thongchai, P., Boonsang, S. and Kulworawanichpong, T. (2012). **Effect of Generator Outage Contingency on Distance Relay Operation.** *In Proceedings of Asia-Pacific Power and Energy Engineering Conference.* Shanghai, China, March 27-29, 2012, pp. 1-4.

Paper Title:

Improvement of Substation Reliability Based on Preventive Maintenance

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Abstract:

This paper is shown improvement reliability of substation by preventive maintenance (PM) related about failure rate and reliability for the performance and service life of an equipment. The objective of paper to focus on estimation of failure rate and reliability of specific equipment in the system such as transformer, circuit breaker, etc. which is too complex to finally estimate in a system as a whole. This paper considers the failure rate and reliability of the simplified arrangement of the HV substation system (single bus-single breaker one bay and double bus-double breaker one bay) and apply to the HV substation 115/22 kV Nongki substation located in Nakhon Ratchasima, Thailand. The contribution of preventive maintenance was considered in every 1, 2, 3, 5 and 10 years. Results showed that in a shorter preventive maintenance the failure rate of substation is highly reduced. The percentage of increment reliability

more than 95% of all case study for one year of PM, and more than 50% for five years of PM. Similarly, improved reliability was also obtained in a shorter preventive maintenance. It was concluded that, performing preventive maintenance especially in a shorter period may improve both reliability as well as failure rate of the substation.

Keyword: Power Substation, Failure Rate, Reliability, Preventive Maintenance

1. Introduction

Efficient operation of medium voltage substations over extended service times is one among the major efforts of any utility company all over the world. Currently, prolongation of high voltage equipment in the substation is performed by improving their reliability and minimizing their failure rates [1]. Preventive maintenance is the powerful technical process employed to improve the reliability of HV equipment in the substation [1], [2], [3], [6] which restores an equipment into a good working condition [1], [4] and enables it to operate into the nearly factory specifications [6]. Hence, extension of service life in substation is highly dependent on the performance of the preventive maintenance.

Utilities consider preventive maintenance among the important activities to enhance the system reliability over a service time. Various approaches have been employed in performing preventive maintenance such as Time Based Maintenance; Time Based Condition Maintenance; Condition Based Maintenance; Online Condition Maintenance [5]. Reliability centered maintenance (RCM) has long been described as the maintenance plan that ensure the maintenance at the right time and right activity [7]. But this technique is only being applicable to one HV equipment in the substation such as power transformer, disconnecting switch, circuit breaker, etc. [8], [9]. Chang and

Yang [2] nominated a pareto-based multiobjective evolutionary algorithms to optimize the maintenance activities. Pourahmadi et al. [3] proposed an RCM game theory called shapely value to evaluate the component vitality for the system overall reliability. It pin-pointed the contribution of each equipment to the system reliability when a high-order contingency occur under different loading conditions. Carneiro et al [5-6] developed an RCM based methodology for prioritizing actions in predictive maintenance of substation equipment applied to the power transformer. Tavares et al [7] discussed the use of RCM to a digital protective relay installed in a primary distribution substation. Unfortunately, most of the RCM preventive measures concern with one equipment in the substation.

This paper resents the study of system failure rate and reliability for the whole substation. Two simplified arrangement substation system which are single bus-single breaker and double bus- double beaker one bay) were employed for case study. Nongki substation 115/22 kV with two incoming transmission lines rated 115 kV, two power transformers, two bays and each bay has seven feeders available in Nakhon Ratchasima, Thailand was taken as a case study also. The study involved 1, 2, 3, 5 and 10 years of preventive maintenance, respectively.

This paper organizes a total of five sections. Next section, section two, theories of failure rate and reliability model includes series and parallel arrangement. Addition, The preventive maintenance modeling is included in section two also. Section three is case studies for simulation. Section four gives simulation results and discussion. Finally, conclusion is in section five.

2. Submission Reliability and preventive maintenance concept

Reliability in the substation depends on the manner in its components are arranged i.e. parallel or series arrangement. The life of system component is hereby considered to be exponentially distributed and time dependent [10]. The reliability needs to transform the components into formula and solve them by software calculation packages.

2.1 Series reliability

System components are said to have series reliability if the failure of one or more than one component before the intended mission is reached can result to the failure of the whole system [10-11]. Therefore, the reliability of the entire system takes into an account that the reliability of individual component succeeds the mission. The concept of reliability based on the series arranged component is described below.

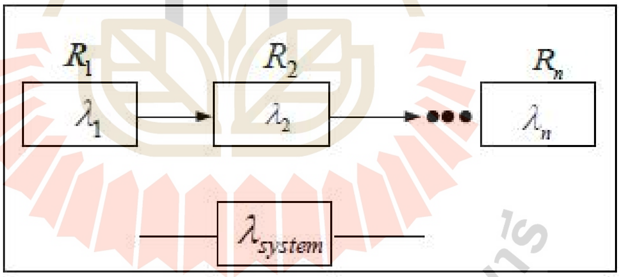

Fig.1 Series system of "n" identical and independent components

Fig 1 shows the series of "n" identical and independent substation components. The system reliability concept from the given components in Fig 1 can be expressed as shown in (1) which combines the reliability of each component. From that concept, the exponential series reliability of each component and hence the entire system can be obtained as shown through (2) to (5) [10-11].

System reliability is $$R_{system} = R_1 \bullet R_2 \bullet R_3 \cdots R_n = [R_i]^n \quad (1)$$

Where, $$R_i = e^{-\lambda t} \quad (2)$$

So, $$R_{system} = e^{-\lambda_1 t} \bullet e^{-\lambda_2 t} \bullet e^{-\lambda_3 t} \cdots e^{-\lambda_n t} \quad (3)$$

$$R_{system} = e^{-\left(\lambda_1 + \lambda_2 + \lambda_3 \ldots \lambda_n\right)t} = e^{-\left(\lambda_{system}\right)t} \quad (4)$$

Thus, $$\lambda_{system} = \lambda_1 + \lambda_2 + \cdots \lambda_n = \sum_{i=1}^{n} \lambda_i \quad (5)$$

Where: R_{system} is the reliability of the system, R_1 or R_i to R_n are element of each reliability, n is the number of identical components $i = 1, 2, 3, \ldots, n$, λ_{system} is the failure rate of system, λ_1 or λ_i to λ_n are elements of each failure

2.2 Parallel reliability

On the other hand, a system can be said to have parallel reliability if the failure of one component does not result into the system failure. The parallel configuration has higher reliability than the reliability of any single system component. A graphical representation of parallel reliability for "n" identical and independent components is shown is Fig 2.

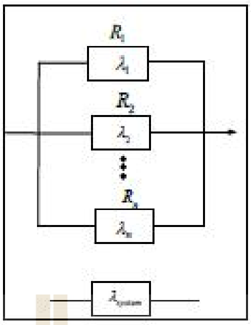

Fig. 2 Parallel system of "n" identical and independent components

In [8] the unreliability of this system can be expressed as given in (6). System reliability for the parallel components with similar individual reliability as well as different individual reliability are given in (7) and (8) respectively.

$$Q_{system} = Q_1 \bullet Q_2 \bullet Q_3 \cdots Q_n \quad (6)$$

$$R_{System} = 1 - \prod_{i=1}^{n}(Q_i) = 1 - (Q_1) \times (Q_2) \times \cdots (Q_n) \quad (7)$$

$$\begin{aligned} R_{System} &= 1 - \prod_{i=1}^{n}(1 - R_i) = 1 - (1 - R_1)x(1 - R_2)x \cdots (1 - R_n) \\ &= 1 - (1 - R_i)^n \end{aligned} \quad (8)$$

The exponential parallel reliability of the system with "n" components is very complicated to evaluate. To solve this, a simple parallel system composed of n= 2 identical component was considered. The mission time T only if the first component, or the second component or both components survive is shown in Fig 3. In the language of "statistical event", this can be expressed as given in (9).

$$\begin{aligned} R(T) &= P\{System\ Survive\} \\ &= P\{X_1 > T\ or\ X_2 > T\ or\ BOTH > T\} \end{aligned} \quad (9)$$

where: $R(T)$ is survival function, $P(X)$ is criteria of event, X is event, T is mission time

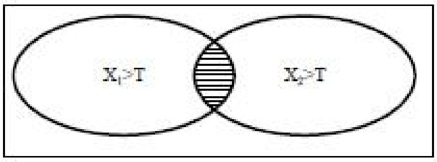

Fig. 3 Event diagram model of either component or both surviving mission time

By using the statistical formulation of the survival function $R(T)$ given in (9), one can obtain system mean time to failure ($MTTF$) for an arbitrary mission time (T). For, say $n=2$ arbitrary components given in (10) can lead to the mean time to failure ($MTTF: \mu$) as shown in (11).

$$R(T) = 1-[1-R_1(T)][1-R_2(T)] = 1-[1-e^{-\lambda_1 T}][1-e^{-\lambda_2 T}] \\ = e^{-\lambda_1 T} + e^{-\lambda_2 T} - e^{-(\lambda_1+\lambda_2)T} \quad (10)$$

$$MTTF = \mu = \int_0^{\infty} R(T)dT = \int_0^{\infty} (e^{-\lambda_1 T} + e^{-\lambda_2 T} - e^{-(\lambda_1+\lambda_2)T})dT \\ = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1+\lambda_2} \quad (11)$$

Therefore, the system failure rate (λ_S) can easily be obtained from the theoretical definition of failure rate (FR). By considering n=2, system failure rate can be given as in (12) to (13) [12].

$$FR = \lambda_s = \frac{Density\ Function}{Survival\ Function} = \frac{-\frac{\delta}{dt}R(T)}{R(T)} \quad (12)$$

$$FR = \lambda_S(T) = \frac{\lambda_1 e^{-\lambda_1 T} + \lambda_2 e^{-\lambda_2 T} - (\lambda_1+\lambda_2)e^{-(\lambda_1+\lambda_2)T}}{e^{-\lambda_1 T} + e^{-\lambda_2 T} - e^{-(\lambda_1+\lambda_2)T}} \quad (13)$$

Even though the individual failure rates are constant, the obtained parallel system Hazard Rate $\lambda_s(T)$ in (13) is time-dependent.

2.3 Preventive Maintenance model

In the real world practice, a new installed electrical component suffers from relatively high failure rate when connected to the system. It is due to the fact that a new built component, especially complex electrical components, may experience industrial flaws such as poor design, substandard items, inadequate manufacturing control, damages during transportation, installation, improper installation [11], [13].

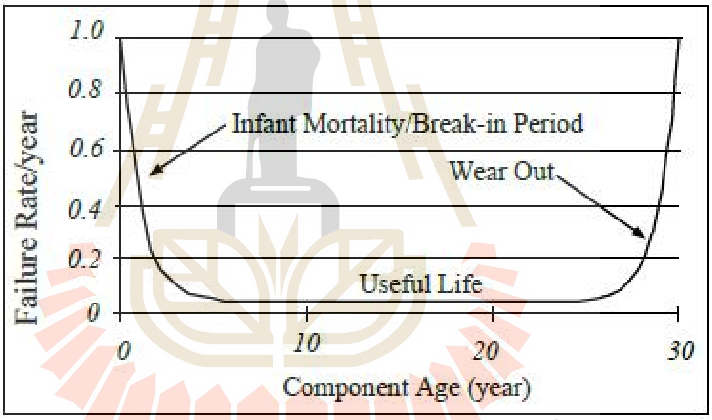

Fig. 4 Bath tub *[11], [13]*

The behaviour of failure rate with time of the system component after installation, useful life and nearly to its end of time is modelled as shown in Fig 4. Fig 4 is normally termed as Bath tub and as seen it shows three kinds of failure rates which are Decreasing Failure Rate (DFR), Constant Failure Rate (CFR) and Increasing Failure Rate (IFR). The failure rate may be termed as Hazard rate which means the probability of the component to fail at time t while it is still working at time t [11].

A bathtub with the modified curve in the constant failure rate to represent hazard rate function is called Saw tooth bath tub and is shown in Fig 5.

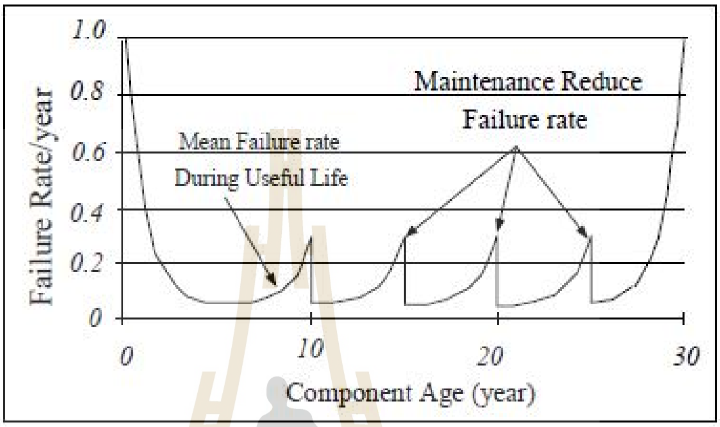

Fig. 5 Saw tooth Bath tub [11]

Preventive maintenance can minimize the rise in failure rate during the useful life and restore into the younger one. The PM model for failure rate reduction in the finite time period (L) is shown in Fig 6.

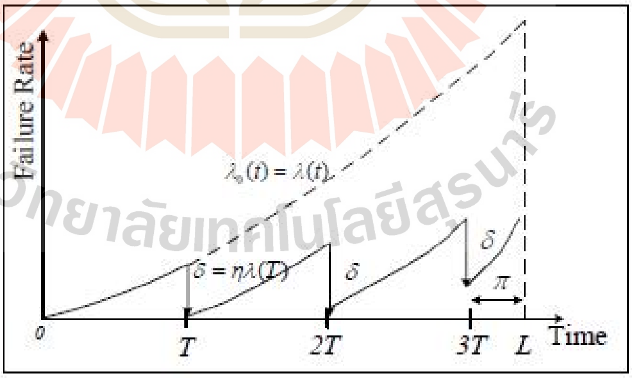

Fig. 6 PM model

Where: L = finite useful lifetime of the component

N = number of pm undertaken in the finite lifetime L

T = time interval for every PM (N)

δ = amount of failure rate reduced after every pm

π = time interval between the N^{th} and L pm ($\pi = L - NT$)

η= restoration factor to measure the amount of restoration after PM

The failure rate is given in (14) whereby A, B and C are constants computed based on (15) to (17) and later summarized in Table 1 [11].

Failure rate, $$\lambda(t) = Ae^{Bt} + C \quad (14)$$

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \quad (15)$$

$$B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right) \quad (16)$$

$$C = \lambda(0) - A \quad (17)$$

3. Simulation Procedure

The simple algorithm was employed to perform simulation as shown below. It aimed to reduce the failure rate compared with the conventional preventive maintenance (PM) in a preventive maintenance period of 1, 2, 3, 5 and 10 years.

1. Define initial values of expected lifetime (*Tf*) of the equipment (in year) and preventive maintenance period (in year, *Tpm*)
2. Define parameters of failure rate constant of each equipment in the power substation (*A, B and C*) in (15) to (17). Equipment are incoming system, DS, CB, Bus bar and transformer.

3. Calculate failure rate (FR) value from (14) before and after maintenance with check criteria of time (*T*); if it is more than *Tpm* then the system should adopt PM. The PM reduces FR to the minimum level.
4. Collect FR values after every stopping criteria of the simulation.
5. Consider the arrangement of busbar in the substation, to compute series and parallel FR.

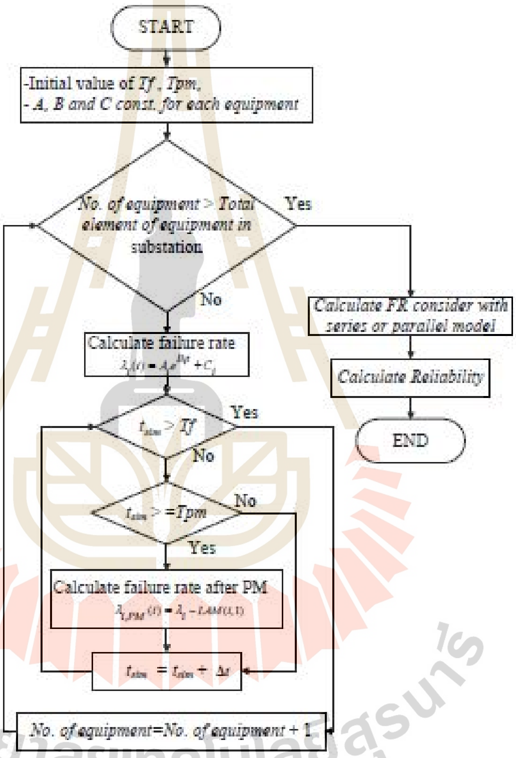

Fig. 7 The algorithm for simulation failure rate and reliability

For calculation total FR of substation.

6. Calculate the failure rate in (5) for series and reliability in (4) for series.

Calculate the failure rate in (13) for parallel and reliability in (10) for parallel.

7. Collect FR values after every stopping criteria of the simulation.

This procedure can be summarized as the flow diagram in Fig. 7.

4. Simulation Results and Discussion

The simulation for test systems were done in the same computer which was an Intel®, Core (TM) i5-6200U, CPU @2.3 GHz, 4.0 GB RAM. The results of reliability and failure rate of the simplified bus configuration in single bus-single breaker one bay, double bus-double breaker one bay and the case study of 115/22 kV Nongki substation are presented in the next subsections.

4.1 Single bus single bay system

For the substation containing HV components as shown in Fig 8, the failure rate can be given as in (14) whereby *A*, *B* and *C* are constants. In [11] the values of *A*, *B* and *C* have been given based on equipment inspection data and have been summarized in Table 1.

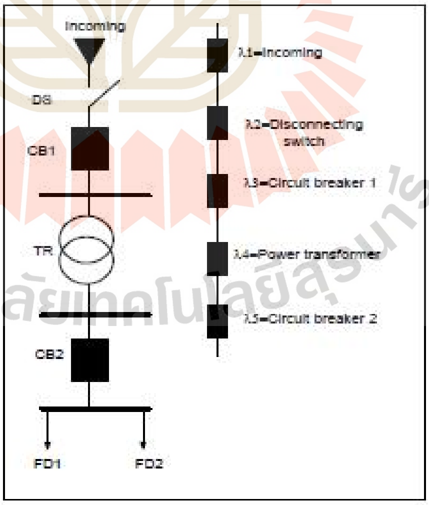

Fig. 8 Single bay single bus

Table 1 Failure rate modeling of substation components

Parameter	Incoming	DS	CB1	TR	CB2
A	0.01976	0.00021	0.00223	0.01565	0.00223
B	3.42959	7.31426	3.32146	2.24786	3.32146
C	-0.00976	-0.00179	-0.00173	-0.00815	-0.00173

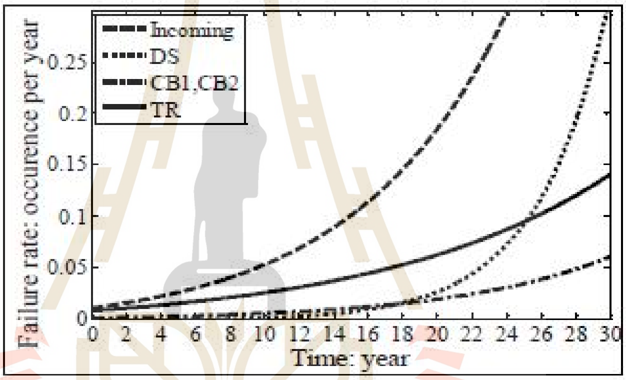

Fig. 9 Failure rate of each element in a substation

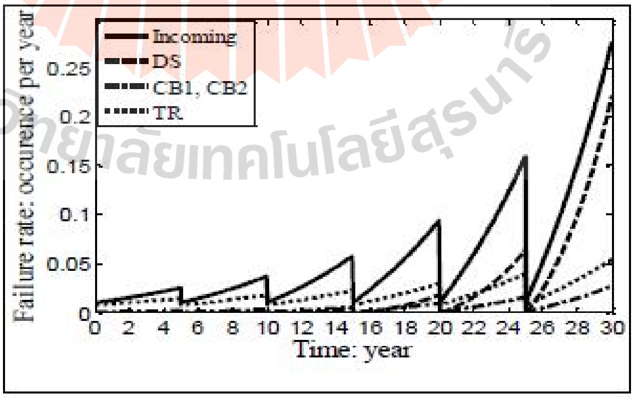

Fig.10 Failure rate with a maintenance period of every 5 years

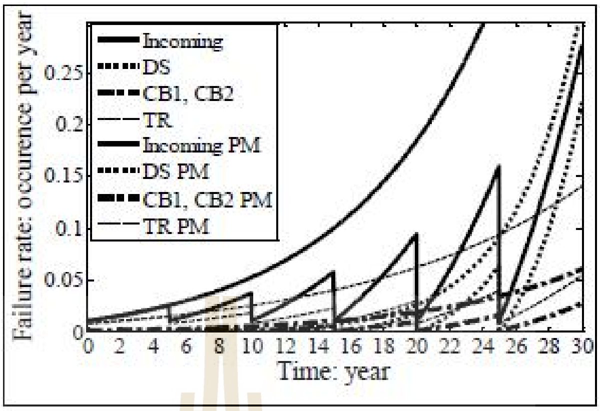

Fig. 11 Comparison of failure rate with and without a maintenance period of every 5 years

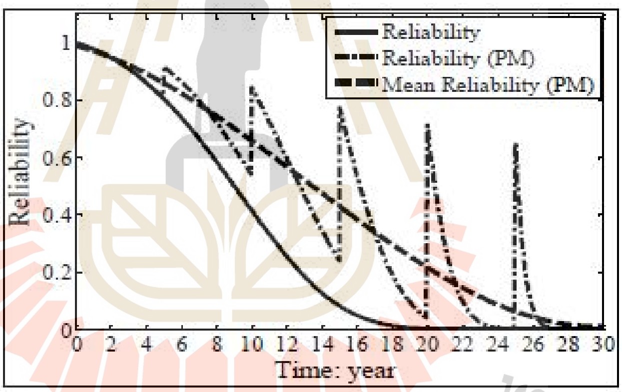

Fig. 12 Comparison of reliability with and without a maintenance period of every 5 years

When considering the maintenance period of five years and use constants given in Table 1, the failure rates of each substation components are as shown in Fig 9. Fig 10 shows the failure rate after maintenance period of every five years. The comparison of failure rate and reliability and without a maintenance period of every 5 years is shown in Fig 11 and Fig 12, respectively. Fig 13 is shown increment of system reliability with preventive maintenance. In Table 2 is comparison between no maintenance and with maintenance periods.

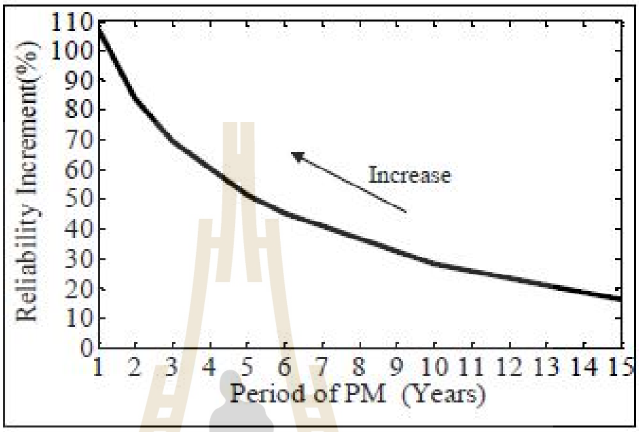

Fig. 13 Increment of system reliability with preventive maintenance

Table 2 Reliability comparison of maintenance periods of single bus-single breaker system

	No PM	Period (Years)						
		1	2	3	5	6	10	15
Area	8.9	18.6	16.5	15.2	13.6	13.0	11.5	10.4
Increment(%)	-	107.1	83.8	69.4	51.4	45.1	28.3	16.1

4.2 Double bus-double breaker system

A substation with HV components arranged as shown in Fig 14 can be described as a double bus-double breaker system. The failure rate of the system without preventive maintenance and with preventive maintenance of every five years is shown in Fig 15. Fig 16 compares the reliability of the whole substation with two incomings, four disconnecting switches, three circuit breakers, and one power transformer without maintenance and with preventive maintenance of every five years. Increment of the system reliability in a period of 1, 2, 3, 5, 6, 10 and 15 years as obtained by finding the area under the graph in Fig 16 in between no maintenance and with maintenance periods are given in Table 3. The graph showing the increments is depicted in Fig 17.

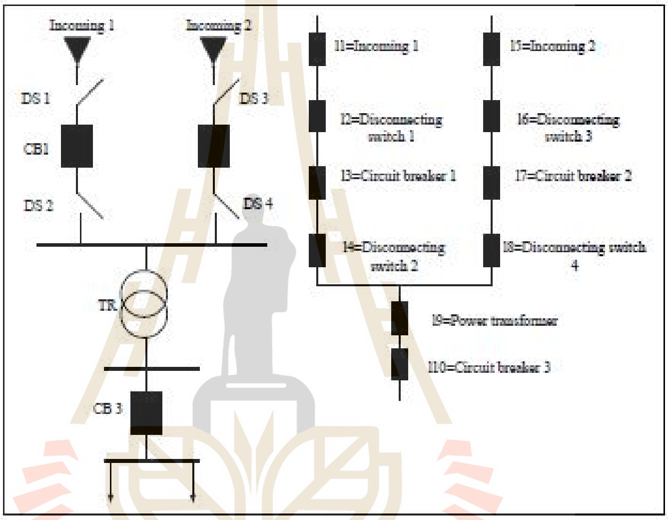

Fig. 14 Double bus double-breaker system

Table 3 Reliability comparison of maintenance periods of Double bus double-breaker system

	No PM	Period (Years)						
		1	2	3	5	6	10	15
Area	9	24	21	19	16	15	13	11
Increment (%)	-	95	82	71	54	48	31	17

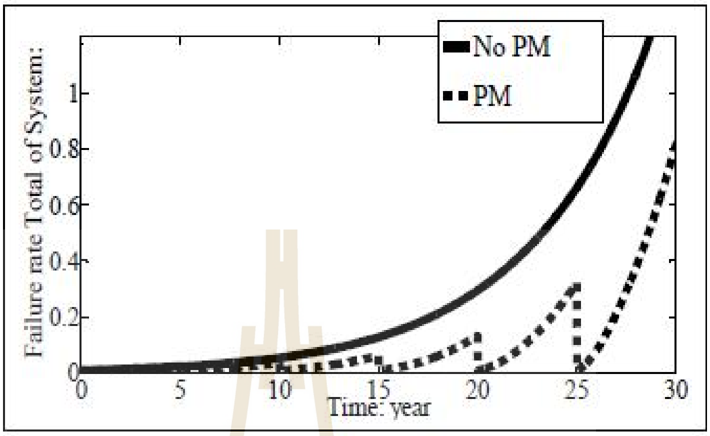

Fig. 15 Total Failure rate of the system without and with a maintenance period of every 5 years

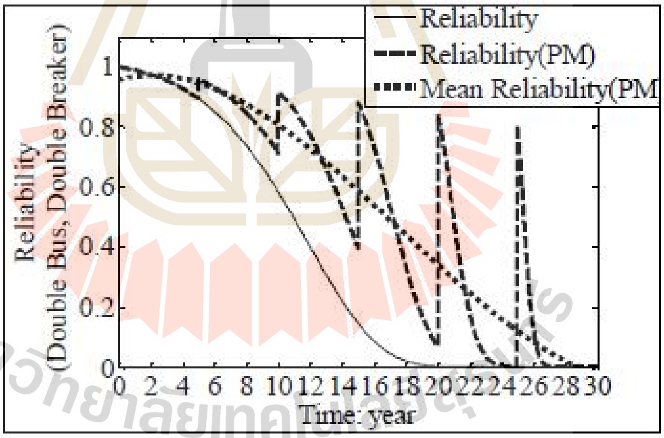

Fig. 16 Comparison of reliability without and with a maintenance period of every 5 years

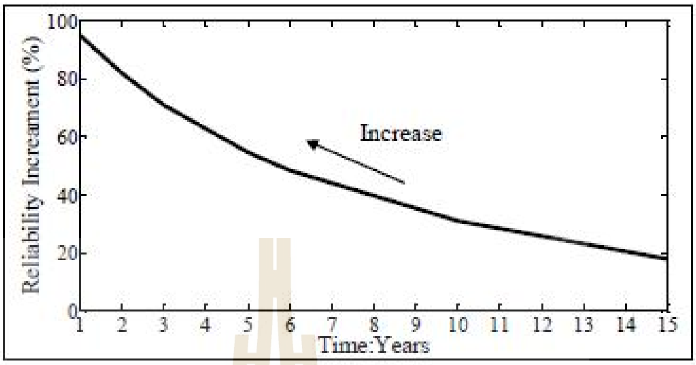

Fig. 17 Increment of system reliability with preventive maintenance.

4.3 Case study of Nongki substation

A 115/22 kV Nongki substation was used as a case study for evaluating the failure rate and reliability of substation. This substation is 80 km from Nakhon Ratchasima Provice and around 95 km from buriram provinve; and is controlled and monitored by Dispatching Center (North-East) NakhonRatchasima area 3 (see Fig. 18). Nongki-substation was employed as a special case to study the effectiveness and performance of the system. It steps down voltage from 115 kV to 22 kV and has bus alignment "main and transfer bus system". It has two incoming, two power transformer, two medium voltage bus bars each bus bar have seven feeder lines to distribution load. The single line diagram of Nongki-substation is shown in Fig 19. The simplified single line diagram and representation of failure rate of the Nongki substation is shown in Fig 20. The failure rate and reliability were simulated by using MATLAB software version 2014 the notebook with specifications: Intel core i5, RAM 4 GB 2.4 GHz. The study of reliability and failure rate were performed with the preventive maintenance of 1, 2, 3, 5 and 10 years.

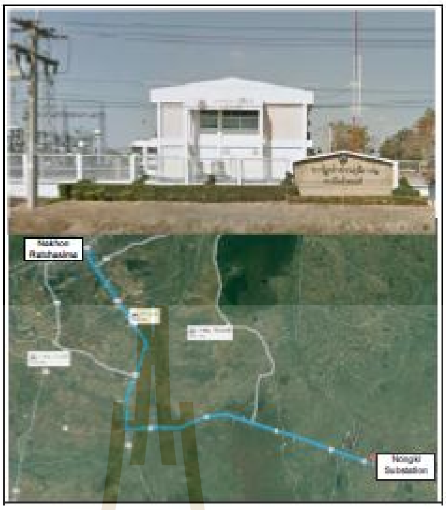

Fig. 18 Location of Nongki Substation in Nongki District, Buriram, Thailand.

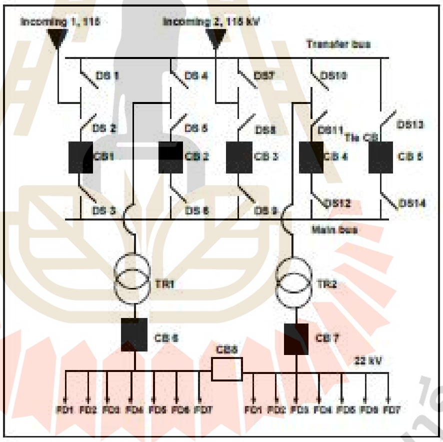

Fig. 19 Single line diagram of the Nongki substation

Fig 21 shows the total failure rate of the system (Nongki substation) . It compares the total failure rates of the system without preventive maintenance and with preventive maintenance of every 1, 2, 3, 5 and 10 years. It is observed that, generally, the inclusion of preventive maintenance reduces the total system failure rate. By performing the preventive maintenance in the period of 1 year the failure rate of the system is highly reduced compared to when the preventive maintenance period is extended (2, 3, 5, 10 years). Unlikely, when the preventive maintenance period is highly extended i.e. for 10 years in Fig 21, small difference of total failure rate is resulted from no maintenance. This means that, when the substation has critically extended preventive maintenance schedule it sometimes becomes close to no maintenance substation with high failure rate. In [4] preventive maintenance was stated to minimize the deterioration or failure rate of the system. On the other side, the higher failure rate can lead to costly operations [11]. Although the substation is well maintained it has the possibility to have the same failure rate as the system with no maintenance over a long period of maintenance (see Fig 21 beyond 30 abscissa).

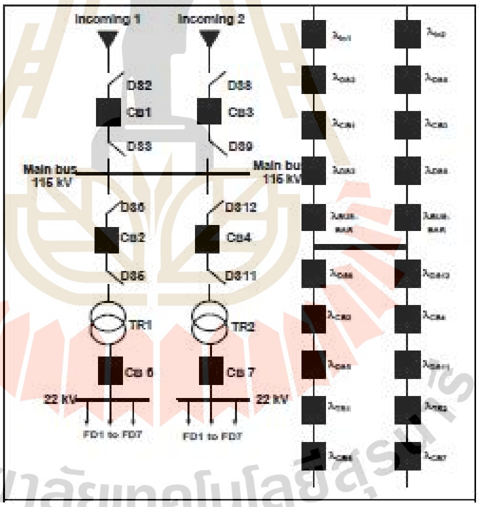

Fig. 20 The simplified single line diagram of Nongki substation

In Fig 22 the results of reliability of the system (Nongki substation) are described. The comparison of reliability of the system without preventive maintenance and with preventive maintenance of every 1, 2, 3, 5 and 10 years are shown. It can also be seen that the preventive maintenance increases the total reliability of the system.

Observation shows that, preventive maintenance in the period of 1 year improves much the reliability of the system compared to when the preventive maintenance period is extended (2, 3, 5, 10 years). This can be seen clearly in Fig 22. When the preventive maintenance period is highly extended i.e. for 10 years in Fig 22, small difference of reliability is resulted from no maintenance. In [1] the high reliability was defined as the best mean to extend the service life of an existing substation. In Table 4 is comparison between no maintenance and with maintenance periods of Nongki substation system

In generally, lower system failure rate was achieved by implementation of preventive maintenance in the shorter period (say 1 year for this case). However, the higher reliability was also obtained by implementation of preventive maintenance in the shorter period. This shows that, lowest failure rate and the highest reliability of the system may be obtained together in shorter preventive maintenance [16].

Table 4 Reliability comparison of maintenance periods of Nongki substation system

period(Years)	Area of the graph-[Reliability*t]		
	NO PM	PM	Increment (%)
1	15.06	27.37	81.67
2	13.43	23.70	76.39
3	12.56	21.17	68.57
5	11.55	17.89	54.82
6	11.22	16.74	49.14
10	10.40	13.73	32.01
15	9.85	11.63	18.03

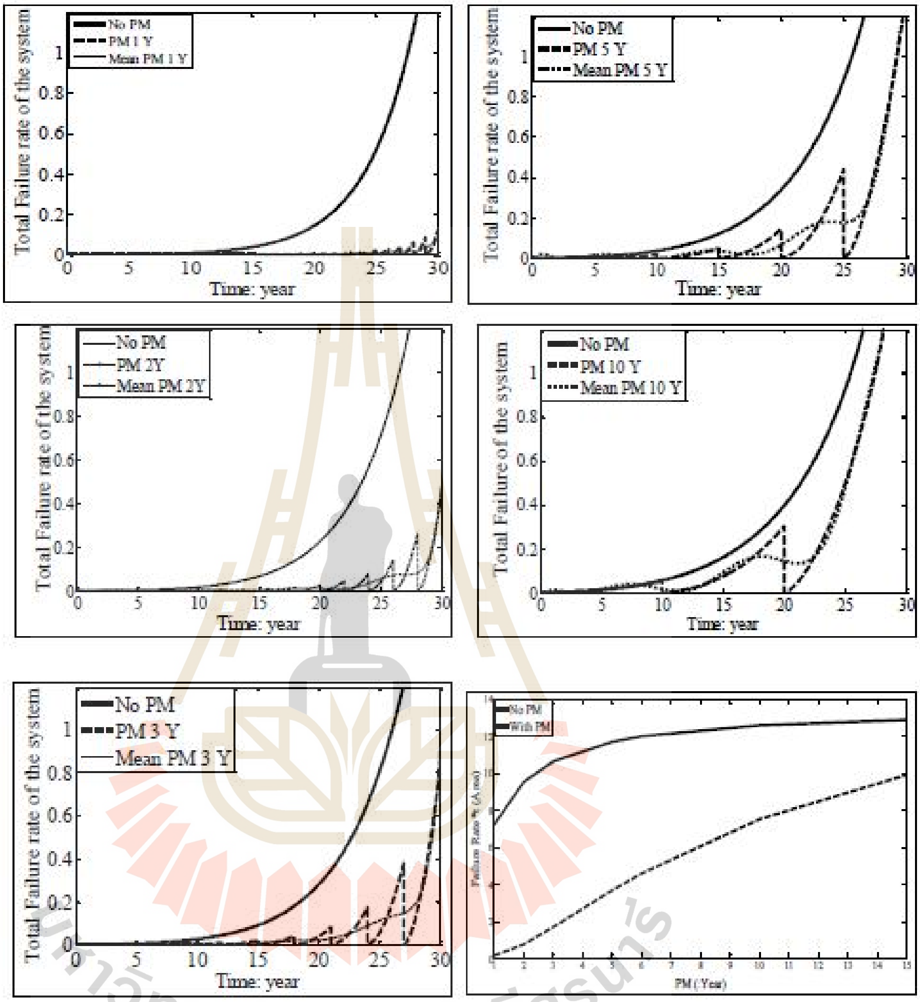

Fig 21 Total failure rate of the Nongki substation for every 1, 2, 3, 5, and 10 years of preventive maintenance

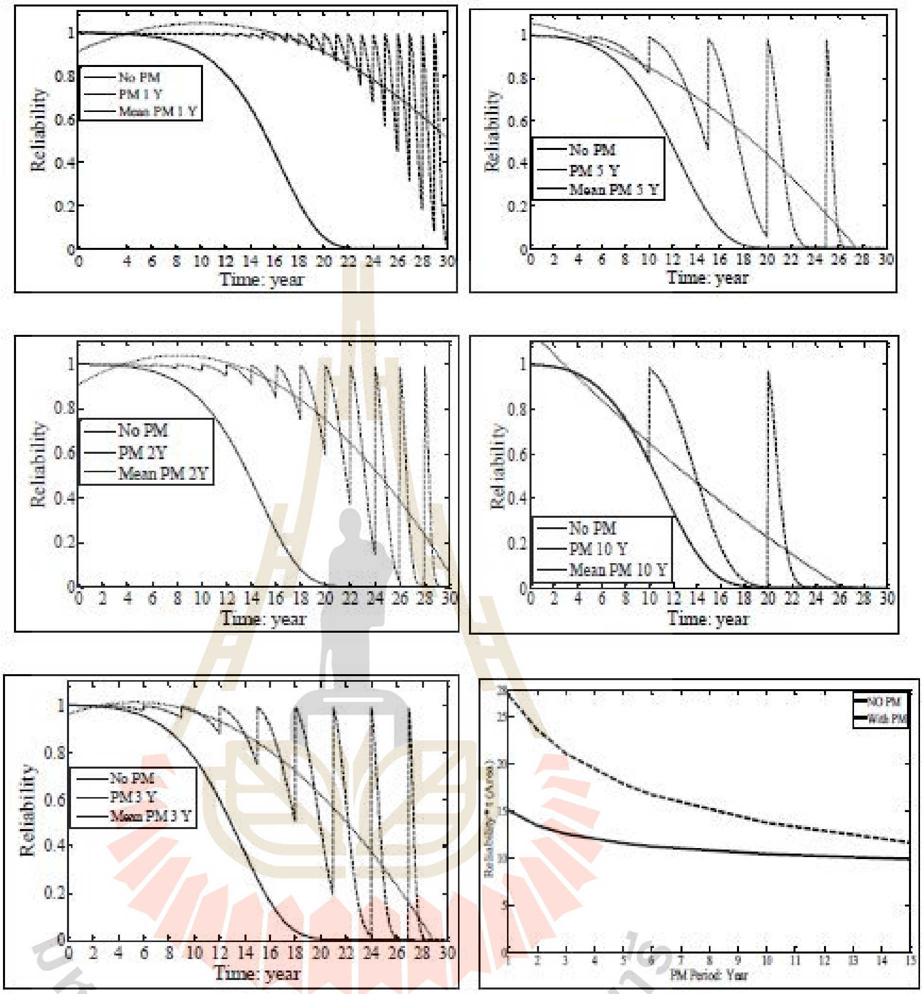

Fig 22 Total system reliability of the Nongki substation for every 1, 2, 3, 5, and 10 years of preventive maintenance

5. Conclusion

The study of total failure rate and reliability of the system integrating system components such as incomings, disconnecting switches, circuit breakers, mains bus bars and power transformers have been done. The existing 115/22 kV Nongki substation with "main and transfer bus system", two incoming, two power transformers, two medium voltage bus bars each bus bar having seven feeder lines to distribution load; was used to study the effectiveness and performance of the system. The failure rate and reliability were simulated by using MATLAB software with the preventive maintenance of every 1, 2, 3, 5 and 10 years. The result shown that in a shorter preventive maintenance the failure rate of substation is highly reduced. The percentage of increment reliability more than 95% of all case study for one year of PM, and more than 50% for five years of PM.

6. Acknowledgment

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7. References

[1] B. L. Marusa, R. R. Ferlic, and J. Pihler, "Strategic Maintenance of 400-kV Switching Substations," *IEEE Transactions on Power Delivery*, Vol. 28, No. 1, 2013, pp. 394-401.

[2] C. S. Chang, and F.Yang, "Evolutionary Multi-objective Optimization of Substation Maintenance using Markov Model," *International Conference on Intelligent Systems Applications to Power Systems*. pp. 1-6, 2007.

[3] F. Pourahmadi, M. Fotuhi-Firuzabad, and P. Dehghanian, "Application of Game Theory in Reliability-Centered Maintenance of Electric Power Systems," *IEEE Transactions on Industry Applications*, Vol. 53, No. 2, 2017, pp. 936-946

[4] C. Cheng, X. Zhao, M. Chen, and T. Sun, "A Failure-rate–reduction Periodic Preventive Maintenance Model with Delayed Initial Time in a Finite Time Period," *Quality Technology and Quality Management*, Vol. 11, No. 3, 2014, pp. 245-254.

[5] J. C. Carneiro, "Substation Power Transformer Risk Management: Preventive Methodology Based on Reliability Centered Maintenance Data," *4th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)*, 2013. DOI: 10.1109/PowerEng.2013.6635825.

[6] J. C. Carneiro, J. A. Jardini, and J. L. P. Brittes, "Substation Power Transformer Risk Management: Reflecting On Reliability Centered Maintenance and Monitoring," *6th IEEE/PES Transmission and Distribution: Latin America Conference and Exposition (T&D-LA)*, 2012, pp. 1-8. DOI: 10.1109/TDC-LA.2012.6319123.

[7] H. Tavares, H. Leite, A. Pinto, P. Vidal, and J. Santos, "Applying Reliability Centered Maintenance to a Digital Protective Relay," *3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 2013, pp. 1-5. DOI: 10.1109/ISGTEurope.2012.6465758.

[8] K. Dimitr, "Reliability Engineering Handbook," Vol.2. DEStech Publications, Inc: USA, 2002.

[9] G. Balzer, "Condition Assessment and Reliability Centered Maintenance of High Voltage Equipment," *Proceedings of 2005 International Symposium on Electrical Insulating Materials*, 2005, pp. 259-263.

[10] J. L. Romeu, "Understanding Series and Parallel Systems Reliability," *START 2004-5 S&P SYSREL*, Vol. 11, No. 5, pp. 1-8.

[11] R. E. Brown, "Failure Rate Modeling," Vol.2. DEStech Publications, Inc: USA, 2002.

[12] R. E. Barlow, and F. Proschan, "Mathematical Theory of Reliability," *Society for Industrial and Applied Mathematics*: NY, 1996.

[13] R. Smith, and R. K. Mobley, "Rule of Thumb for Maintenance and Reliability Engineers", *Butterworth-Heinemann*, 2007.

[14] J. De-Kock, and C. Strauss, "Practical Power Distribution for Industry," *IDC Technologies*: NY, 2004.

[15] J. J. Burke, "Practical Power Distribution Engineering," *Fundamental and Application*," Marcel Dekker Inc, 1994.

[16] C. Cheng, J. Chen, T. Sun, and M. Liu, "A Modified Preventive Maintenance Model with Failure-rate–reduction under Warranty Consideration," *Scientific Cooperation Workshops on Engineering Branches*, 2015, pp. 168-172.

8. Biography

Pheeraphong Thongchai was born in Nakhon Ratchasima, Thailand. He received B.Eng. in Electrical Engineering from King Mongkut's University of Technology North Bangkok, Bangkok, Thailand (1986) and M. Eng. in Electrical Engineering at Chulalongkorn University, Bangkok, Thailand (1992), Thailand. Currently, he acquired his Ph.D. at the School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand. Mr. Pheeraphong's research fields are interesting to the Power Substation Maintenance, Power System Construction, High voltage equipment installation, transmission line constructions and connection to grid, underground cable platform constructions, power transformer installation, Power transformer assembly, oil puerile and grounding system testing. Currently, he is a

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BIOGRAPHY

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