Reliability-Centered Maintenance and Replacement for Transformer

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Deregulated and competitive power market places utilities under high pressure to assure providing power with a satisfactory level of power continuity. This objective entails a high level of reliability which in turn demands a high financial budget for design, operation, and maintenance. Therefore, the need for utilities to balance these factors has been increasing to become the core of a utility's asset management activities.

Maintenance is a key aspect of asset management. The main objective of maintenance is to extend the lifetime of equipment and/or reduce the probability of failure. Maintenance activities play an important role in improving system reliability by keeping the condition of a system's equipment within an acceptable level. Generally speaking, technical requirements and budget constraints are the most influential factors in assigning maintenance activities. The most cost-effective maintenance approach is the approach that can sustain a high level of reliability while maintenance cost is minimized.

The transformer has a significant role in the power system due to its remarkable effect on the overall level of reliability in addition to its extensive investments in the power grid. Transformer management is comprised of identifying the appropriate type and frequency to maintain the transformer, and the appropriate time to replace the transformer in a cost-effective manner.

The essential objective of this thesis is to introduce a novel framework for transformer management. An approach which links maintenance and replacement decisions is presented in this thesis. This approach proposes a methodical decision-making system to determine the optimal time to replace the transformer. Indeed, the proposed approach essentially investigates the cost-effectiveness of replacing the transformer both before and after the lifetime is extended by maintenance. To properly investigate the effect of maintenance, maintenance activities should first be scheduled effectively. Therefore, this approach introduces a maintenance strategy based on reliability-centered maintenance (RCM) concept and genetic algorithm (GA) to optimally schedule maintenance activities. Two replacement studies are conducted: with and without the effect of maintenance. A comparison between replacement studies is discussed in the proposed approach.

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Hani Aldhubaib
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Nomenclature

AHP	Analytical Hierarchical Process
(A/P,i,m)	uniform-series capital recovery factor at interest rate *i* for *m* years
BV_t	Book Value at the end of year *t*
C	capital cost
C^C	capital cost of the challenger
CB	Circuit Breaker
CBM	Condition-Based Maintenance
CIC	Customer Interruption Cost
CIC_t	Customer Interruption Cost at year *t*
CM	Corrective Maintenance
COFA	Consequence of Failure Analysis
D_c	monthly demand charge
D_j	depreciation charge for year *j*
EPRI	Electric Power Research Institute
ESL	Economic Service Life
EUAC	Equivalent Uniform Annual Cost
$EUAC_m$	Equivalent Uniform Annual Cost at year *m*
$EUAC_{min}$	Minimum Equivalent Uniform Annual Cost
$EUAE_{t_{rp}}$	Equivalent Uniform Annual Expenses at t_{rp}
(F/P,i,n–t)	Single-payment compound amount factor at interest rate *i* for *n*-*t* years
FMEA	Failure Modes and Effects Analysis
FWCA	Future Worth Cost Advantage
$FWCA_{RS_j}$	Future Worth Cost Advantage of Replacement Strategy *j*
GCDF	Group Customer Damage Function
GA	Genetic Algorithm
k	number of extended years
L	average load
LF	Load Factor
MV	Market Value

MC	Maintenance Cost
MGC	Marginal Cost
MGCt	Marginal Cost at year *t*
MCS	Monte Carlo Simulation
MV_m	Market Value at year *m*
MV_O^D	Market Value of the defender at the end of the normal operating region
$MV_{t_{rp}}^D$	Market Value of the defender at t_{rp}
$MV_{t-1} - MV_t$	loss in market value from year *t–1* to year *t*
$MV_{t-1} \times i$	foregone interest
OC	Operating Cost
OC_t	Operating Cost at year *t*
P_{au}	auxiliary losses
(P/F,i,m)	single-payment present worth factor at interest rate *i* for *m* years
P_l	power losses
PM	Preventive Maintenance
P_{nl}	no-load power losses
Prob.	probability of the operation of the auxiliary equipment
PV	Present Value
RADPOW	Reliability Assessment of Distribution Power Systems
RS_j	Replacement Strategy *j*
RS_{opt}	Optimal Replacement Strategy
RTF	Run-to-Failure
s	number of load sectors
$SCDF_u$	Sector Customer Damage Function for load sector *u*
TAC	Total Annual Cost
TAC_j^D	Total Annual Cost of the defender at year *j*
TAC_m	Total Annual Cost at year *m*
$TAC_{t_{rp}}^D$	Total Annual Cost of the defender at t_{rp}
tariff	energy tariff
TBM	Time-Based Maintenance
$TE_{t_{rp}}$	Total Expenses at t_{rp}

t_{rp}	optimal replacement year
w_{u}	percentage of load sector *u*
λ_{t}	failure rate at year *t*

Chapter 1

Introduction

1.1 Motivation

Power system sector has become more competitive due to the rapid increase in demand by customers in addition to fierce rivalry between utilities to provide satisfactory level of power continuity. Therefore, utilities are required to assure the optimum utilization of their in-place assets. This utilization involves assigning the proper type of maintenance at the appropriate periodicities and then determining the optimal time for disposal (replacement). Thus, the concept of asset management has been a key issue in this competitive market environment.

Critical assets in the power systems which have remarkable effects from a reliability perspective should be considered with attention to their maintenance and replacement. Transformer is one asset that with a notable role in the power system due to its effect on reliability as well as its extensive investments in the power grid. The significance of transformer necessitates utilities to be concerned about transformer management. Transformer management is comprised not only of identifying the appropriate type and frequency to maintain the transformer, but also the appropriate time for replacement in a cost-effective manner.

As a result, maintenance and replacement approaches should not be decoupled from each other. According to the author's best knowledge, most research in the literature focuses on either scheduling maintenance activities or on finding optimal replacement year for asset(s). No research found in the literature incorporates the effect of maintenance on replacement. Instead, most studies related to scheduling maintenance activities consider the replacement action as a corrective maintenance assigned after the occurrence of failure. On the other hand, studies concerned with finding optimal replacement time do not consider the effect of maintenance on extending the physical lifetime of the assets. This gap between maintenance and replacement approaches may result in performing an excessive number of maintenance activities, even though it could be economically and reliably better to replace the asset instead. However, this gap may not show how maintenance can postpone replacement time by extending physical lifetime; hence, the asset may be replaced while its lifetime has not been completely utilized. More details about this issue will be extensively discussed in Chapter 5. Thus, there is an obvious need to consider the effect of maintenance upon conducting replacement studies. Transformer has been chosen in this thesis to be under study for this issue due to its significance and importance in the power system.

1.2 Research Questions

This thesis primarily focuses on answering the following essential question *should the transformer be maintained or replaced in its wear-out region?* To answer this big question, the following secondary questions related to transformer management should be answered:

1. Which maintenance policy should be applied and how often maintenance activities should be performed during the wear-out region?
2. What is the optimal time to replace the transformer?
3. Is it worthwhile from reliability and economic perspectives to maintain the transformer during the wear-out region?
4. How can utilities make a decision to compromise between maintenance and replacement decisions?

1.3 Research Objectives

The main objectives of this thesis are as follows:

- Find the missing link between maintenance and replacement approaches. Instead of conducting each study in isolation, the option of replacing the transformer early should be considered even if the physical condition is within an acceptable threshold. This objective entails developing the conventional aging states model used to determine the condition state of the asset by carrying out inspection activities at some deterministic inspection intervals. Instead, it is assumed in this thesis that changes in the aging state of the transformer are expressed in terms of changes in the failure rate.

- Demonstrate the effect of maintenance on determining the replacement year. As one of maintenance objectives is extending the lifetime of the asset, this objective should be manifested by showing how maintenance can postpone the replacement time of the transformer. Therefore, two replacement studies are conducted in this thesis. The first replacement study is conducted over the original lifetime of the transformer while the second replacement study is conducted after the lifetime of the transformer has been extended due to incorporating the effect of maintenance. To incorporate the effect of maintenance, maintenance activities should be scheduled in a cost-effective manner. Therefore, a maintenance strategy based on reliability-centered maintenance (RCM) concept and genetic algorithm (GA) is introduced in this thesis to optimally schedule maintenance activities. For both replacement studies, the optimal replacement times are determined.

- Compromise between maintenance and replacement. Maintenance plays an essential role in extending the physical lifetime and therefore exploits the transformer to the extent in which it is fully utilized. However, this advantage should be compared with the advantage of installing a new transformer in economic and reliability frameworks. In this thesis, a new economic term is introduced in order to compromise between replacing the in-place transformer without extending its lifetime and replacing it after its lifetime is extended for some years.

1.4 Thesis Outline

This thesis is comprised of seven chapters. Chapter 1 is an introductory chapter presenting the motivation, main objectives, and organization of the thesis. The remaining chapters are organized as follows:

Chapter 2 introduces the concept of maintenance as a key aspect of asset management. The definition of maintenance, its evolution through different generations, and its types are discussed in detail.

Chapter 3 highlights how traditional types of maintenance are developed to consider the concept of reliability in maintenance. The concept of reliability-centered maintenance (RCM) is introduced. Topics in RCM such as history of RCM, development of maintenance types, classification of equipment, and implementation process are discussed.

Chapter 4 discusses some applications of RCM in power system sector. Some studies have implemented the concept of RCM in transmission or distribution systems while other studies have utilized the concept of RCM for certain equipment.

Chapter 5 introduces the concept of the proposed approach in this thesis which is the reliability-centered maintenance and replacement (RCMR) approach. The reason behind proposing this approach and its importance are first introduced. Then, the four main parts of RCMR approach are presented.

Chapter 6 numerically illustrates the concept of RCMR through a case study. The four parts of RCMR are applied and the obtained results are discussed.

Chapter 7 concludes the thesis, summarizes the most important points addressed, and presents the main contributions. Furthermore, some future research works are suggested.

1.5 Summary

This chapter is an introductory chapter for this thesis. The motivation for the research and the main objectives has been pointed out, and the organization of the thesis has been outlined.

Chapter 2

Maintenance: Definition, Evolution, and Types

2.1 Introduction

One aim of asset management is to effectively utilize the lifetime of existing equipment. Indeed, asset management is defined in [1] as *"the process of maximizing the return on investment of equipment over its entire life cycle by maximizing performance and minimizing costs"*. Reference [2] structures the framework of asset management based on three functions. These functions are asset owner, asset manager, and asset service provider as shown in Fig. 2-1.

Fig. 2-1: Asset Management Framework [2]

Maintenance, an important part of the asset management framework, significantly affects asset condition and hence system reliability. Because of the clear role of maintenance in asset management framework, this chapter primarily addresses the concept of maintenance and its definition, evolution, and types.

Maintenance has been defined in the literature both amply and extensively. It is defined in [3] as *"an activity wherein an unfailed device has, from time to time, its deterioration arrested, reduced or eliminated".* The main objective of maintenance is to extend the lifetime of equipment and/or reduce its failure likelihood. Technical requirements and budget constraints are the most influential factors in assigning maintenance activity [4].

2.2 Evolution of Maintenance

Maintenance has been evolving since the1930s. The evolution of maintenance can be chronologically divided into three generations [5] as shown in Fig. 2-2. More attention will be focused on the evolution of maintenance throughout these generations in the following subsections.

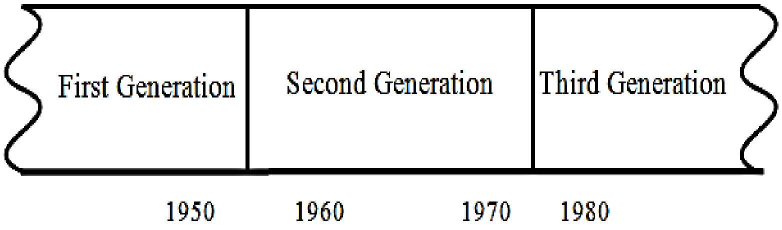

Fig. 2-2: Chronological Evolution of Maintenance

2.2.1 First Generation

In this generation, the concern of preventing failure prior to its occurrence was not given high priority because most equipment at this time was over-designed and simple. Most equipment operated on Run-to-Failure (RTF) basis due to the belief that failure is proportional to age. Fig. 2-3 depicts the concept of the relationship between failure and age during this generation. The figure shows that as equipment ages, the probability of failure increases. Simple routine maintenance techniques were used such as cleaning, servicing, and lubrication [5].

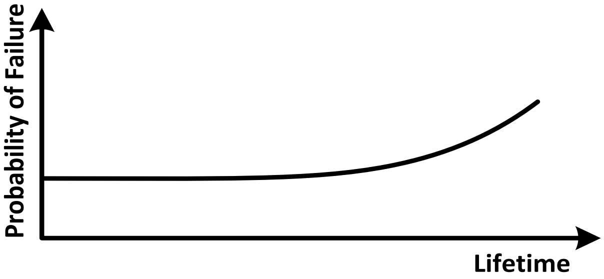

Fig. 2-3: Age-Related Failure Rate

2.2.2 Second Generation

With the passage of time, equipment became more complex; thus, concern for failure was considered and the view on equipment failure changed. In this generation, the concept of "infant mortality failure" appeared to represent the possibility of failure occurrence even for newly installed equipment. Fig. 2-4 incorporates this possibility in the relationship between failure and lifetime and introduces what is called bathtub pattern. As a result, maintenance techniques were developed in attempts at preventing failure before its occurrence. Accordingly, preventive maintenance (PM) approach emerged in this generation. PM at that time was restricted to performing scheduled maintenance at specific time intervals. Even though RTF approach is simple, it is costly compared with PM. Therefore, this generation began to be concerned with maintenance cost [5].

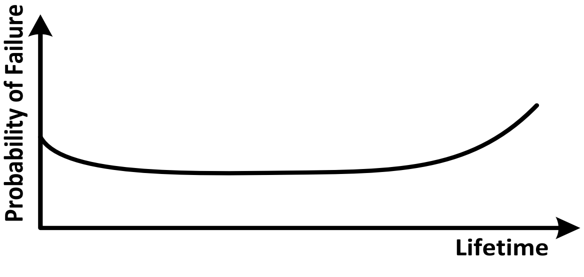

Fig. 2-4: Bathtub Curve

2.2.3 Third Generation

In this generation some changes in expectations, research, and techniques began emerging. From the expectations perspective, concern about downtime and its effects which began in the second generation; became essential in the third generation. Thus, concepts including reliability, availability, safety, and environmental conditions were considered in maintenance. Moreover, costs associated with maintenance jumped to become the first priority for most utilities [5].

The expectations of maintenance concerns have grown and changed through the generations. With regard to research, the relationship between age and failure evolved. Four more patterns were added to the previous two patterns to form the framework of the relationship between the probability of failure and the lifetime of equipment. Fig. 2-5 shows the four new patterns of failure. In the third generation, some new developments and techniques were introduced. These developments included some supporting decision tools used for studying failure modes and analyzing failure effects [5].

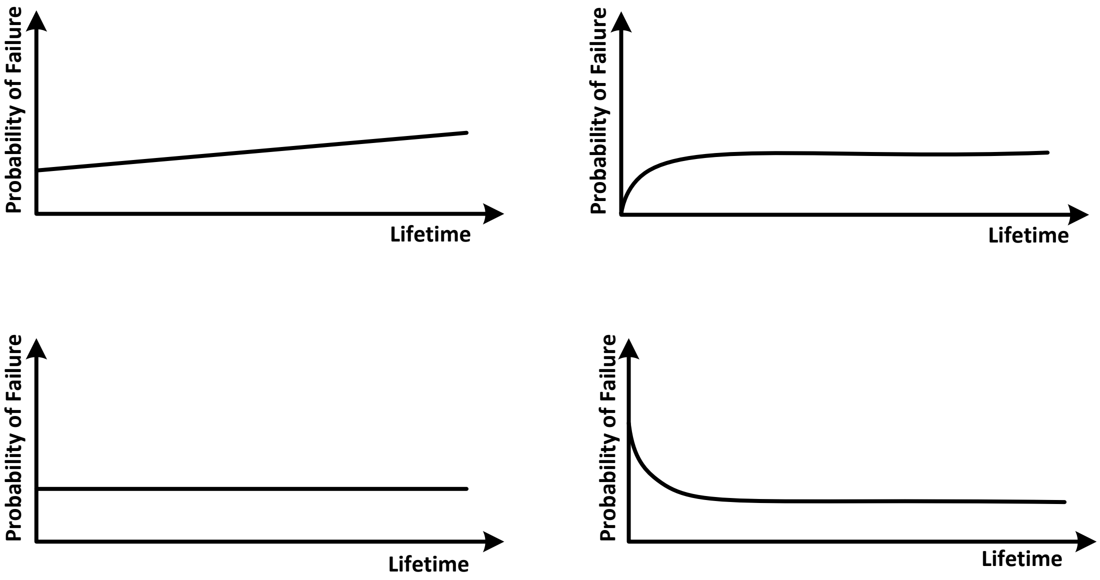

Fig. 2-5: Four New Failure Patterns in the Third Generation

In addition, the concept of monitoring the condition of equipment was introduced to preface a new maintenance technique based on condition state. Moreover, reliability was considered in the design stage. Based on these developments, maintenance activities could be divided into two main types: preventive maintenance (PM) and corrective maintenance (CM) [5]. These types will be presented in detail in the next section.

2.3 Types of Maintenance

Utilities need to prevent any potential failures by performing preventive maintenance prior to failure occurrence or corrective maintenance should a failure occur. Accordingly, the traditional maintenance activities can be divided into two main categories: Preventive Maintenance (PM) and Corrective Maintenance (CM) [4], [6].

CM is the simplest type of maintenance to perform. Simply, its strategy is to fix/replace the equipment once it fails. Nonetheless, CM cannot be assigned to equipment whose failure may result in catastrophic consequences; it is assigned to equipment that runs on the Run-To-Failure (RTF) basis [1], [4], [6–9].

On the other hand, PM is performed to prevent failure before it occurs. It can further be divided into two types. The first type is called Time-Based Maintenance (TBM). This type of PM is often performed at regular scheduled time intervals regardless of equipment's condition and based on either the recommendations of equipment's manufacturer or experience of personnel with similar equipment. Although this type of maintenance can overhaul the condition and improve the overall system's reliability, it cannot prevent failures that have occurred prematurely or during infant mortality period unless the predetermined interval is reduced [1], [4], [6–9].

As a result, Condition-Based Maintenance (CBM), the second type of PM, is introduced. CBM involves measuring, monitoring, and analyzing the condition of equipment. The essence of CBM is that maintenance should be performed if the condition of the equipment necessitates it. Therefore, CBM requires some measurement, communication, and storage tools to obtain and utilize the requisite information in order to determine the deterioration state and maintain equipment before condition deteriorates to unacceptable state. However, continuous monitoring of equipment is costly [1], [4], [6–9]. Fig. 2-6 shows the traditional maintenance types.

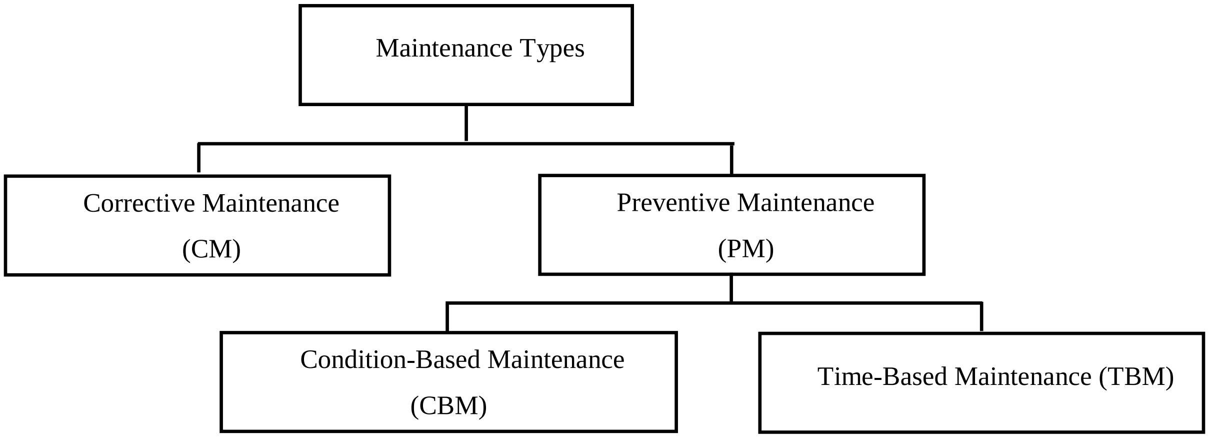

Fig. 2-6: Maintenance Types

Nevertheless, neither TBM nor CBM consider the probability of failure and its consequence. In other words, these types do not consider the value of equipment to the whole system since all equipment has the same level of reliability importance. Therefore, exiting maintenance types should be developed and enhanced to involve the necessary concept of reliability in maintenance [1], [4], [6–9].

2.4 Summary

Maintenance was introduced in this chapter as one of the important aspects of the framework of asset management. Maintenance was defined with a universal definition presenting its functions and purposes. Then, the origination of maintenance and its evolution over time were addressed. The evolution of maintenance was divided into three generations. Some classical maintenance techniques were used in the first generation. The concepts of time-based maintenance and condition-based maintenance were introduced in the second and third generations respectively. Briefly, the types of maintenance and the clear differences between these types were illustrated.

Chapter 3

Introduction to Reliability-Centered Maintenance

3.1 Introduction

Maintenance has a significant impact on keeping equipment in good condition and hence preserving the reliability of the whole system within acceptable reliability level. Since failure consequences differ from a piece of equipment to another based on equipment function and system configuration, this contrast in consequences should be taken into account upon performing maintenance activities which is referred to as reliability importance of the equipment. Due to the drawback of traditional types of maintenance in considering the reliability importance of equipment, an enhancement type has been introduced to draw the integral picture of maintenance which is called Reliability-Centered Maintenance (RCM) approach. RCM has various definitions in the literature [5], [6], [10]. However, the ultimate goal of RCM is to precisely identify the failure modes for each system and/or equipment and the severity of failure consequence in order to determine the applicable maintenance technique in a cost-effective manner [11]. Identifying failure modes and consequences can be done by either of two analyses: Failure Modes and Effects Analysis (FMEA) or Consequence of Failure Analysis (COFA) [5], [6]. These analyses will be discussed through presenting the implementation process of RCM in section 3.4. RCM approach has the ability to distinguish between equipment based upon reliability importance. RCM is not a new type of maintenance, but is rather an enhanced method for performing maintenance activities [12].

RCM is an improvement to TBM and CBM as it considers both the probability of failure and its consequences [9]. In RCM, maintenance activities are prioritized based on equipment importance to the whole system. This importance can be indicated by some indices or reliability criteria set by the utility [6], [7]. RCM essentially maximizes the system reliability while minimizing the associated maintenance cost. This qualifies RCM to be the most cost-effective maintenance approach. The primary new feature involved in RCM is the focus on studying the failure mode in addition to potential consequence of failure; furthermore, external causes of failure such as weather, animals, and human errors are embraced in most

RCM implications. RCM subsequently considers the probability, consequence, and associated costs of failure [5], [6].

The major obstacle which has arisen in implementation of RCM is the need for expertise in accurately and precisely identifying the functions, failure modes, and consequence of failure. Thus, the approach is almost empirical [4], [13]. RCM has effectively enhanced the traditional maintenance strategies from two perspectives. First, new maintenance types are introduced. Second, the classification of equipment is modified, which in turn gives a novel methodology of prioritizing maintenance activities based on equipment importance.

In addition to the existing two types of maintenance, PM and CM, Design Change is introduced as a new type of maintenance. Furthermore, PM has introduced Failure Finding to join the TBM and CBM. With regard to classification, equipment is classified into five essential classifications. The RCM classification of equipment consists of critical equipment, potentially critical equipment, commitment equipment, economic equipment, and run-to-failure equipment [6]. Fig. 3-1 and Fig. 3-2 present new development of maintenance types and equipment classification respectively.

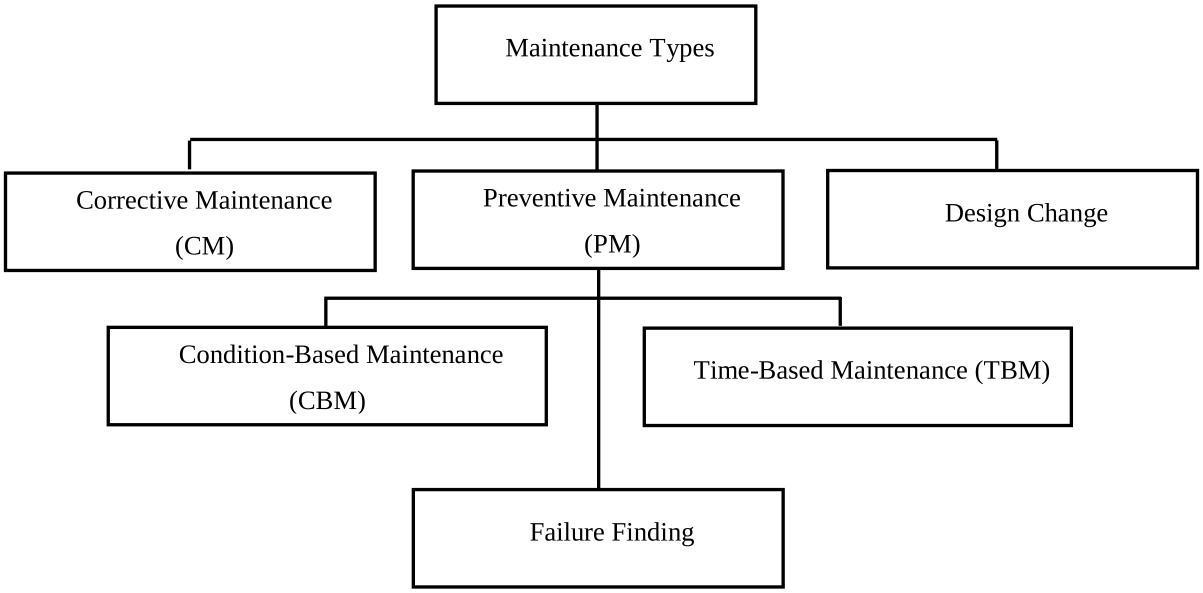

Fig. 3-1: Development of Maintenance Types

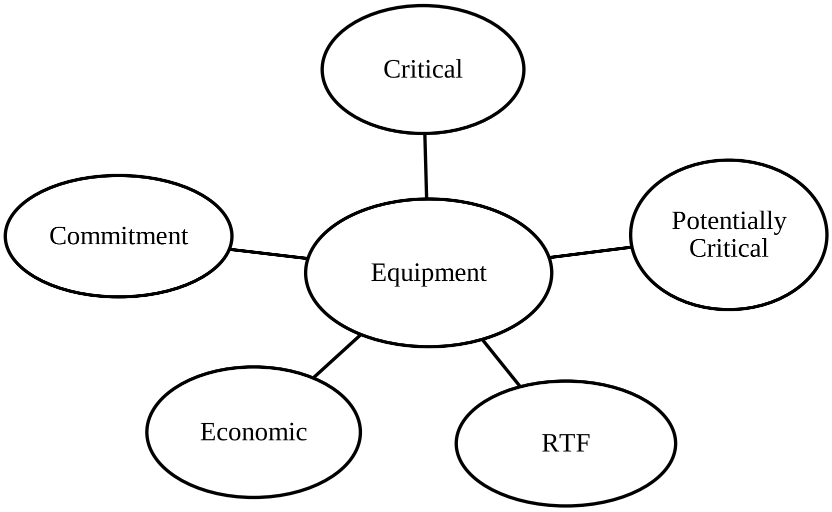

Fig. 3-2: RCM Equipment Classification

3.2 History of RCM

RCM was implemented for the first time in the commercial aviation sector in the 1970s. A report introduced by The United Airlines and authored by Stanley Nowlan and Howard Heap found after rigorous study that many types of failures may not be prevented or effectively reduced by traditional scheduled maintenance. Due to the rapid growth of airline fleet and increased cost of maintenance in addition to the need to optimize maintenance activities with high reliability requirements for this sector, the report concluded with the imperative need to develop and implement reliability programs in the area of maintenance [5], [14].

The initial RCM program was successfully implemented in a Boeing 747 airplane, and also employed in some other types of airplanes [5], [14]. The findings were satisfactory in terms of cost and reduction in resources with no effect upon reliability. After the effective implementation of RCM in the aviation industry, numerous industries commenced applying the RCM concept in their sectors [5].

RCM has been implemented in electrical power industry since the 1980s in a nuclear power generation facility [5]. Today, RCM is adopted by various electrical utilities [15].

However, reference [6] pointed out the difficulty and confusion in understanding the language and process of RCM encountered upon transferring the concept of RCM from aviation industry to other industries. As a result, approximately more than 60 percent of RCM programs have failed to be implemented [6].

3.3 Equipment Classification Hierarchy

Traditional maintenance types classify equipment based on criteria other than reliability importance, such as the amount of investment. Moreover, equipment classification may be limited to either important or not important. In contrast, RCM takes the initiative to give equipment classification more attention. As the first step in implementation process is classifying equipment, reference [6] introduces a novel equipment classification hierarchy based on equipment reliability importance. Precise and proper classification helps specify the appropriate maintenance activity. Equipment classification shown in Fig. 3-2 is presented in the following subsections ordered from most to least importance [6]. All system examples illustrated in the following subsections are originally taken form [6] and then modified to represent electric power system examples.

3.3.1 Critical Equipment

The criticality of equipment can be viewed from two sides: the effect of failure and its evidence. The effect of failure herein always signifies unwanted and adverse consequence affecting one or more reliability criteria. Failure is considered evident if it can be detected by monitoring instrumentation or even by the operator. It is definitely considered evident when the effect of failure occurs simultaneously with the failure. Therefore, if at least one of the reliability criteria is immediately affected due to an evident failure of a piece of equipment (component), this component is classified as critical [6].

To clearly illustrate this concept, Fig. 3-3 shows a generator named G1 feeding a load. It is assumed that if a failure occurs to G1, some reliability criteria will be affected as soon as failure occurs. In addition, the occurrence of failure is quite evident as the operation of G1 is monitored by a monitoring device.

As a result, G1 is a critical component. Generally speaking, equipment is classified critical if two conditions are satisfied:

- Failure is evident.
- Failure will immediately affect at least one utility reliability criteria [6].

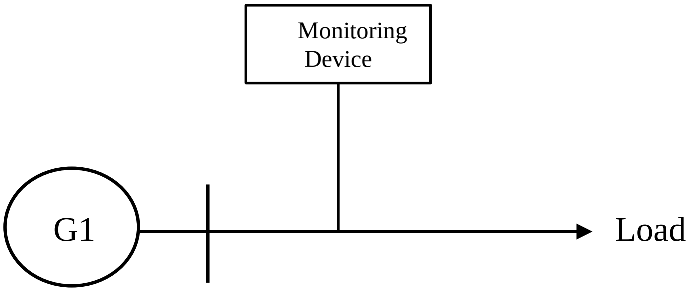

Fig. 3-3: Single-Failure Analysis

Fig. 3-4 shows another scenario in which two generators, G1 and G2, are operating simultaneously to feed a load. The operation requires both generators to operate together in order to feed the load. Due to the two reasons mentioned above, the two generators are considered critical [6].

Another scenario could be considered in Fig. 3-4 is only one generator is operating to feed the load whereas the other one is a backup. The backup generator is considered critical. However, the original generator in this situation is also critical due to system configuration [6].

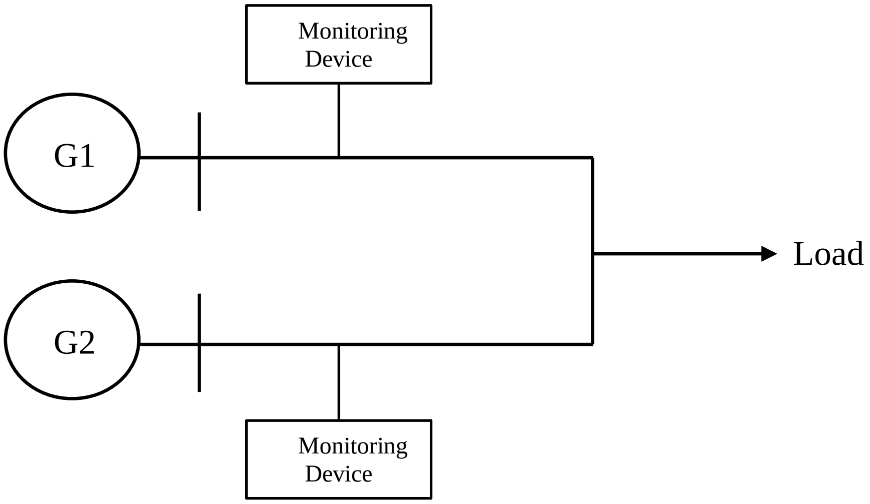

Fig. 3-4: Backup Function Analysis

3.3.2 Potentially Critical Equipment

Fig. 3-5 illustrates generators G1 and G2. Both generators are operating simultaneously to feed a load; nevertheless, either generator can meet the required demand by itself.

There is no individual monitoring of operation for each generator; rather, the operation of both generators is monitored together. Hence, the failure of generator G1 (or G2) is not evident since the monitoring device will not indicate any power interruption in the load. In addition, the failure will not result in an immediate effect unless the other generator fails. Therefore, generators G1 and G2 are potentially critical equipment for two reasons:

- Upon the failure of either G1 or G2, there is no an immediate effect affecting any utility reliability criteria; however, if both generators fail, at least one utility reliability criterion will be affected.
- The failure is not evident.

Note that the failure of either generator has no immediate effect on system level[1] but it may have effect on utility level[2] when the other generator fails [6].

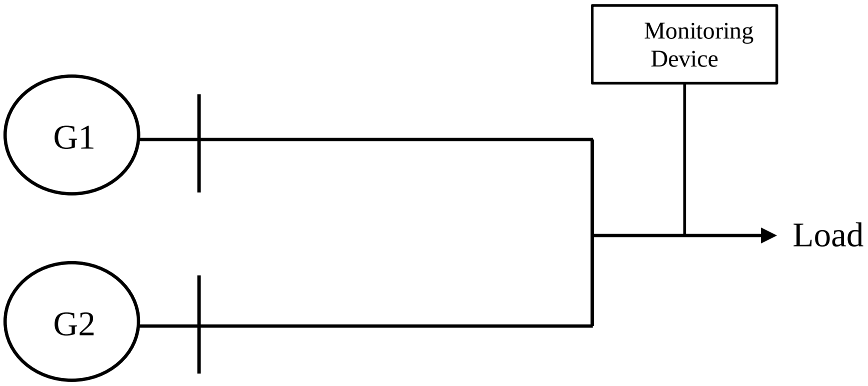

Fig. 3-5: Multiple-Failure Analysis

3.3.3 Commitment Equipment

This type of equipment must be maintained due to certain regulatory, environmental, insurance, or other commitments. Regardless of whether the failure is evident or hidden, there is no effect on reliability criteria upon failure occurrence. Often, the utility has some components which are already classified as commitment but due to their failure effects on reliability criteria, they are classified as critical or potentially critical [6].

3.3.4 Economic Equipment

Similar to commitment equipment, it does not matter whether the failure of economic equipment is evident or hidden. In addition, the failure of economic equipment has no effect on reliability criteria. Instead, the failure has only an economic effect such as cost of labor and/or materials. Of course, the failure of any equipment results in economic effect regardless of its classification; the reason behind considering this type of classification is to differentiate between equipment whose failure may affect one or more reliability criteria and the equipment whose failure is limited to financial losses [6].

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[1] System level in Fig. 3-5 contains generators G1 and G2 in addition to the load fed by the generators.

[2] Utility level contains any other components that are not responsible for feeding the load of the system level but will be affected by the failures of generators G1 and G2

Furthermore, this classification would help the utility prioritize maintenance activities since it is not logically acceptable, for example, to perform PM activity to equipment whose failure will cost very little before equipment whose failure will cause power interruption. Since this type of equipment has no effect on reliability criteria, the key issue is identifying the cost for the utility to perform the PM. The cost of PM should be less than the cost of fixing the equipment after it fails, which is the CM cost [6].

3.3.5 Run-to-Failure Equipment

Run-to-Failure (RTF) simply means do not perform any preventive maintenance until the equipment fails. There have been two misconceptions about RTF equipment:

- As long as there is no immediate effect upon equipment failure, the equipment is RTF.
- Having redundant equipment, the original equipment is RTF.

RTF equipment does not mean this equipment is trivial, but instead means that some equipment should be maintained first and some equipment's maintenance should be left until after it has failed.[6]

Fig. 3-6 shows generators G1 and G2 operating simultaneously to feed a load. Either generator can meet the required demand by itself. The operation of each generator is monitored individually. Hence, the failure of G1 (or G2) is evident. Generators G1 and G2 are considered RTF equipment if all of the following conditions are satisfied:

- The failure of G1 or G2 will not result in an effect upon any reliability criteria.
- The cost of corrective maintenance after failure is less than the cost of preventive maintenance.
- The failure is evident.
- There is no commitment to perform PM [6].

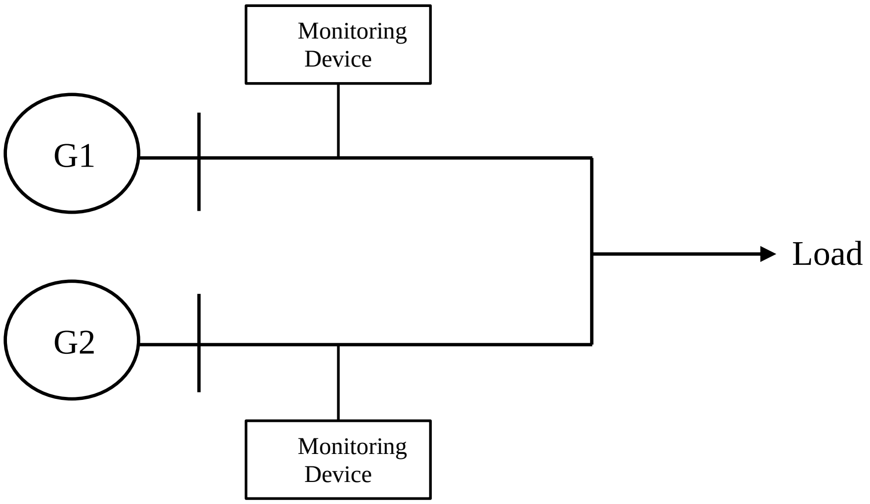

Fig. 3-6: Run-to-Failure Analysis

3.4 The Implementation Process of RCM

The process of implementing RCM to any component or system entails answering seven questions [5], [6]:

Question 1: What are the functions of the component?
Question 2: What are the functional failures?
Question 3: What are the failure modes?
Question 4: What are the failure effects?
Question 5: What are the failure consequences?
Question 6: What are the PM tasks?
Question 7: What must be done if a PM task cannot be specified?

FMEA and COFA are the two analyses considered to implement the RCM [5], [6]. Both FMEA and COFA achieve the same goal of identifying the consequence of failure for each component failure mode [11]. However, the process of the FMEA begins from the system level, whereas the COFA process starts from the equipment level [6]. The implementation process of RCM via FMEA and COFA are extensively addressed in [5] and [6] respectively. The implementation processes of RCM via COFA will be discussed in more detail followed by a brief overview of the implementation process of RCM via FMEA.

3.4.1 Implementation Process of RCM via COFA

The COFA divides the process of RCM implementation into three phases [6] as follows.

Phase 1: Identifying all important equipment.

Phase 2: Assigning the appropriate PM activities for equipment identified in phase 1. These activities must be effective and applicable.

Phase 3: Performing PM activities assigned in phase 2.

3.4.1.1 Phase 1: Identifying all Important Equipment

In this phase, the equipment population that the utility wishes to maintain is identified. The ultimate objective of this phase is to properly classify all equipment whose failures should be avoided. Phase 1 has 9 steps to accomplish [6].

3.4.1.1.1 Define Utility Reliability Criteria

Each utility has some reliability criteria such as safety, regulatory and operational. All these criteria should be defined clearly and precisely, as RCM program aims to preserve the utility from the failures that may negatively affect these criteria. These criteria may differ between industries [5], [6]. An example to an operational reliability criterion of distribution system is: *the Expected Energy Not Supplied (EENS) must not be greater than X MWh.*

3.4.1.1.2 List all Equipment in the Utility

All equipment whose failures may negatively affect the reliability criteria of the utility are entered into a database and given an ID [6].

3.4.1.1.3 Describe all Functions for Each Piece of Equipment

Each piece of equipment is installed in order to accomplish at least one function which signifies the purpose of installing the equipment in the system. In other words, the function is what the equipment must fulfill whether in normal or emergency state. Often, a component has more than one function to accomplish. Therefore, all functions which the equipment is expected to accomplish are described. However, if a specific level of performance is desired to meet the function, a performance standard must be defined and considered in the equipment function [5], [6]. For example, one circuit breaker function is *to isolate the faulted area*; nevertheless, a performance standard could be specified to precisely determine the desired function as: *to isolate the faulted area in less than 100 ms.*

3.4.1.1.4 Describe the Functional Failures

Functional failure defines the way each function can fail. Since most equipment usually has more than one function, the loss of any function may not necessarily result in complete failure to the equipment. Moreover, the term "failure" can be defined relatively; in addition, the term does not accurately describe the failed state of equipment. Therefore, the term "functional failure" is used to define the ways each function can fail [6].

Functional failure is the exact opposite of the function. Although it does not contribute new value to the analysis, it adds more clarity, especially in the case of inability to meet a desired performance standard [6]. For instance, the functional failure of circuit breaker (CB) is *fails to isolate the faulted area or fails to isolate the faulted area in less than 100 ms.*

3.4.1.1.5 Describe the Dominant Equipment Failure Modes for Each Functional Failure

As functional failure describes the failed state, failure mode describes the inability event of the equipment to provide its specified function(s). Therefore, for each functional failure, the dominant failure modes are described. For instance, the failure mode of *fails to isolate the faulted area* could be *CB fails to open*. However, since a host of failure modes could be identified for each functional failure, only dominant and realistic failure modes are considered [6].

3.4.1.1.6 Determine Whether the Occurrence of the Failure Mode is Evident or Hidden

This step entails answering the following question with *YES* or *NO*: Is the occurrence of the failure mode evident? If the failure can be detected by monitoring instrumentations or by continuously monitoring rounds, it is evident otherwise it is hidden [6].

3.4.1.1.7 Describe the System Effect for Each Failure Mode

The hierarchy of any utility usually consists of many systems. Each system can further be divided into subsystems. This partitioning is based on the function that each system/subsystem performs. Thus, all equipment installed to perform specific function(s) is partitioned together in one system/subsystem. The effect of failure of any equipment is described within its system/subsystem. Therefore, failure effect describes the impact of failure for each failure mode at the system's level. This preliminary clearly identifies the consequence (effect) of failure at utility level. This step is considered because some equipment which may not have failure effects at system level may have failure effects at utility level, such as potentially critical equipment, as explained in subsection 3.3.2 [6].

3.4.1.1.8 Describe the Consequence of Failure Based on the Reliability Criteria

Each utility has some reliability criteria that should be preserved. If any of these reliability criteria are affected as a consequence of failure, the anticipated impact is defined in order to properly specify the appropriate maintenance activity [6].

3.4.1.1.9 Define the Equipment Classification

The final step in the first phase of RCM implementation is defining the equipment classification by filtering all equipment. Each piece of equipment is filtered based on its importance. Critical and potentially critical equipment occupy the highest level of importance. Commitment and economic equipment are placed at the third and fourth level of importance respectively whereas RTF equipment has the least importance [6].

All equipment is filtered by three filters: the RCM COFA Logic Tree, the Potentially Critical Guideline, and the Economically Significant Guideline. Filtering process can be shown in Fig. 3-7. First, equipment begins with the RCM COFA Logic Tree to identify whether it is critical. If the equipment is not critical, it proceeds to the next filter which is the Potentially Critical Guideline to identify whether it is potentially critical or commitment. Economically Significant Guideline is embedded in case equipment is neither critical, potentially critical, nor commitment. Economically Significant Guideline identifies whether or not the equipment is economic. If the equipment is not caught by any filter, it is RTF equipment [6]. The filtering process is summarized in Fig. 3-8.

Suppose a piece of equipment performs three functions. Therefore, each function has a functional failure and consequently the equipment has three dominant failure modes. Based on these failure modes, the equipment is classified. In other words, failure modes identify whether the failure of equipment is evident or hidden and identify the consequence of failure. Thus, some failure modes may classify the equipment to certain classification whereas some other failure modes may classify the equipment to another classification. Which classification should the utility consider? In such a situation, the utility needs to default the classification to the highest level. For instance, the RCM COFA filter may indicate that the equipment has three classifications based on its three failure modes. These classifications are critical, potentially critical, and economic. Then, the final classification of this equipment should be considered as critical equipment [6].

By defining the classification of all utility equipment, phase 1 is completed. The next step is to select the applicable and effective PM activities for critical, potentially critical, commitment and economic equipment in order to prevent or at least mitigate failures of these components.

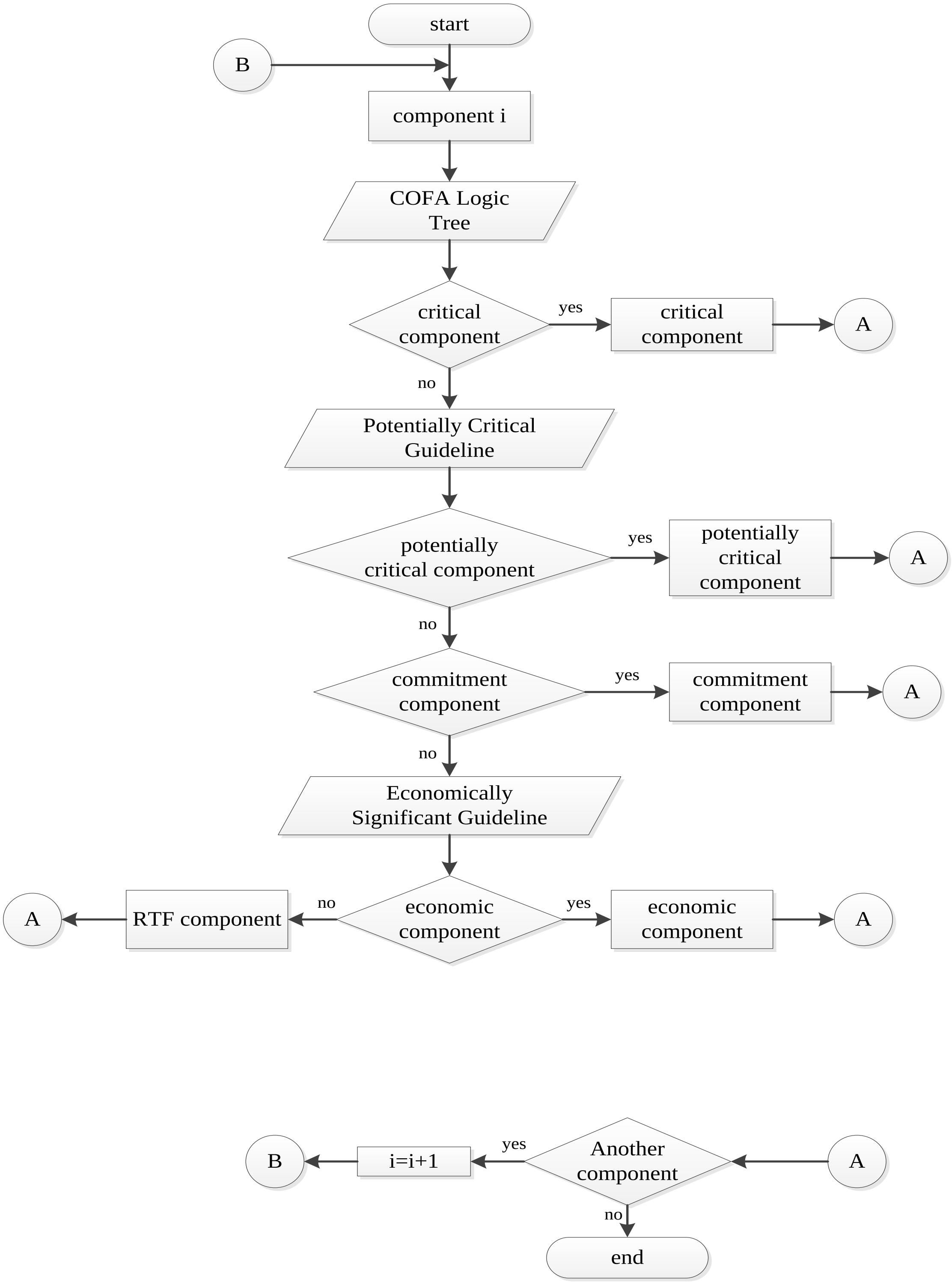

Fig. 3-7: RCM Filter

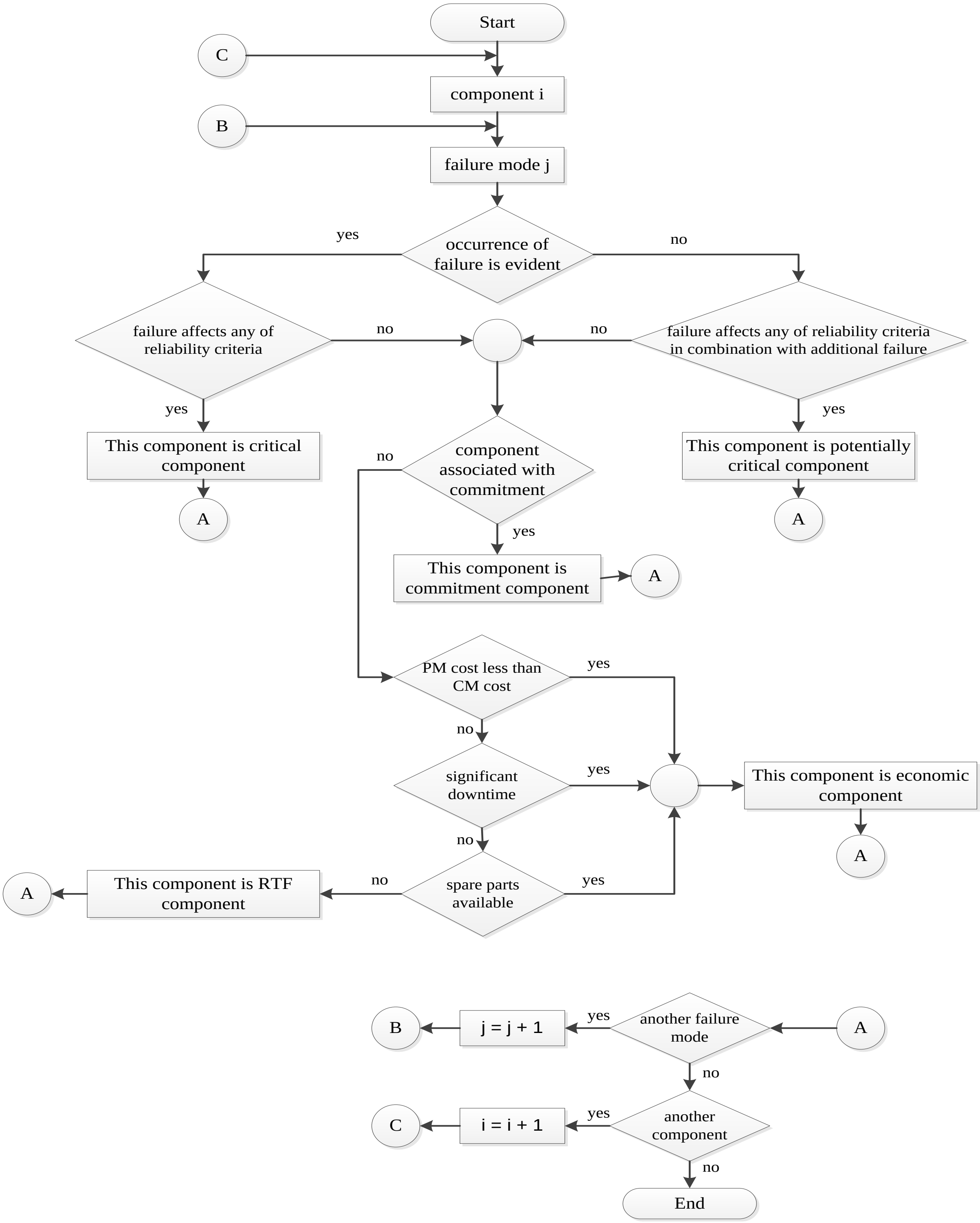

Fig. 3-8: Process Inside RCM Filter

3.4.1.2 Phase 2: Assigning the Appropriate PM Activities

The traditional PM maintenance strategies are developed by introducing a new PM type: failure finding. Failure finding aims to prevent the failure at utility level rather than component level. This means that failure finding does not work to prevent the failure itself as CBM and TBM do; instead, it works at specific intervals to only detect the failed equipment before it results in negative effect upon any reliability criteria in combination with another failure. Therefore, failure finding is only applicable to equipment whose failure is hidden. Nevertheless, if there is no applicable and effective PM assigned to prevent or at least mitigate the failure, a design change must be considered. However, it is rare that no PM activity could prevent or mitigate the failure. Indeed, design change option is only considered for critical, potentially critical, commitment and economic components. Assigning the appropriate PM activities entails two steps [6].

3.4.1.2.1 Identify the Cause of Failure Modes

For critical, potentially critical, commitment and economic equipment, all realistic causes of failure for each component failure mode must be identified. Since most components have several failure modes, they can fail in different manners. Therefore, it is necessary to identify the causes of each failure mode in order to specify the appropriate PM activity to prevent these causes [6].

3.4.1.2.2 Analyze Equipment in the PM Task Selection Logic Tree

The main goal of the PM Task Selection Logic Tree is to assign the appropriate activities of maintenance for all equipment except RTF equipment. It contains all types of PM (CBM, TBM, and failure finding) in addition to design change. As mentioned previously, design change is only considered when no effective and applicable PM task can be specified. The process is launched by determining whether a CBM can prevent the cause of failure. If there is no CBM can prevent the cause of failure, TBM is the second choice [6].

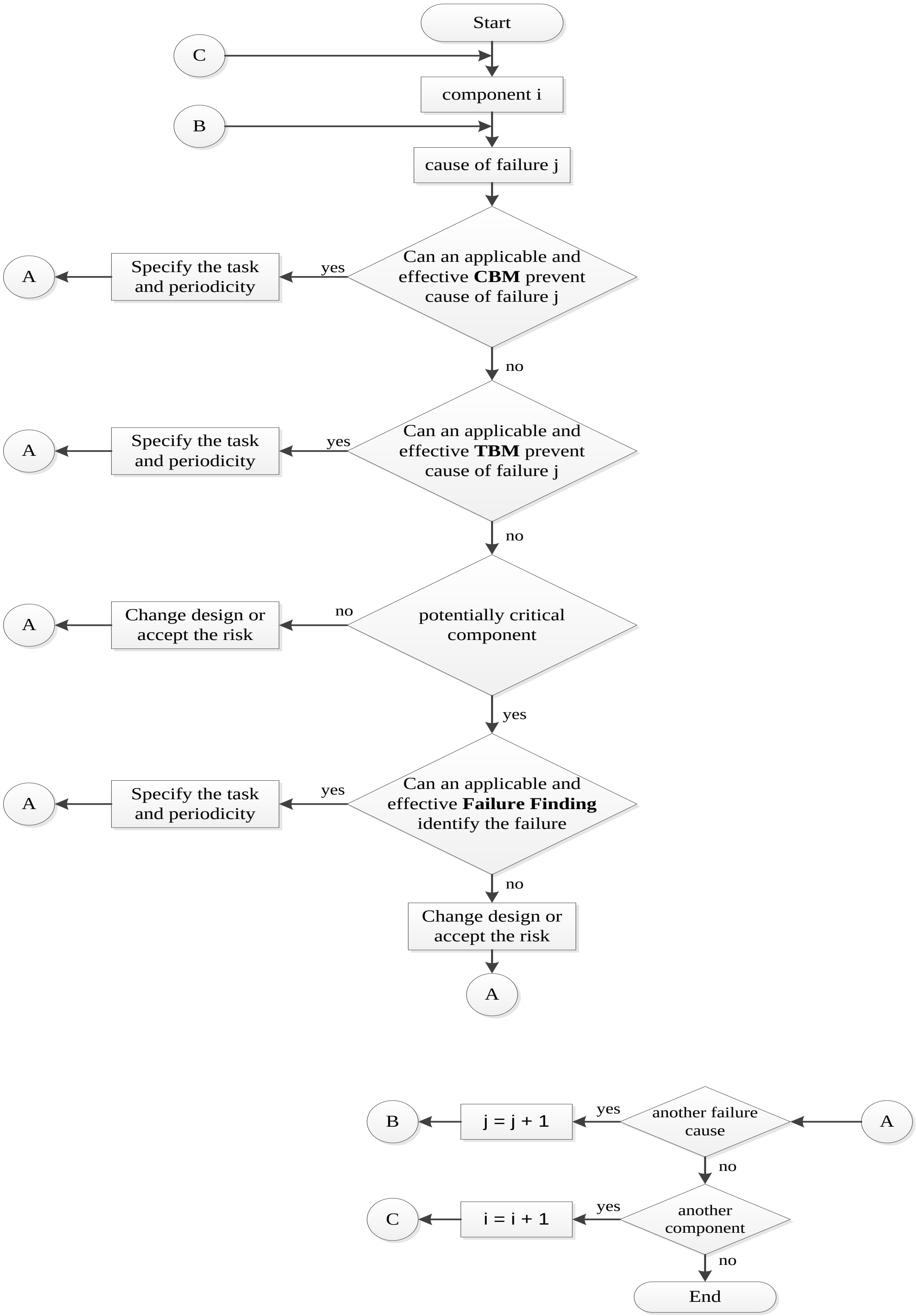

Fig. 3-9: PM Task Selection Logic Tree [6]

Usually, TBM is performed at predetermined periodicities including intrusive activities such as overhauls. The process launches with CBM because it is a nonintrusive task, thereby its inspection interval is usually less than the inspection interval of intrusive tasks. As a result, CBM often has the capability to prevent the premature failures in addition to failures that may occur during the infant mortality period. Fig. 3-9 illustrates the process of analyzing the components to determine the appropriate activities of maintenance via the PM Task Selection Logic Tree [6].

The significance of RCM is clearly demonstrated in this process as it treats each cause of failure individually. The traditional maintenance methodology usually considers only one type of maintenance whereas RCM compares different maintenance policies and selects the most cost-effective. The most cost-effective policy may involve specifying more than one type of maintenance for the same component at different periodicities [6].

After analyzing all components and assigning their appropriate activities of maintenance, phase 2 is completed. This leads to the next step of performing the maintenance tasks.

3.4.1.3 Phase 3: Performing PM Activities

The last step in implementing RCM is to perform maintenance activities. However, scheduling these tasks by determining the frequency and interval is a definite challenge. The optimum maintenance scheduling should take into account many considerations which differ from one utility to another. These considerations are comprised of but not limited to component and utility histories, manufacturer recommendations, regulatory and environmental requirements, other tasks scheduled on the same component, operating considerations, planned outage and accessibility to the component [6].

Since RCM is almost an empirical and heuristic approach, the need for incorporating some mathematical models to help schedule maintenance activities is increased [4]. In mathematical models, the outcomes can be optimized for maximizing reliability or minimizing costs under some assumptions and constraints. Mathematical models could be deterministic or probabilistic [3]. A host of research in the literature has proposed several mathematical models [16–19].

3.4.2 Implementation process of RCM via FMEA

3.4.2.1 Determine System Boundaries

The utility is divided into several systems based on the functions(s) performed. All components required to fulfill the system function(s) are grouped together provided that the component which already resides in one system cannot reside in another system [5], [6].

3.4.2.2 Determine Subsystem Boundaries.

Similarly, within a system, the components that are in charge of performing particular function(s) are partitioned into subsystems. Likewise, a component cannot reside in more than one subsystem [5], [6].

3.4.2.3 Determine Interfaces

Once the boundaries of all systems and subsystems are determined, the boundary point components are identified in order to ensure that these components are analyzed and not disregarded; moreover, to ensure that these components reside in either system/subsystem. The residing of any boundary point component is based on where it provides its function. Accordingly, these boundary point components can be divided into in-system and out-system boundary interfaces. The component is considered an out-system boundary interface if it provides its function from the subsystem being analyzed to another subsystem whereas it is considered an in-system boundary interface if it provides its function from another subsystem to the subsystem being analyzed [5], [6].

3.4.2.4 Determine Functions

After dividing the systems into smaller subsystems, all functions of each subsystem are defined. When determining all functions at the system level, it can sometimes be difficult to capture all functions, especially in complex systems. This main drawback in FMEA is overcome in COFA. Determining the functions at component level as COFA does is much easier with a low probability of missing some component functions [5], [6].

3.4.2.5 Determine the Functional Failures

The ways that each subsystem function can fail are determined [5], [6].

3.4.2.6 Determine which Components are Responsible for Functional Failures.

The component(s) whose failure(s) would result in functional failures are defined. The remaining steps of determining the dominant failure modes, system effects, and consequence of failure at utility level are similar to the steps of COFA implementation [5], [6].

3.5 Summary

In this chapter, the main concept of RCM was discussed through addressing how RCM enhanced the traditional maintenance types. First, the new features and enhancement aspects of RCM were elucidated. Second, the origination of RCM and how it has been adopted by many industries were described. Next, a detailed presentation of the equipment classification proposed by RCM was presented. Then, the implementation process of RCM via COFA was illustrated in detail. Finally, a brief presentation of the process of implementing RCM via FMEA was provided. In summary, what has been covered in this chapter is applicable to any sector. The following chapter will discuss the implementation of RCM in power system in particular.

Chapter 4

Applications of RCM in Electrical Power System Sector

4.1 Introduction

As mentioned previously, RCM was first introduced in commercial aviation industry and then adopted by other industries. RCM was brought into the nuclear power industry in 1984 by the Electric Power Research Institute (EPRI) [5]. After that, RCM was implemented in certain transmission and distribution utilities. Nonetheless, RCM has been not widely implemented in power system since its proper implementation requires broad expertise in identifying the functions, failure modes, and consequence of failure for each piece of the system's equipment [4], [13]. This obstacle may combine with other obstacles such as financial constraints which make most utilities, especially small-sized utilities, be reluctant and unwilling to build RCM model. Furthermore, the process of RCM implementation may be time consuming first by classifying all equipment and last by performing maintenance activities. All of these obstacles and factors indicate the lack of research of RCM in power system compared with traditional maintenance. This chapter will address some applications and research of RCM in power system. Some studies discuss the application of RCM for transmission or distribution systems while others explore the implementation process of RCM for certain equipment.

4.2 RCM for Transmission and Distribution Systems

Reference [20] proposed a program to implement RCM in transmission line. This program aims to improve three important factors: safety, reliability, and security of transmission systems. With regard to safety, the program works to monitor safety issues related to transmission systems such as vegetation growth and soil erosion in order to assure meeting the required safety standards. Regarding reliability, the program proposed a Decision Matrix to prioritize transmission lines based on their failure modes by identifying some parameters such as age, number of outages, number of customers, type of construction, configuration, and length. After prioritizing all lines, the conditions are determined beginning with the highest priority lines in order to assign the appropriate maintenance activities if required.

Regarding security, the program seeks to avoid catastrophic consequences in case of failure. However, this program did not show how maintenance can effectively improve reliability.

The relationship between maintenance and equipment aging has drawn much attention in RCM. A state model to represent the aging process of equipment had been proposed in [13]. This model was further developed in [21] and [22]. Reference [22] modified the state model to represent the aging process of some selected critical transmission system equipment. The aging model has a normal state where the equipment is new, a failure state, and some transitional deterioration states. Transmission towers and insulators are assumed in [22] to have two deterioration states, whereas overhead lines have three deterioration states. Maintenance is assigned based on the observation of regular equipment inspections to determine the deterioration state. The transition rates from one deterioration state to another, the time-to-state transition time and the frequency of inspections play the most important role in determining the optimal maintenance strategy. The optimal maintenance strategy is the strategy that minimizes the maintenance, repair, generation, and outage costs. Monte Carlo Simulation (MCS) and Genetic Algorithms (GA) are used to determine the optimal maintenance strategy. The proposed maintenance approach is compared with other pre-scheduled maintenance scenarios.

Reference [23] presented an introduction to how RCM can be applied to overhead distribution systems whereas reference [24] was the first attempt to study the implementation of the RCM approach in a whole power distribution system. The objective in [24] was to find cost-effective maintenance techniques for two electrical power distribution systems. The need was to develop the principle of RCM to show the effect of maintenance on reliability in a cost-effective manner. Therefore, a computer program called RADPOW (Reliability Assessment of Distribution Power Systems) was developed for reliability evaluation. The analysis was launched by identifying all critical components in the distribution systems. Second, all potential causes of failures for these components were identified. Moreover, the causes of failures were sorted based on the percentage of contribution that each cause of failure contributed to the total number of failures. The causes of failures and the contribution of each cause were determined from historical data and expertise. Then, the critical components were analyzed in detail to define the relationship between performing PM for these components and the expected improvement in reliability. Each cause of failure was individually analyzed to study the effect of PM to reduce the failures created by that cause by defining and implementing different PM strategies. The effects of PM strategies on improving the failure rate were identified. Finally, a cost/benefit analysis was conducted in order to determine the optimal PM strategy. The cost of the optimal PM strategy was compared with the cost of doing-nothing and performing CM after failure. The most cost-effective maintenance decision is the maintenance that has the lowest total cost. References [21–24] are the most relevant studies in the literature that discussed the implementation of RCM in transmission and distribution systems.

4.3 Other Implementation for RCM in Power System

Other references studied the implementation process of RCM for certain equipment such as capacitor voltage transformers, voltage regulators, and circuit breakers [25–28]. An RCM model for capacitor voltage transformers is presented in [25]. The model utilized 25-year historical failure events of capacitor voltage transformers with more than 3000 records of failure events in a power transmission company in Brazil to determine the failure effects. It was found that the leakage of insulating oil and high power factor were the most frequent failure effects. The capacitor voltage transformers were divided into subsystems. Each subsystem consisted of a set of components. The functions, functional failures, failure evidences, failure causes, and consequences of failures for each component were identified. The maintenance decision was made based on risk analysis for the consequence of each failure type. The level of risk was presented in a matrix and classified into three levels: dangerous, important, and acceptable as shown in Fig. 4-1. The level of risk of the failure could be determined by defining the probability of failure as well as its consequence severity. The probability and the severity of the failure were ranked from one to five where one represented the lowest rank and five represented the highest. As equipment age, its probability of failure increases. Based on risk analysis, actions with respect to maintenance can be taken. However, reference [25] emphasizes the need of experienced personnel to apply RCM for any system or equipment. Defining the probability of failure in addition to the severity of failure consequences are essential and cannot be done arbitrarily. In addition to the risk perspective, maintenance decisions should consider incorporating the cost perspective. This reference neither embraced cost evaluation nor showed how the risk matrix could be employed to schedule real maintenance activities.

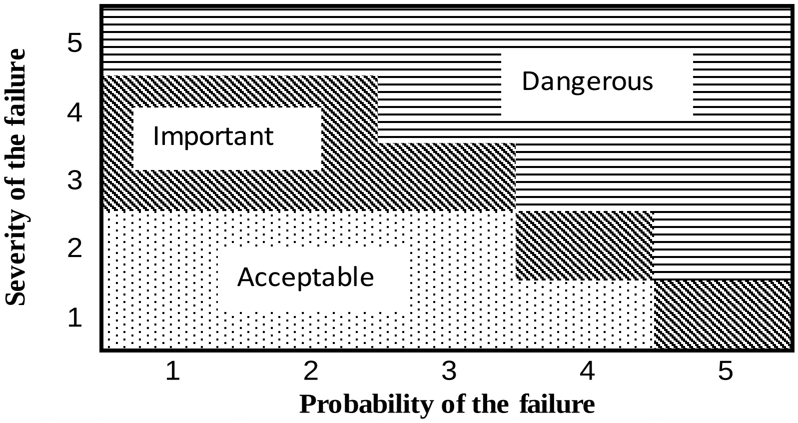

Fig. 4-1: Matrix Risk Evaluation [25]

Reference [26] performed an RCM study on voltage regulators for an electric utility. The study aimed to find a relationship between the voltage regulators types in the utility and the recorded failures as well as forecast the future failures in order to assign the appropriate maintenance activities, avoid unplanned outages, and improve the overall system reliability. Historical data such as the time between failures, the number of operations, and the causes of failures for the utility's voltage regulators was utilized in the study. After collecting this data, voltage regulators were categorized based on manufacturer, size, and age. Moreover, failures were categorized into mechanical and electrical. A discriminant analysis with the utilization of hypergeometric computations on the failure data was employed to correlate between the data collected in order to find the relationships between the categories of voltage regulators and the categories of failures. Then, a regression analysis was utilized to forecast potential types of failures. A set of regression equations were developed to estimate the probability of failure.

The implementation of RCM for circuit breakers was studies in [27] and [28]. The concept of RCM was utilized in [27] to decide the appropriate maintenance decision for circuit breakers based on importance and technical condition. This utilization was further discussed in [28], where a decision system was developed for maintenance of circuit breakers based on the concept of RCM. The circuit breakers under study were ranked based on the two criteria of technical condition and importance. Therefore, two indexes were introduced: the technical condition index (c) and the importance index (i) to numerically represent the condition of each circuit breaker and the respective consequence of its failure. The importance index was defined once the circuit breaker was installed and kept unchanged while the condition index changed based on the parameters that may have contributed to the failure occurrence. All contributing parameters to the failure such as vacuum level, contact resistance, location of circuit breaker in the system, age of circuit breaker, time since last maintenance activities, and number of operations were identified. These parameters were then analyzed to determine the failure modes and failure consequences that could be originated by these parameters. Based on this analysis, the parameters were weighted and the condition index was evaluated. The importance index was evaluated based on the outage cost due to the failure. This cost varied depending on many factors such as the load type, outage duration, repair/replacement cost, bus configuration and customer expectations. The relationship between the outage cost and the importance index was proportional. After both condition and important indexes were evaluated, they were placed on a decision map to make the final maintenance decision. The decision map had four decision areas including corrective maintenance, replacement, maintenance, and no action as shown in Fig. 4-2. C_r, C_m, and I_c are discrete values to separate the decision areas. For example, if $i > I_c$ whilst $C_m < c < C_r$, the final decision was to perform maintenance to improve the condition index and so on. However, the implementation model of RCM for circuit breaker in this reference focused only on determining the maintenance decision without providing explanation of what type of maintenance should be performed and how frequent. Moreover, the decision map would be more beneficial and effective if it was formed in a probabilistic model using, for instance, fuzzy logic.

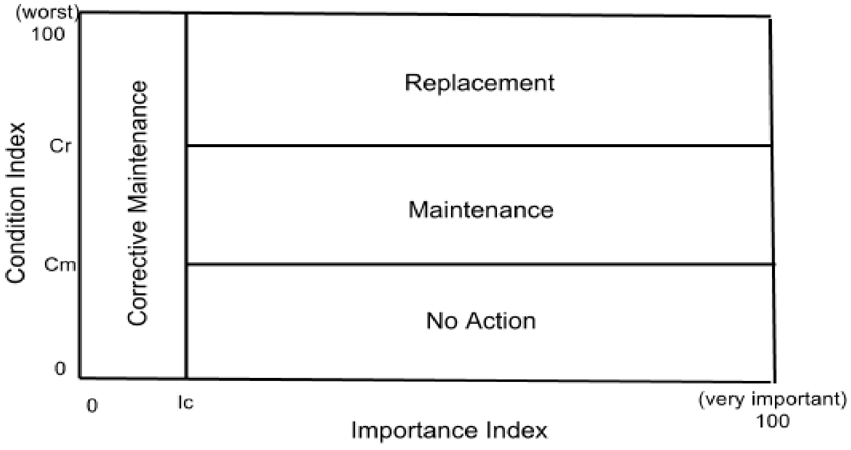

Fig. 4-2: Decision Making Map of Maintenance Action for Circuit Breakers [28]

The concept of RCM has been discussed differently in other references. Reference [29] incorporated a portion of the RCM principle in a transmission cable replacement analysis by investigating different replacement periods to select the best replacement period with the lowest risk operation mode. The study did not perform real maintenance activity showing how maintenance could extend equipment lifetime.

One essential step of RCM is to prioritize components based on their reliability importance prior to assigning maintenance activities. Reference [30] proposed an approach to determine and prioritize the critical components for maintenance using the analytical hierarchical process (AHP) and fuzzy set. The approach developed the conventional AHP by using fuzzy scale ratios instead of crisp numbers for pairwise comparison. The approach used the triangular membership functions. The components were prioritized based on the following set of criteria: total number of components, total number of failure for each component, repair duration, investment cost, and maintenance cost.

4.4 Summary

This chapter presented studies which have examined the implementation of RCM in electrical power system. Although the application of RCM in power system is relatively limited, the presented studies in this chapter utilized the RCM concept differently. Some studies, such as [24], performed real and complete RCM program. However, the RCM program in [24] was not performed for all equipment in the distribution systems, but only for the most critical components. On the other hand, other studies utilized the concept of RCM to propose some approaches that help identify critical components and/or prioritize maintenance activities. Nevertheless, based on the author's best knowledge, all studies that discussed the implementation of RCM program in power system handled the program without taking into account the option of replacement. This drawback and its resolution will be discussed in the next chapter.

Chapter 5

The Proposed Reliability-Centered Maintenance and Replacement Approach

5.1 Introduction

While utilities work to optimally schedule their equipment for maintenance, they may overlook the option of replacing the equipment. As a result, some equipment may be left to operate although their economic lifetime is expired. The aging state models proposed in [13], [21] and [22] can be utilized to assign maintenance activities based on the condition of the equipment; however, these models do not properly consider the replacement option. On the contrary, they represent the replacement activity as a corrective maintenance assigned after the occurrence of failure. In fact, generalizing this representation for all equipment is not accurate since the corrective maintenance should be assigned only for RTF equipment. From the reliability point of view, critical equipment whose failure significantly affects the reliability of the system cannot be classified as RTF [6]. Rather, critical equipment in the power systems must be replaced before reaching the failure state due to its failure impacts on the reliability of the system. Hence, these equipment aging models should be modified to involve the replacement option, especially upon implementing RCM for critical equipment. Furthermore, these aging models do not consider rapid changes in the failure rate taking place during the later years of the equipment's age due to wear and tear.

As references [13], [21] and [22] focused only on assigning maintenance activities, other references, such as [31], focused only on finding the optimal replacement time without considering the effect of maintenance. Reference [31] proposed a replacement model for power transformers; however, the effect of maintenance on extending lifetime was not taken into account upon determining the replacement year.

This chapter will introduce the proposed method of this thesis. This thesis proposes a reliability-centered maintenance and replacement (RCMR) approach which aims to identify the missing link between reliability-centered maintenance (RCM) and replacement approaches. The RCMR approach will demonstrate the effect of maintenance on determining the replacement year and methodically compromise between maintenance and replacement decisions.

5.2 Equipment Lifetime

Equipment aging is critical issue in asset management business. As a piece of equipment ages, the probability of failure and the associated maintenance costs increase. In addition, spare parts may not be produced or the equipment may even be no longer technologically valid [32]. Accordingly, equipment lifetime can be viewed from three perspectives: physical, technical, and economic [33].

1. **Physical Lifetime:** A piece of equipment may need to be replaced because it reaches a state in which it can no longer operate under normal operating conditions. Physical lifetime can be extended by preventative maintenance [33].
2. **Technical Lifetime:** Because of technical reasons such as new technology emerging or spare parts obsolescence, a piece of equipment may need to be replaced regardless of its physical and economic lifetimes [33].
3. **Economic Lifetime:** A piece of equipment may need to be replaced because it is not economically worthwhile to keep it in-place compared to installing a new piece of equipment, although it may be physically and/or technically usable. The economic lifetime can be estimated by determining the capital cost of the equipment as well as the total annual costs [33].

The RCMR approach has the capability to consider both the physical and economic lifetimes in the analysis. In the following sections, the concept of RCMR will be discussed in detail.

5.3 RCMR Approach

The main objective of RCMR approach is to first find the most cost-effective maintenance policy via implementing the concept of RCM, and then identify the most economical replacement year. In addition, RCMR approach investigates whether it is worthwhile to perform maintenance activities.

The concept of RCMR approach is applied to one of the most critical pieces of equipment in the power system: the power transformer.

First, a replacement study is conducted when no overhaul maintenance is assigned for the remaining lifetime of the in-place transformer. After that, a proposed maintenance strategy is introduced in order to determine the most cost-effective maintenance policy for the in-place transformer over its remaining lifetime. Then, another replacement study is conducted which takes into account the effect of maintenance. Finally, a comparison between the two replacement studies is made. The proposed approach consists of four parts: replacement study without the effect of maintenance, optimal maintenance policy, replacement study with the effect of maintenance, and final decision.

5.4 Part 1: Replacement Study without the Effect of Maintenance

Changes in the aging states of the transformer over its lifetime can be represented by the well-known and most accepted model, bathtub curve. Bathtub curve, which represents the relationship between the failure rate and the lifetime of the transformer, consists of three main regions: infant mortality region, normal operating region, and wear-out region [32]. Thus, the bathtub curve can be segmented into three segments. Each segment represents an aging state based on changes in the transformer failure rate as shown in Fig. 5-1.

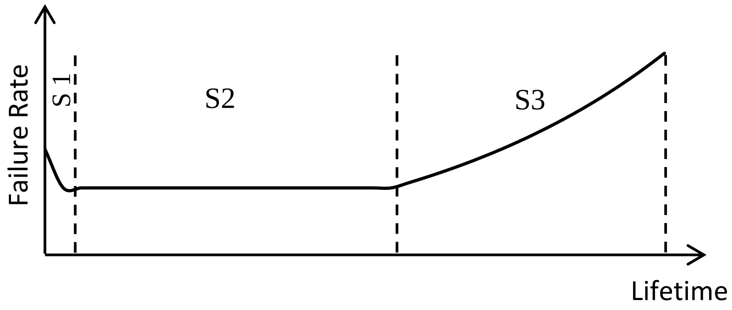

Fig. 5-1: Transformer Aging States Based on Failure Rate Change

S_1 represents the initial state where the transformer is new in the infant mortality region. S_2 represents the state of the transformer in the normal operating region. S_3 represents the deterioration state where the transformer is in the wear-out region. Thus, S_3 comprises all wear-out region years. The transformer is assumed to be in the failure state when it reaches its end of physical life where the failure rate is at the maximum value.

The replacement decision of the transformer is usually initiated once it starts to wear out. Thus, each year of the wear-out region years of the in-place transformer is likely to be the replacement year. These years are referred to as the remaining lifetime years of the in-place transformer.

Replacement study can be conducted via different methods such as dynamic programming and shortest path [34–36]. Whatever method is used, the total annual cost (TAC) and the market value (MV) for each year over the lifetime of the new transformer (challenger) and over the remaining lifetime of the in-place transformer (defender) should be determined. One of the commendable replacement methods is the future worth cost advantage (FWCA) approach [37].

The FWCA approach is used in this thesis to determine the transformer replacement year. In FWCA approach, TAC and MV are utilized to calculate both the marginal costs (MGCs) over the remaining years of the defender and the minimum equivalent uniform annual cost ($\mathrm{EUAC}_{\mathrm{min}}$) of the challenger. Throughout the span of the study period, different replacement strategies are defined. The FWCA for each replacement strategy is computed. A replacement strategy with the highest FWCA is identified as the optimal strategy [37]. The following subsections discuss the process of the replacement study using the FWCA approach.

5.4.1 Calculation of the Total Annual Cost

The total annual cost (TAC) of the transformer is comprised of three costs: customer interruption cost (CIC), maintenance cost (MC), and operating cost (OC). The non-owner viewpoint approach [38] is applied upon calculating the total annual cost of the in-place transformer. The non-owner viewpoint approach considers only the future costs while it considers the previous costs as sunk costs and irrelevant to the replacement study [39].

$$TAC = CIC + MC + OC \tag{5.1}$$

Customer interruption cost represents the economic costs due to power outages. A Canadian survey was conducted for different customer sectors to estimate the costs resulting from power interruptions [40], [41]. The results obtained from the survey show that the cost of an interruption depends on the customer type and the interruption duration. Therefore, a sector customer damage function (SCDF) was created to express the economic cost per kW outage for different sectors as shown in Table 5-1.

If the interrupted load is composed of several sectors, the group customer damage function (GCDF) is used instead, whereupon the percentage of each sector (w) should be identified [40], [41]. CIC can be calculated by using (5.3).

Table 5-1: SCDF for all Sector Types [41]

Sector	**Interruption Duration (min.) & Cost ($/kW)**				
	1 min.	20 min.	60 min.	240 min.	480 min.
Larger user	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.16	55.81
Commercial	0.381	2.969	8.552	31.32	83.01
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.69
Govt.& Inst.	0.044	0.369	1.492	6.558	26.04
Other	4.778	9.878	21.06	68.83	119.2

$$GCDF = \sum_{u=1}^{s} SCDF_u \times w_u \tag{5.2}$$

$$CIC_t = \lambda_t \times L \times GCDF \tag{5.3}$$

Where

CIC_t Customer interruption cost at year *t* ($);

λ_t Transformer failure rate at year *t* (failure/year);

L Average load (kW);

$SCDF_u$	Sector customer damage function for load sector *u*;
GCDF	Group customer damage function;
w_u	Percentage of load sector *u*;
s	Number of load sectors.

Maintenance cost includes all costs paid to perform maintenance activities. Since the first investigation involves performing the replacement study without considering the effect of maintenance, no maintenance is performed at this part.

Operating cost, which is the third term in total annual cost equation, consists of two costs: energy cost and demand cost [31].

$$OC_t = \left(P_{nl} + P_l \times LF^2 + P_{au} \times prob.\right) \times 8760 \times tariff + \left(P_{nl} + P_l + P_{au}\right) \times D_c \times 12 \tag{5.4}$$

Where

OC_t	Operating cost at year *t* ($);
P_{nl}	No-load power losses (kW);
P_l	Power losses (kW);
LF	Load Factor;
P_{au}	Auxiliary losses (kW);
Prob.	Probability of the operation of the auxiliary equipment;
tariff	Energy tariff ($/kWh);
D_c	Monthly demand charge ($/kW).

5.4.2 Estimation of the Transformer Market Value

The market value is the estimated value of the asset upon selling it out [38], [39] and [42] There is no exact method to precisely estimate this amount at each year during the transformer's lifetime; therefore, the market value of the transformer at any year is deemed to be equal to its book value at that year as assumed in [31]. Reference [31] assumed that transformer capital cost depreciates each year during infant mortality and normal operating regions by straight line depreciation method whereas it depreciates by sum-of-year-digits method during the wear-out region. The transformer is assumed to have no worth at the end of its physical lifetime. The book (market) value of the transformer at any year can be calculated as follows:

$$BV_t = C - \sum_{j=1}^{t} D_j \tag{5.5}$$

Where

BV_t	Transformer book value at the end of year *t* ($);
C	Transformer capital cost ($);
$\sum_{j=1}^{t} D_j$	Accumulated depreciation charges from the first year until year *t* ($).

5.4.3 Computation of the FWCA

Determining the most economical year to replace the in-place transformer is dependent on the FWCA. FWCAs are computed by determining the minimum equivalent uniform annual cost ($EUAC_{min}$) of the new transformer over its lifetime in addition to the marginal costs (MGCs) of the in-place transformer over its remaining lifetime [37].

The EUAC at year *t*, which represents the equivalent annual cost from the first year until the end of year *t*, can be calculated by converting all cash flows during this span into an equivalent uniform annual amount [38], [39] and [42]. On the other hand, the MGC at year *t* represents the additional cost incurred due to not replacing the in-place transformer at year *t*. The MGC at year *t* consists of three terms: the loss in the market value of the in-place transformer, the foregone interest because money remains invested in the in-place transformer, and the total annual cost at year *t* [43]. The steps needed to compute the FWCA are presented as follows:

1) Calculate the EUAC for each year for the new transformer over its lifetime

$$EUAC_m = \left[C + \left(TAC_m - MV_m\right)\left(P/F,i,m\right) + \sum_{j=1}^{m-1} TAC_j \left(P/F,i,j\right) \right] \left(A/P,i,m\right) \quad (5.6)$$

Where

$EUAC_m$	Equivalent uniform annual cost at year *m* ($);
C	Capital cost ($);
(P/F,i,m)	Single-payment present worth factor at interest rate *i* for *m* years;
(A/P,i,m)	Uniform-series capital recovery factor at interest rate *i* for *m* years;
TAC_m	Total annual cost at year *m* ($);
MV_m	Market value at year *m* ($).

The single-payment present worth factor (P/F,i,m) and the uniform-series capital recovery factor (A/P,i,m) can be calculated by (5.7) and (5.8) respectively

$$\left(P/F,i,m\right) = \frac{1}{\left(1+i\right)^m} \quad (5.7)$$

$$\left(A/P,i,m\right) = \frac{i\left(1+i\right)^m}{\left(1+i\right)^m - 1} \quad (5.8)$$

2) Determine the economic service life (ESL) of the new transformer where the $EUAC_{min}$ occurs.

3) Since replacement decision is only initiated when the in-place transformer undergoes the wear-out region, choose the remaining lifetime of the in-place transformer as a study period *n*.

4) Calculate the MGC of the in-place transformer for each year over the study period *n*.

$$MGC_t = \left(MV_{t-1} - MV_t\right) + \left(MV_{t-1} \times i\right) + TAC_t \quad (5.9)$$

Where

MGC_t	Marginal cost at year *t* ($);

$MV_{t-1} - MV_t$	Loss in market value from year *t–1* to year *t* ($);
$MV_{t-1} \times i$	Foregone interest ($);

Note that upon calculating the MGC at year 1, the MV at year 0 represents the market value at the end of the normal operating region.

5) Define alternative replacement strategies. A replacement strategy RS_j is defined as using the in-place transformer until the end of year *j-1* and then replacing it with a new transformer at the beginning of year *j* where *j* = 1, 2… *n*. Due to the significance of the transformer in the power grid from the reliability perspective, it is assumed that the in-place transformer must be replaced before it reaches its end of physical life, no later than the end of year *n-1*.

6) For all defined replacement strategies, compute the FWCAs. The FWCA of RS_j is given by:

$$FWCA_{RS_j} = \sum_{t=j}^{n} \left[\left(MGC_t \right) - \left(EUAC_{\min} \right) \right] \times \left(F / P, i, n-t \right) \tag{5.10}$$

Where

$FWCA_{RS_j}$	Future worth cost advantage of replacement strategy RS_j;
MGC_t	Marginal cost of the in-place transformer at year *t* ($);
$EUAC_{min}$	Minimum equivalent uniform annual cost of the new transformer ($);
(F/P,i,n–t)	Single-payment compound amount factor at interest rate *i* for *n-t* years

The single-payment compound amount factor can be calculated as follows

$$\left(F / P, i, n-t \right) = \left(1 + i \right)^{n-t} \tag{5.11}$$

The FWCA of RS_j can be positive, negative, or zero. Only strategies with non-negative FWCA are acceptable. Therefore, the optimal replacement strategy RS_{opt} is the strategy that has the highest non-negative FWCA [37].

7) Define the optimal replacement year t_{rp}.

Conducting the replacement study using the FWCA approach is superior to other replacement approaches because all other replacement approaches are concerned only with finding the optimal replacement time. In contrast, FWCA approach provides all acceptable replacement strategies. This advantage allows the utility to compromise the replacement decision in case of expediting or postponing the replacement time of the defender [37].

5.5 Part 2: Finding the Optimal Maintenance Policy

Solely from a reliability perspective, transformer should be replaced once it reaches S_3 state because the probability of failure increases every year in the wear-out region due to the dramatic increase in the failure rate; nevertheless, this decision may not be the most cost-effective. When a replacement decision is studied, all enhancing options should be considered that may improve the condition of the in-place transformer and hence the reliability. These enhancing options may comprise of some overhaul major maintenance activities. A cost/benefit analysis may be conducted to decide whether it is cost-effective to perform replacement or overhaul major maintenance.

S_3 state is a significant state since the likelihood of failure is high; therefore, changes in the deterioration state of the transformer during S_3 should be determined for each year of S_3 years. Thus, the proposed approach further segments S_3 into sub-states equal to the number of years in S_3. For instance, if the duration of the wear-out region is *n* years, then S_3 has *n* sub-states: $S_{3\text{-}1}$, $S_{3\text{-}2} \ldots S_{3\text{-}n}$. Each sub-state represents a deterioration state per se.

Changes in the deterioration state of S_3 are expressed in terms of changes in the failure rate. $S_{3\text{-}n}$ designates the failure state. Based on this, for each sub-state, two maintenance decisions can be applied which are either *do nothing* or *perform major maintenance*. The effect of major maintenance reduces the transformer's failure rate value to the value of the first year of the wear-out region as considered in [44]. The maintenance is assumed to be performed perfectly.

For example, if major maintenance is performed when the in-place transformer is at $S_{3\text{-}4}$, the failure rate value of $S_{3\text{-}4}$ is reduces to the failure rate value of $S_{3\text{-}1}$. After that, the failure rate increases again according to the deterioration pattern of the transformer unless another maintenance activity is assigned in subsequent year(s). Both maintenance decisions are examined for all sub-states except S_{3-1}. The Genetic Algorithm [45] can be used to find the optimal maintenance policy.

5.5.1 Generating Population

Possible maintenance policies can be formed in terms of chromosomes. Each chromosome represents a maintenance policy with a length equal to *n-1*. Each year is represented by a bit with a value of "0" or "1" for *do nothing* or *perform major maintenance* respectively. Thus, each maintenance policy represents a string of maintenance decisions (variables). The Genetic Algorithm can be employed as a search tool [45], [46] to randomly generate different maintenance policies. The full search space would be $2^{(n-1)}$. To illustrate, if the failure rate of a 25-year-lifetime equipment is considered to follow the bathtub pattern and starts to wear out at the end of the 21st year, the remaining lifetime in the wear-out region is four years. Therefore, the equipment has four sub-states in S_3 which are S_{3-1}, S_{3-2}, S_{3-3}, and S_{3-4}. The full search space of this equipment is $2^3 = 8$. Assume that the equipment has the failure rate values in the wear-out region as shown in Table 5-2. Because the search space size of possible maintenance policies in this example is small, it can be manually illustrated as shown in Table 5-3.

Table 5-3 shows all possible maintenance policies for equipment with a wear-out region of four years. Maintenance policy 1 shows the decision of *do nothing* which allows the failure rate to keep increasing according to the original deterioration pattern of the equipment. In contrast, policy 3, for example, shows that maintenance is assigned to be performed when the equipment is at S_{3-3}. As a result of policy 3, the failure rate value of S_{3-3} would be improved from 0.07 to 0.05. As there is no maintenance assigned when the equipment is at S_{3-4}, the failure rate of the equipment would deteriorate again with the same deterioration rate; however, the failure rate value of S_{3-4} would be updated to be 0.06 instead of 0.08. Applying policy 8 would keep the failure rate constant at 0.05.

Table 5-2: Failure Rates in the Wear-Out Region for Example Equipment

Sub-State	λ (f/yr)	Sub-State	λ (f/yr)
S_{3-1}	0.05	S_{3-3}	0.07
S_{3-2}	0.06	S_{3-4}	0.08

Table 5-3: All Possible Maintenance Policies for Example Equipment

Maintenance Policy	Sub-State		
	S_{3-2}	S_{3-3}	S_{3-4}
1	0	0	0
2	0	0	1
3	0	1	0
4	0	1	1
5	1	0	0
6	1	0	1
7	1	1	0
8	1	1	1

5.5.2 Problem Formulation

The concept of RCM can be implemented by examining all possible maintenance policies to find the optimal maintenance policy which is the main objective of part 2. To do this, the present value (PV) method of the total cost is applied [12]. For each maintenance policy, the TACs are calculated as explained in sub-section 5.4.1. Then, the summation of TACs is converted into PV at the first year of the wear-out region years using (5.12). The optimal maintenance policy has the lowest PV (fitness function). The proposed maintenance strategy schedules maintenance activities at specific time intervals based on changes in the failure rate values. This clearly shows the implementation of RCM that combines both TBM and CBM.

$$PV = \sum_{j=1}^{n} \frac{TAC_j}{(1+i)^{j-1}} \tag{5.12}$$

Where

PV	Total present value cost at the first year of the wear-out region years ($);
TAC_j	Total annual cost at year *j* ($);
n	Remaining lifetime years of the in-place transformer (number of sub-states at S_3);
i	Interest rate.

5.5.3 Selection, Crossover, and Mutation

Fig. 5-2 outlines the procedure of finding the optimal maintenance policy using the GA. First, an initial population of maintenance policies (individual chromosomes) is randomly generated. After that, the fitness function for each maintenance policy is calculated. Then, the rank-based technique is applied to rank the maintenance policies based on their fitness. Maintenance policies with high fitness scores have a greater chance of being selected as parents. Next, offspring chromosomes are generated using the uniform crossover technique with a probability of 0.5. To preserve diversity, a mutation rate of 0.1 is considered. For each variable, a random number between 0 and 1 is generated. The variables whose random numbers are less than or equal to the mutation rate will be mutated. This mutation involves changing a 0 to a 1 and vice versa. The optimal maintenance policy is defined after all possible maintenance polices have been examined where the maximum number of iterations have been reached.

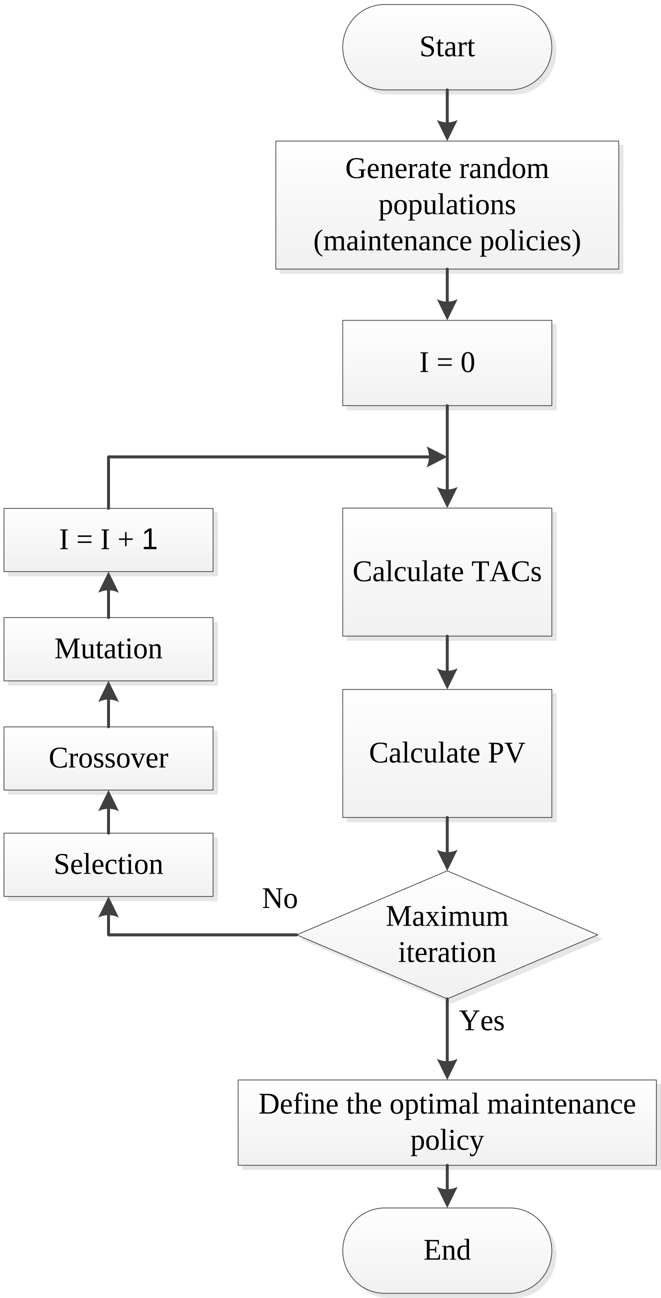

Fig. 5-2: Flowchart for the Procedure of Finding the Optimal Maintenance Policy using GA

5.6 Part 3: Replacement Study with the Effect of Maintenance

The same process followed in Section 5.4 will be followed in this part; however, few notes should be indicated herein. These notes can be summarized as follows:

1) Maintenance cost (MC) is involved in TAC calculations. Whenever maintenance is performed during the study period, MC is considered.
2) Applying the optimal maintenance policy will extend the lifetime of the in-place transformer. As an effect of maintenance, the failure rate values of the years which are assigned maintenance activities are set to the failure rate value of S_{3-1}. Consequently, the failure rate values of subsequent years are positively modified. This modification definitely changes the failure rate value of S_{3-n}. In other words, the original failure state, S_{3-n}, of the in-place transformer is deferred *k* years and hence the failure state becomes S_{3-n+k}. The number of extended years *k* can be determined by the following steps:
    - The original failure rate values of S_3 before assigning any maintenance activities are determined.
    - After applying the optimal maintenance policy, all failure rate values are updated.
    - The newly updated failure rate at the last year of the original lifetime, S_{3-n}, is determined.
    - No maintenance activities are assigned beyond the original lifetime over the extended years. As a result, the failure rate begins to increase again starting from S_{3-n+1} according to the deterioration pattern of the transformer until it reaches the original value of S_{3-n}.
    - Then, the new failure state, S_{3-n+k}, is defined and the number of extended years *k* is determined.
3) The study period is modified to be $n+k$ instead of n.
4) Maintenance activities have no effect on the market value of the transformer.

5.7 Part 4: Final Decision

By computing the FWCA and determining the t_{rp}, the replacement study is completed. In this thesis two replacement studies have been conducted. The first study was conducted over the original remaining lifetime of the defender whereas the second study was conducted after the lifetime of the defender had been extended.

The axiomatic question that arises is *which replacement decision should the utility follow?* To answer this substantial question, the utility needs to determine all expenses incurred since the defender started to wear out until the challenger is installed for both studies taking into account the time value of money. Therefore, a new economic term is introduced which is the equivalent uniform annual expenses (EUAE).

The purpose of calculating the EUAE is to find the equivalent annual expenses which are paid by the utility from the beginning of the study period until the end of the replacement year. The method of calculating the EUAE is identical to the method of calculating the EUAC. However, the number of interest periods in the EUAE is always set to be equal to t_{rp}; in addition, the capital cost of the challenger is involved in the calculations. Therefore, calculating the EUAE entails finding the MV of the defender at the end of the normal operating region, the TACs of the defender from the first year of its wear-out region until the end of the replacement year, the MV of the defender at the replacement year, and the capital cost of the challenger. The replacement studies are handled as two alternatives and the alternative that has the lowest EUAE is chosen as the best replacement decision. The EUAE can be calculated as follows:

$$EUAE_{t_{rp}} = \left[MV_O^D + TE_{t_{rp}} \left(P/F, i, t_{rp}\right) + \sum_{j=1}^{t_{rp}-1} TAC_j^D \left(P/F, i, j\right) \right] \left(A/P, i, t_{rp}\right) \quad (5.13)$$

Where

$\mathrm{EUAE}_{t_{rp}}$	Equivalent uniform annual expenses at t_{rp} (\$);
$\mathrm{MV}_{\mathrm{O}}^{\mathrm{D}}$	Market value of the defender at the end of the normal operating region (\$);
$\mathrm{TE}_{t_{rp}}$	Total expenses at t_{rp} (\$);
$\mathrm{TAC}_{\mathrm{j}}^{\mathrm{D}}$	Total annual cost of the defender at year j (\$).

The total expenses (TE) at the replacement year t_{rp} can be calculated using (5.14)

$$TE_{t_{rp}} = TAC_{t_{rp}}^{D} + C^{C} - MV_{t_{rp}}^{D} \tag{5.14}$$

Where

$TAC_{t_{rp}}^{D}$	Total annual cost of the defender at t_{rp} (\$);
C^{C}	Capital cost of the challenger (\$);
$MV_{t_{rp}}^{D}$	Market value of the defender at t_{rp} (\$).

5.8 Summary

This chapter introduced the proposed RCMR approach. The RCMR approach is a novel method which aims to compromise maintenance and replacement decisions. The approach investigates whether it is beneficial to extend the lifetime of equipment by maintenance. The main parts of RCMR were addressed in detail. The first part is comprised of conducting replacement study without taking into account the effect of maintenance. The second part, as preliminary to the third part, is comprised of finding the optimal frequencies of performing maintenance activities. Taking the effect of maintenance into account upon conducting the replacement study is the third part in the RCMR approach. Finally, a comparison between the first and third parts was made in the fourth part.

Chapter 6

The RCMR Approach: Case Study

6.1 Introduction

The proposed approach will be numerically illustrated in this chapter. As previously discussed, the concept of RCMR approach will be applied to one of the most critical pieces of equipment in the power system: the power transformer.

6.2 Case Study

6.2.1 Data Initialization

The proposed approach is illustrated numerically in this section. Most input data used in this case study has been obtained from [31]. Reference [31] provided data for an industrial load fed by a 2-MVA power transformer as shown in Fig. 6-1. The maximum load demand is 1.7 MW with a load factor of 0.8. The original physical lifetime of the power transformer under study is 35 years. The in-place transformer has completed 20 years in service and has just begun wearing out. The duration of the infant mortality region is one year. The failure rates in the infant mortality region and in the normal operating region are 0.105 failure/year and 0.07 failure/year respectively [31]. According to [31], the failure rate of the power transformer doubles every ten years in the wear-out region.

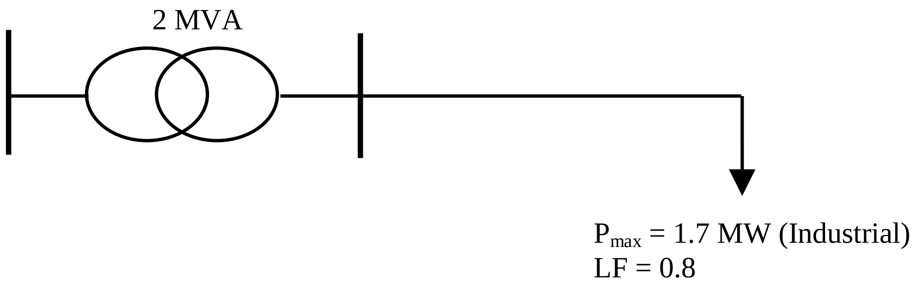

Fig. 6-1: Single Line Diagram for the Case Study

In [31], however, maintenance activities were scheduled to be performed at specific frequencies. Moreover, the effect of maintenance on improving the condition of transformer was not taken into account. As pointed out earlier, in RCMR approach maintenance activities should be scheduled in a cost-effective manner while considering the effect of maintenance. The cost-effectiveness of maintenance in RCMR approach is investigated by conducting two replacement studies: with and without the effect of maintenance. As a result, the two-state outage model in [47] is utilized instead of the outage model of [31] as it is much closer to reality. In [47], two outages are considered: forced and planned. According to [47], the repair times for the forced and planned outages are 29.78 hours and 30.11 hours respectively. The transformer's terminals are assumed to be 100 percent reliable. The technical specifications of the in-place and new transformers are identical. The capital cost of the new transformer is $250,000 whereas the in-place transformer was purchased with $150,000 [31]. The capital cost of new transformer is fixed regardless of purchase year. The minimum acceptable rate of return is 10 percent.

6.2.2 Part 1: Replacement Study without the Effect of Maintenance

6.2.2.1 Total Annual Cost Calculations

In the first study, the TAC consists of two terms which are OC and CIC. As the transformer feeds only an industrial load, only the associated interruption costs of the SCDF for the industrial load are considered. The OC is a constant annual cost as the energy tariff is assumed to be constant. The no-load power losses are 5 kW whereas the load power losses are 15 kW. The energy tariff is ¢5/kWh. The monthly demand charge is $5/kW. No auxiliary is needed for these transformers [31]. The TACs of the new transformer are calculated using (5.1) and shown in Fig. 6-2. The TACs of the in-place transformer over the wear-out region are identical to the TACs of the new transformer over the corresponding region.

6.2.2.2 Market Value (MV) Estimation

The market values of the in-place and new transformers are estimated based on the assumption made in sub-section 5.4.2. Fig. 6-3 shows the market values for both in-place and new transformers.

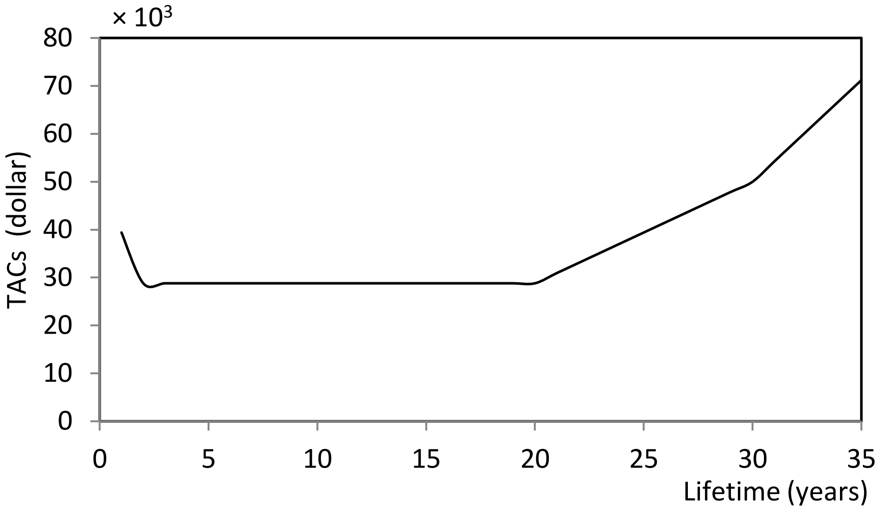

Fig. 6-2: TACs of the New Transformer

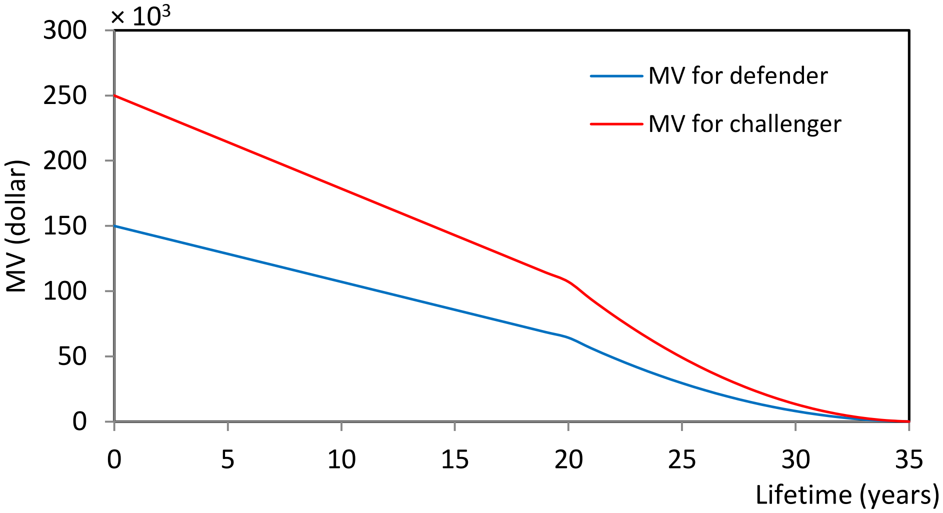

Fig. 6-3: MVs for both In-Place (Defender) and New (Challenger) Transformers

6.2.2.3 FWCA Computation

The EUACs for each year of the new transformer are calculated using (5.6) and depicted in Fig.6-4, which shows that the EUAC_{min} of the new transformer occurs at year 30. Since the duration of the wear-out region of the in-place transformer is 15 years, the study period *n* is

15 years. The marginal costs of the in-place transformer over the study period are calculated using (5.9) and tabulated in Table 6-1. Alternative replacement strategies are first defined and then the FWCA for each replacement strategy is computed in Table 6-2. The optimal replacement strategy RS_{opt} is found to be RS_{11} which means that the defender should be replaced by the end of its year 30 (the 10th year in the study period).

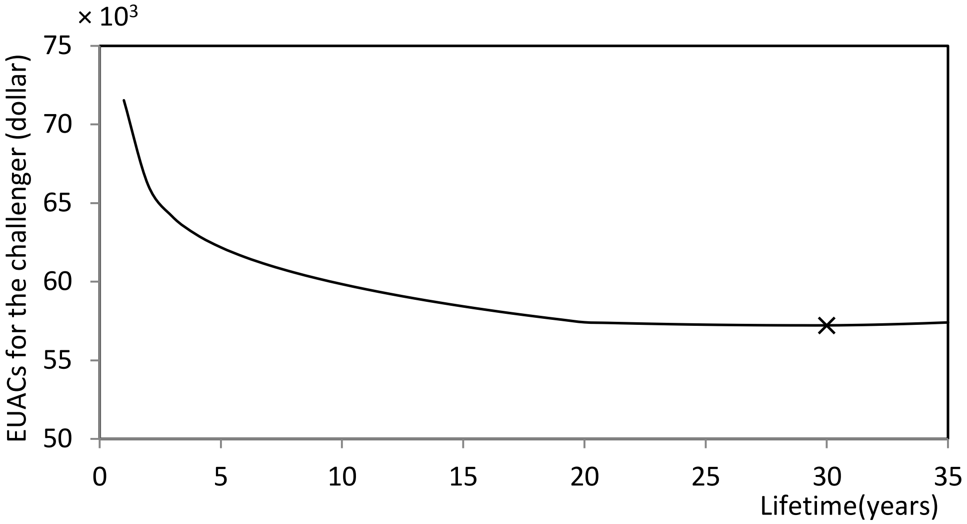

Fig. 6-4: EUACs for the New Transformer

Table 6-1: Marginal Costs of the In-Place Transformer over the Study Period

Year	MGC ($)	Year	MGC ($)
1	45,377.09	9	53,121.35
2	46,157.62	10	54,330.46
3	46,991.73	11	57,712.95
4	47,879.40	12	61,149.02
5	48,820.65	13	64,638.66
6	49,815.47	14	68,181.87
7	50,863.86	15	71,778.66
8	51,965.82		

Table 6-2: Replacement Strategies and Associated FWCA

RS	FWCA	RS	FWCA
1	-175522	9	29591.514
2	-130533.2	10	36859.681
3	-92328.92	11	41519.831
4	-60215.52	12	40804.021
5	-33554.17	13	35579.881
6	-11757.93	14	26608.202
7	5711.1018	15	14554.6
8	19344.724		

6.2.3 Part 2: Finding the Optimal Maintenance Policy

The defender has 15 sub-states in the wear-out region: $S_{3\text{-}1}$, $S_{3\text{-}2}$…$S_{3\text{-}15}$. Therefore, the full search space is $2^{14} = 16384$. According to [44], the overhaul major maintenance task costs $10,000 and involves complete analysis including parts replacement, complete off-line testing and corresponding maintenance and oil change. The optimal maintenance policy obtained is shown in Table 6-3. The total present value at year 21 of the optimal maintenance policy is calculated using (5.12) and found to be $296,378.58.

Table 6-3: Optimal Maintenance Policy

Sub-State	Decision	Sub-State	Decision
$S_{3\text{-}1}$	N/A	$S_{3\text{-}9}$	0
$S_{3\text{-}2}$	0	$S_{3\text{-}10}$	1
$S_{3\text{-}3}$	0	$S_{3\text{-}11}$	0
$S_{3\text{-}4}$	1	$S_{3\text{-}12}$	0
$S_{3\text{-}5}$	0	$S_{3\text{-}13}$	1
$S_{3\text{-}6}$	0	$S_{3\text{-}14}$	0
$S_{3\text{-}7}$	1	$S_{3\text{-}15}$	0
$S_{3\text{-}8}$	0		

6.2.4 Part 3: Replacement Study with the Effect of Maintenance

The effect of maintenance extends the physical lifetime of the defender by 12 years. Thus, the study period becomes 27 years. It is found that the optimal replacement strategy is RS_{24}. Therefore, by the end of year 43 (the 23rd year in the study period), the defender should be replaced.

6.2.5 Part 4: Final Decision

The replacement decisions for parts 1 and 3 are presented in Table 6-4. To make the best replacement decision, the EUAE at the replacement year t_{rp} for both replacement studies are calculated by using (5.13) and presented in Table 6-5. The results clearly show that the equivalent annual expenses will be reduced by $17,443 if the defender is replaced after it was maintained, and accordingly its lifetime was extended. These results emphasize the positive effect of maintenance and its remarkable role in effectively exploiting the lifetime of the transformer. Although the results obtained in this case study show the beneficial effect of replacing the defender after extending its lifetime, results could differ in other cases. This effect is dependent on many factors such as transformer type, load sector type(s), load demand, and inflation rate. Regardless of changes in these factors, the decision-making system proposed in this thesis can determine the appropriate and most cost-effective years to maintain and replace the in-place transformer.

Table 6-4: Replacement Decisions for Part 1 and Part 3

Replacement Study	t_{rp} (year)	Actual lifetime (year)
without maintenance	10	30
with maintenance	23	43

Table 6-5: EUAEs for the Replacement Studies

Replacement Study	t_{rp} (year)	Actual lifetime (year)	EUAE ($)
without maintenance	10	30	64,454.45
with maintenance	23	43	47,011.45

6.3 Summary

The concept of RCMR was illustrated by a case study in this chapter. A replacement study without performing any overhaul maintenance activities was conducted. Likewise, another replacement study was conducted which considered the effect of maintenance on extending the lifetime. To effectively incorporate the effect of maintenance in the investigation, a proposed maintenance strategy has been presented. The Genetic Algorithm in conjunction with the Present Value method was utilized to determine the optimal maintenance policy. A new economic term was introduced to compare replacement studies. The results show how maintenance can increase the lifetime of the transformer and help reduce the equivalent annual expenses.

Chapter 7

Conclusion and Summary

7.1 Thesis Summary

This thesis proposed an approach to help utilities determine whether the in-place transformer should be maintained or replaced in its wear-out region. In addition, the proposed approach can determine how often maintenance activities should be performed and when the in-place transformer should be replaced. The proposed approach takes into consideration the reliability as well as the economic issues. The essential question of this thesis was *should the transformer be maintained or replaced in its wear-out region?* Answering this question entailed answering the following questions:

1. Which maintenance policy should be applied and how often maintenance activities should be performed during the wear-out region?
2. What is the optimal time to replace the transformer?
3. Is it worthwhile from reliability and economic perspectives to maintain the transformer during the wear-out region?
4. How can utilities make a decision to compromise between maintenance and replacement decisions?

The first question was answered in section 5.5. Section 5.5 discussed how the proposed approach segmented the wear-out region of the transformer into sub-states representing the changes in the deterioration states of the transformer at that region. Based on this, a proposed maintenance strategy for the in-place transformer was proposed in order to find the optimal maintenance policy and determine the frequencies of performing the maintenance activities over its remaining lifetime. The second question was addressed in section 5.4 and section 5.6. In section 5.4, a replacement study was conducted without considering the effect of maintenance. The replacement study was conducted over the original lifetime of the in-place transformer. However, the effect of maintenance upon conducting the replacement study was considered in section 5.6. The last two questions were answered in the last part of the analysis where a new economic term was introduced. The new economic term, EUAE, was introduced to compare the replacement studies and hence make the final decision which answers the essential question of the thesis.

The most important points of the thesis are summarized as follows:

- Maintenance concept was introduced as an important element of asset management. Its role, definition, objectives, and evolution throughout generations were discussed. The relationship between maintenance and aging was presented. Furthermore, types of maintenance and the features of each type were addressed. The main flaw of existing maintenance types was indicated which is not considering the reliability importance of the asset upon assigning maintenance activities.
- Reliability-centered maintenance (RCM) was then introduced. Some important topics related to RCM were addressed, including the difference between RCM and traditional maintenance types, major emerging obstacles upon implementing RCM, how RCM developed the traditional maintenance types, how RCM first originated in aviation industry and then was adopted by other industries, how RCM classified equipment, the analysis considered to implement RCM, and the implementation process of RCM via COFA and FMEA. Nest, the applications of RCM in power system sector were presented. Some studies have researched the implementation of RCM in transmission or distribution system while others have utilized the concept of RCM for certain equipment or applications.
- The missing link between maintenance and replacement approaches was pointed out. A novel approach to fill in the gap between maintenance and replacement approaches was introduced, RCMR approach. The need for RCMR approach and its main objectives were presented. The four parts of RCMR were explained in detail. The first part of RCMR involves performing a replacement study without considering the effect of maintenance. Part 2 involves finding the optimal maintenance policy for the transformer over its remaining lifetime. In part 3, another replacement study is conducted; however, the effect of maintenance obtained in part 2 is incorporated in the

replacement study. In part 4, a comparison between replacement studies conducted in parts 1 and 3 is made in order to determine which replacement decision is the best. The concept of RCMR is illustrated by a case study.

7.2 Main Contributions

The main contributions in this thesis can be summarized as follows:

- Introduce maintenance strategy based on RCM concept and using GA. This maintenance strategy works to define alternative maintenance policies using GA and then identify the optimal maintenance policy among them.
- Express changes in the deterioration state of the transformer in the wear-out region in terms of changes in the failure rate.
- Incorporate the effect of the optimal maintenance policy on the replacement decision.
- Conduct replacement studies for the transformer by utilizing the future worth cost advantage approach.
- Introduce a new economic term to make the replacement decision.

7.3 Suggestions for Future Work

The proposed RCMR approach in this thesis can be applied to other important and critical assets in power system such as circuit breakers. Moreover, this approach can be developed to consider a set of assets in a system to be analyzed together. Also, risk assessment can be considered by taking into account the effect of transformer's terminals.

References

[1] O. Tor and M. Shahidehpour, “Power distribution asset management,” *2006 IEEE Power Engineering Society General Meeting*, 2006.

[2] R. E. Brown and B. Humphrey, “Asset management for transmission and distribution,” *IEEE Power and Energy Magazine*, vol. 3, no. 3, pp. 39–45, 2005.

[3] J. Endrenyi and G. J. Anders, “Aging, maintenance, and reliability approaches to preserving equipment health and extending equipment life,” *IEEE Power and Energy Magazine*, vol. 4, no. 3, pp. 59–67, 2006.

[4] J. Endrenyi, S. Aboresheid, R. N. Allan, G. J. Anders, S. Asgarpoor, R. Billinton, N. Chowdhury, E. N. Dialynas, M. Fipper, R. H. Fletcher, C. Grigg, J. McCalley, S. Meliopoulos, T. C. Mielnik, P. Nitu, N. Rau, N. D. Reppen, L. Salvaderi, A. Schneider, and C. Singh, “The Present Status of Maintenance Strategies and the Impact of Maintenance on Reliability,” *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 638–646, 2001.

[5] J. Moubray, *Reliability-Centered Maintenance*, 2nd ed. New York: Industrial Press, 1997.

[6] N. B. Bloom, *Reliability Centered Maintenance (RCM): Implementation Made Simple*. McGraw-Hill, 2006.

[7] J. McCalley, T. Van Voorhis, Y. Jiang, and A. P. Meliopoulos, “Risk-Based Maintenance Allocation and Scheduling for Bulk Transmission System Equipment,” PSERC, Ithaca, NY, 2003.

[8] A. E. B. Abu-Elanien and M. M. A. Salama, “Asset management techniques for transformers,” *Electric Power Systems Research*, vol. 80, no. 4, pp. 456–464, Apr. 2010.

[9] F. Li and R. E. Brown, “A Cost-Effective Approach of Prioritizing Distribution Maintenance Based on System Reliability,” *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 439–441, Jan. 2004.

[10] A. M. Smith, *Reliability-Centered Maintenance*. New York: McGraw-Hill, 1993.

[11] E. M. Gurumeta, “Reliability Centered Maintenance,” *9th International Conference Electrical Power Quality and Utilization*, 2007.

[12] W. Li, *Risk Assessment of Power Systems: Models, Methods, and Applications*. Wiley-IEEE Press, 2005.

[13] J. Endrenyi, G. J. Anders, and A. M. Leite da Silva, “Probabilistic evaluation of the effect of maintenance on reliability - An application,” *IEEE Transactions on Power Systems*, vol. 13, no. 2, pp. 576–583, 1998.

[14] F. S. Nowlan and H. F. Heap, "Reliability-Centered Maintenance," National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA, 1978.

[15] L. Bertling, R. Allan, and R. Eriksson, "A Reliability-Centered Asset Maintenance Method for Assessing the Impact of Maintenance in Power Distribution Systems," *IEEE Transactions on Power Systems,* vol. 20, no. 1, pp. 75–82, 2005.

[16] A. Abdulwhab, R. Billinton, A. A. Eldamaty, and S. O. Faried, "Maintenance Scheduling Optimization Using a Genetic Algorithm (GA) with a Probabilistic Fitness Function," *Electric Power Components and Systems*, vol. 32, no. 12, pp. 1239–1254, Dec. 2004.

[17] R. Leou, "A flexible unit maintenance scheduling considering uncertainties," *IEEE Transactions on Power Systems*, vol. 16, no. 3, pp. 552–559, 2001.

[18] R. Naresh and J. Sharma, "Hydro System Scheduling Using ANN Approach," *IEEE Transactions on Power Systems,* vol. 15, no. 1, pp. 388–395, 2000.

[19] S. H. Sim and J. Endrenyi, "Optimal preventive maintenance with repair," *IEEE Transactions on Reliability,* vol. 37, no. 1, pp. 92–96, Apr. 1988.

[20] M. E. Beehler, "Reliability centered maintenance for transmission systems," *IEEE Transactions on Power Delivery*, vol. 12, no. 2, pp. 1023–1028, Apr. 1997.

[21] M. Ghavami and M. Kezunovic, "Probabilistic evaluation of the effect of maintenance parameters on reliability and cost," *2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems,* pp. 71–76, Jun. 2010.

[22] J. Heo, M. Kim, G. Park, Y. T. Yoon, J. K. Park, S. Lee, and D. Kim, "A Reliability-Centered Approach to an Optimal Maintenance Strategy in Transmission Systems Using a Genetic Algorithm," *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2171–2179, 2011.

[23] J. W. Goodfellow, "Applying Reliability Centered Maintenance (RCM) to Overhead Electric Utility Distribution Systems," *2000 IEEE Power Engineering Society Summer Meeting*, pp. 566–569, 2000.

[24] L. Bertling, "Reliability centred maintenance for electric power distribution systems," Ph.D. dissertation, Dept. Elect. Power Engineering, KTH, Stockholm, Sweden, 2002.

[25] D. R. Morais, J. G. Rolim, J. Coser, and H. H. Zurn, "Reliability Centered Maintenance for Capacitor Voltage Transformers," *2006 International Conference on Probabilistic Methods Applied to Power Systems*, pp. 1–6, Jun. 2006.

[26] D. W. Holladay, H. E. Rec, B. D. Dallman, and C. H. Grigg, "Reliability Centered Maintenance Study on Voltage Regulators," *ESMO 2006-2006 IEEE 11th International Conference on Transmission & Distribution Construction, Operation and Live-Line Maintenance*, 2006.

[27] J. Schlabbach and T. Berka, “Reliability-centred maintenance of MV circuit-breakers,” *2001 IEEE Porto Power Tech Proceedings*, vol. 4, 2001.

[28] T. Chan, C. Liu, and J. Choe, “Implementation of Reliability-Centered Maintenance for Circuit Breakers,” *2005 IEEE Power Engineering Society General Meeting*, pp. 684 – 690, 2005.

[29] W. Li and J. Korczynski, “A Reliability-Based Approach to Transmission Maintenance Planning and its Application in BC Hydro System,” *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 303–308, 2004.

[30] P. Dehghanian, M. Fotuhi-firuzabad, S. Bagheri-Shouraki, and A. A. Razi Kazemi, “Critical Component Identification in Reliability Centered Asset Management of Power Distribution Systems via Fuzzy AHP,” *IEEE Systems Journal*, vol. 6, no. 4, pp. 593–602, 2011.

[31] A. E. B. Abu-Elanien, M. M. A. Salama, and R. Bartnikas, “A Techno-Economic Method for Replacing Transformers,” vol. 26, no. 2, pp. 817–829, 2011.

[32] R. E. Brown, *Electric Power Distribution Reliability*, 2nd ed. Boca Raton, F.L: CRC Press, 2008.

[33] W. Li, E. Vaahedi, and P. Choudhury, “Power system equipment aging,” *IEEE Power and Energy Magazine*, vol. 4, no. 3, pp. 52–58, 2006.

[34] H. Wagner, *Principles of operations research: with applications to managerial decisions*, 2nd ed. Englewood Cliffs, N.J: Prentice-Hall, 1975.

[35] W. Winston and S. Albright, *Practical Management Science*, 4th ed. Mason, OH: South-Western, 2011.

[36] C. S. Park and G. P. Sharp-Bette, *Advanced Engineering Economics*, 10th ed. Toronto: Wiley, 1990.

[37] H. Matsuo, “A Modified Approach to the Replacement of an Existing Asset,” *The Engineering Economist*, vol. 33, no. 2, pp. 109–120, 1988.

[38] M. Bowman, *Applied economic analysis for technologists, engineers, and managers*. Upper Saddle River: Prentice-Hall, 1999.

[39] L. Blank and A. Tarquin, *Basics of Engineering Economy*. New York: McGraw-Hill, 2007.

[40] R. F. Ghajar and R. Billinton, “Economic costs of power interruptions: A consistent model and methodology,” *International Journal of Electrical Power & Energy Systems*, vol. 28, no. 1, pp. 29–35, Jan. 2006.

[41] R. Billinton and P. Wang, “Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques,” *IEEE Transactions on Power Systems*, vol. 13, no. 4, pp. 1245–1250, 1998.

[42] M. Kurtz, *Handbook of Engineering Economics*. New York: McGraw-Hill, 1984.

[43] A. Badiru and O. Omitaomu, *Handbook of Industrial Engineering Equations, Formulas, and Calculations*. Boca Raton, F.L: CRC Press, 2010.

[44] J. McCalley, Y. Jiang, V. Honavar, J. Pathak, M. Kezunovic, S. Natti, C. Singh, and J. Panida, “Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers,” PSERC, Ithaca, NY, 2006.

[45] D. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading,MA: Addison-Wesley, 1989.

[46] A. S. Al-Abdulwahab, “Probabilistic Electrical Power Generation Modeling Using Genetic Algorithm,” *International Journal of Computer Applications*, vol. 5, no. 5, pp. 1–6, Aug. 2010.

[47] W. Wangdee, “Reliability Assessment of Cathedral Square Substationle,” 2006. [Online]. Available: http://transmission.bchydro.com/transmission_system/engineering_studies_data/studies/probabilistic_studies/selected_tech_reports.htm. [Accessed: 11-Jun-2012].