RISK BASED MAINTENANCE OPTIMIZATION USING PROBABILISTIC MAINTENANCE QUANTIFICATION MODELS OF CIRCUIT BREAKER

A Dissertation

by

SATISH NATTI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2008

Major Subject: Electrical Engineering

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ABSTRACT

Risk Based Maintenance Optimization using Probabilistic Maintenance Quantification
Models of Circuit Breaker. (December 2008)

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New maintenance techniques for circuit breakers are studied in this dissertation by proposing a probabilistic maintenance model and a new methodology to assess circuit breaker condition utilizing its control circuit data. A risk-based decision approach is proposed at system level making use of the proposed new methodology for optimizing the maintenance schedules and allocation of resources.

This dissertation is focused on developing optimal maintenance strategies for circuit breakers, both at component and system level. A probabilistic maintenance model is proposed using similar approach recently introduced for power transformers. Probabilistic models give better insight into the interplay among monitoring techniques, failure modes and maintenance techniques of the component. The model is based on the concept of representing the component life time by several deterioration stages. Inspection and maintenance is introduced at each stage and model parameters are defined. A sensitivity analysis is carried out to understand the importance of model parameters in obtaining optimal maintenance strategies. The analysis covers the effect of the inspection rate calculated for each stage and its impact on failure probability, inspection cost, maintenance cost and failure cost. This maintenance model is best suited for long-term maintenance planning. All simulations are carried in MATLAB and how the analysis results may be used to achieve optimal maintenance schedules is discussed.

A new methodology is proposed to convert data from the control circuit of a breaker into condition of the breaker by defining several performance indices for breaker assemblies. Control circuit signal timings are extracted and a probability distribution is fitted to each timing parameter. Performance indices for various assemblies such as, trip coil, close coil, auxiliary contacts etc. are defined based on the probability distributions. These indices are updated using Bayesian approach as the new data arrives. This process can be made practical by approximating the Bayesian approach calculating the indices on-line. The quantification of maintenance is achieved by computing the indices after a maintenance action and comparing with those of previously estimated ones.

A risk-based decision approach to maintenance planning is proposed based on the new methodology developed for maintenance quantification. A list of events is identified for the test system under consideration, and event probability, event consequence, and hence the risk associated with each event is computed. Optimal maintenance decisions are made based on the computed risk levels for each event.

Two case studies are presented to evaluate the performance of the proposed new methodology for maintenance quantification. The risk-based decision approach is tested on IEEE Reliability Test System. All simulations are carried out in MATLAB and the discussions of results are provided.

DEDICATION

To my wife, parents, grandparents, uncle and aunt for their love and support.

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CHAPTER I

INTRODUCTION

Power system equipment such as transmission lines, power transformers and circuit breakers are usually designed for operation over several decades. It is quite natural that equipment deteriorates as it gets aged. Failure of any of this equipment may result in a great impact in both cost and reliability aspects. This drives researchers to come up with better asset management strategies considering the given budget and load to be served, without compromising much on system reliability. This leads to the need for development of optimal maintenance policies for the equipment. Probabilistic maintenance models, though complex to formulate, offer better relationship between maintenance and reliability of device both at component and system level. Further, development of failure probability estimation models helps in quantifying the effect of maintenance. Use of condition-based data for development of failure probability estimation model remains a challenge.

A. Background

Maintenance of power apparatus plays major role in asset management and reliability of power system. Failure of this equipment may greatly affect the power delivery and result in high cost associated with loss of load and/or component replacement. The "remaining life" of power apparatus and maintenance cost are two

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This dissertation follows the style of *IEEE Transactions on Power Systems.*

most important aspects, which affects the maintenance strategies. Incipient failures have a long term-accumulated effect, which may cause major failures if no related maintenance action is taken. Various maintenance strategies are reported in literature so far [1]. They range from scheduled maintenance to reliability-centered maintenance (RCM) and condition based maintenance (CBM) [2]-[4]. Industry is slowly moving from scheduled maintenance to 'maintenance as needed'. Recent trend in maintenance approaches is to maintain the device according to its condition. Preventive maintenance heavily depends on the information obtained from condition monitoring. Technology developments offer various condition monitoring techniques which directly (or indirectly) affects the existing maintenance policies [5]-[12]. Data acquisition systems, signal processing techniques and expert systems made the condition monitoring techniques much more refined and accurate as well [13]-[17]. It was concluded that power apparatus service availability and replacement cost should be balanced in order to get an optimal maintenance strategy. Reference [1] also addresses how probabilistic models can help in optimizing the maintenance intervals and hence to quantify the effect of maintenance on reliability. Probabilistic models can give more insight of interplay between condition monitoring, inspection and maintenance actions. Following section discusses the issue of maintenance both at system level and component level.

B. Problem Formulation

Operator has to ensure proper power flow under network security and economic constraints [18]. Reliability of the equipment and hence of the system may be achieved with increased operating cost including cost of maintenance. In general, given level of maintenance investment is acceptable only if the benefits are greater than cost of maintenance. Since power system network often contains several thousands of components, developing a maintenance strategy at system level is a challenging task. One has to clearly quantify the effect of maintenance not only at component level, but at system level too. Optimization problems have been developed with objective being one of minimizing the cost, maximizing the reliability, maximizing the risk reduction etc. to obtain optimal maintenance strategies. In all these optimization problems, the main idea is to assess the effect of maintenance quantitatively. It is necessary to consider the quantification of maintenance both at component level and system level. A particular maintenance action could result in improvement of component reliability but cannot guarantee the improvement of system reliability. Hence it is very important to consider the maintenance at component level first and then extend the results further to develop system level maintenance strategies. This is how component and system level maintenance strategies are connected in most of the existing approaches in literature. Since differentiating between the two aspects of maintenance, at the system and component level, is critical to the new approach, these two aspects are explained in detail in following subsections.

1. Component Level Maintenance

There is a need to develop models for transmission equipment to be able to quantify the effect of maintenance. Failure rate estimation models such as hazard rate models and Markov models can quantify effect of maintenance in terms of reduction in failure probability and/or extended life time, which can be further used in reliability and risk analysis [19]-[22]. With the use of probabilistic models, it is possible to link the component aging process to reliability by representing it with several deterioration stages [23]. These probabilistic maintenance models find their use in long-term planning of power equipment. They give an idea about inspection rate, maintenance intervals and failure costs associated with the device. They also give an insight of mean time to first failure (MTTFF) and failure probability with respect to maintenance at various stages of the device [24]-[25]. Also if condition-based data is available with the use of automated monitoring equipment, it is necessary to develop models to link the condition-based data to health of the device through performance indices such as failure probabilities.

2. System Level Maintenance

Most of the current equipment in power systems in developed countries was installed long back and aged, and hence demands more maintenance. Preventive maintenance may reduce these costs by extending the components' lifetime and increasing availability. However, too much maintenance may be costly and not offer major performance improvement while too little maintenance may result in catastrophic failure. Moreover, component maintenance may improve the component level reliability but it may or may not improve system reliability. Therefore, it is necessary to develop preventive maintenance strategy at system level taking into consideration individual component reliability and given maintenance budget allocation for the entire system. This leads to formulation of an optimization problem to arrive at optimal maintenance strategies. These system level maintenance strategies make use of the models developed as part of component maintenance.

C. Dissertation Goals

In summary, goals and objectives of the work are to develop:

- Component maintenance strategy using probabilistic maintenance model
- A methodology to quantify the effect of component maintenance
- System level risk-based maintenance strategies with the help of developed methodology for maintenance quantification

Apply the developments to:

- Individual circuit breakers
- Multiple circuit breakers in a power system simultaneously

D. Dissertation Outline

This dissertation is organized as follows. Chapter II presents the existing work and surveys literature in the area of component and system level maintenance strategies for circuit breakers. Chapter III presents the problem formulation along with dissertation research approach. A brief discussion about circuit breaker condition monitoring techniques, failure modes and maintenance tasks is outlined in Chapter IV. A probabilistic maintenance model for circuit breaker is proposed and sensitivity analysis is carried in Chapter V. Chapter VI proposes methodology to quantify the effect of breaker maintenance using condition based data. A system level risk based decision approach is proposed in Chapter VII. Cases studies to test the performance of approaches proposed in Chapter VI and VII are discussed in Chapter VIII. Finally, Chapter IX presents conclusions including contributions and suggestions for future work.

CHAPTER II

EXISTING APPROACHES

A. Introduction

A brief discussion of existing literature about both component level maintenance and system level maintenance is presented in this chapter. It is observed from the literature that the system level maintenance strategies make use of the component level maintenance models. The component level strategies mainly differ in the way the device is modeled and the type of the data used. The system level maintenance strategies mainly defer in their objective such as maximizing the reliability, minimizing the operating cost, maximizing the risk reduction etc. The following subsections are devoted to discuss these strategies.

B. Component Level Maintenance

1. Hazard Rate Models and Markov Models

One way of quantifying the effect of maintenance at component level is by looking at the failure rates of the device before and after the maintenance. The solutions range from standard approaches by taking number of failures per year [19]-[20] to probabilistic approaches such as Hazard rate models and Markov models [21]-[22]. These models can be used to capture the change in failure probability or change in life time or both. In [24], a multi-stage Markov model adapted from [23] is used to compute failure rates of power transformers using condition measurements. It is desirable to develop such failure rate estimation models for circuit breaker and other power apparatus using condition monitoring data.

2. Probabilistic Maintenance Models

Markov models can be further extended to model the aging process by representing the device life time by several stages [23]. These are also called probabilistic maintenance models. A probabilistic maintenance model, taken from [23], is developed and analyzed in [24]-[25]. The analysis covers the mean time to first failure (MTTFF) and failure probabilities with respect to model parameters such as inspection rate at each stage. In addition, the probabilistic maintenance model facilitates the cost analyses with respect to model parameters, which makes them more suitable for long term planning for a given budget. Cost analyses include inspection, maintenance and failure cost of the equipment under consideration. These models may be extended for circuit breakers as well as other power apparatus.

The main advantage of the above mentioned approaches is that it is possible to model the device for its entire life time. However it is not a simple task since it requires a huge data base of failure and maintenance records for the entire life of the device. It becomes further difficult if the device is newly installed, due to lack of sufficient failure and maintenance history. Also, the available approaches are more focused on power transformers than circuit breakers.

In our work, component level maintenance is focused more on circuit breaker. The circuit breaker control circuit data is used to assess the condition of the breaker and in this way the work in this dissertation differs from existing approaches for circuit breakers. In order to develop above mentioned maintenance models for circuit breaker, it is essential to know various monitoring techniques [5]-[10], failure modes and maintenance policies. Furthermore, we should have an idea of which failure mode affects which measurement and, the related maintenance action [11].

C. System Level Maintenance

1. Reliability Centered Maintenance (RCM)

An overview of existing maintenance approaches is reported in [1]. These programs range from scheduled to predictive maintenance such as Reliability Centered Maintenance (RCM). In the RCM approach, several alternative maintenance approaches are compared and most cost effective one with sustained reliability will be selected [12]. RCM approaches are more attractive but they fail to connect the effect of maintenance to the reliability quantitatively.

2. Asset Management Planner (AMP)

A program called Asset Management Planner (AMP) has been developed based on probabilistic maintenance model [2]. It models the component ageing process, by representing the device condition in terms of stages. The AMP models takes state transition rates, mean state durations, maintenance and repair costs, and various decision probabilities as inputs and provides sensitivity due to costs, unavailability or remaining life of the device. It can even provide the optimal value of a desired output variable. However, this approach needs the history of failure and maintenance records of all circuit breakers under consideration. Also, it requires the ability to process the data and find its stage, which is not a simple task. Also, it demands expertise to come up with the transition rates from one stage to other.

3. Risk-Based Resource Optimization

A risk-based resource optimization based on transmission system maintenance has been described in [3]. This approach is based on the cumulative long-term risk caused by failure of individual equipment. First, an hourly risk is calculated associated with various contingencies with the help of a sequential power flow simulator. Second, cumulative risk reduction due to each predefined maintenance task is estimated. Finally, an optimal selection and scheduling of maintenance tasks with an objective being the total cumulative risk reduction is achieved. This approach is useful in short term maintenance planning and resource allocation. Though, transformers, transmission lines and circuit breakers are considered, transformers are give more importance in achieving maintenance quantification at component level. This approach can be improved further by analyzing the circuit breaker condition in more detail to achieve better maintenance strategies.

4. Reliability Centered Asset Management (RCAM)

An attempt was made to compare the effect of different preventive maintenance strategies on system reliability and cost in [4]. This approach, called Reliability-Centered Asset Management (RCAM), has been applied to study the impact of maintenance of distribution cables on system reliability. The method is developed based on RCM principles trying to relate more closely the effect of maintenance on system reliability and cost. This approach models the failure rate of device, obtained from history of failure and maintenance records and achieves the quantification of maintenance. This approach can be improved by considering the condition based data such as control circuit data of breaker.

The control circuit data of circuit breaker can be utilized to assess the performance of the breaker and it is relatively cost effective to monitor the control circuit and obtain the condition based data. This is how our work defers from the above mentioned approaches as none of them utilized the control circuit data to achieve maintenance quantification. This idea is discussed further discussed in detail in Chapter III.

D. Summary

Component maintenance models mainly convert the monitored data into reliability indices such as failure probabilities. These estimated reliability indices have been used in developing system level maintenance strategies with different objectives such as maximizing risk reduction, minimizing operating cost etc.

CHAPTER III

PROBLEM FORMULATION

A. Introduction

An example of power system including typical components such as transmission lines, power transformers and circuit breakers is shown in Fig. 1. These components are very critical to achieve the network balance and their failure could result in catastrophic damage. It is necessary to maintain these devices time to time such that the reliability of the system is achieved all the time. Trying to cut down the budget spent on maintenance every year, utilities need to come up with optimized maintenance schedules while dealing with limited budget. This task involves quantifying maintenance impact, which is bit challenging. This chapter formulates the maintenance problem for circuit breakers, both at component and system level. Finally, expected contributions of this dissertation work are presented.

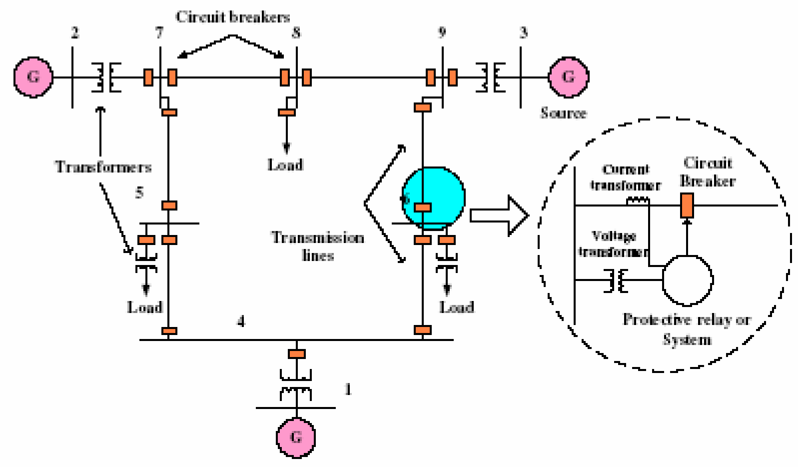

Fig. 1 Example of a power system

B. Top-Down Approach

A concept of “top-down” approach is introduced to summarize various steps in power system planning and operation affected by maintenance strategies. The flow of the process, shown in Fig. 2 links the operation decisions to condition-based data.

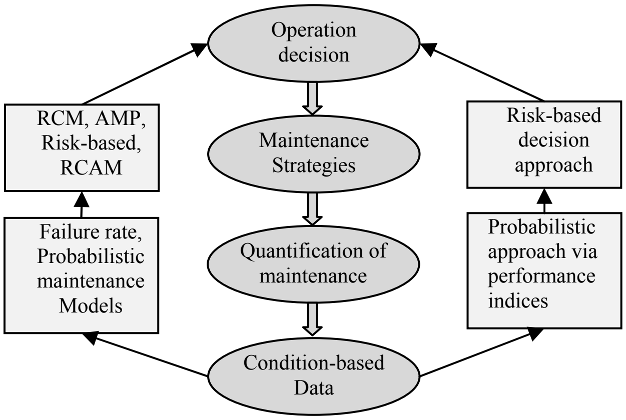

Fig. 2 Top-down approach

Ultimately, one has to ensure required power flow while taking into account decisions regarding asset management and reliability constraints [18]. Asset management policies and reliability of power system can be greatly affected by selected system level maintenance strategies [2]-[4]. The existing approaches are summarized in the left hand part of the diagram of Fig. 1 in which the quantification of maintenance is achieved through failure rate estimation models and probabilistic maintenance models [19]-[25]. These component maintenance models are highly driven by the type of condition based data and there is lack of approaches that can link the condition-based data to system level maintenance strategies making use of component level maintenance models, especially for circuit breakers. Also, the cost of obtaining the condition based data depends on the choice of monitoring parameters of the component. The proposed approach, shown in the right hand side of the diagram, defers the existing approaches in following aspects: (i) the methodology of converting the condition based data into failure probabilities (ii) the type of the condition based data itself (iii) the cost associated with the monitoring equipment to achieve the condition based data.

The quantification of maintenance is achieved through a probabilistic methodology which converts the condition-based data into performance indices, including failure probability index. These indices can be further used in developing risk-based decision approaches at the system level. With the proposed methodology it is possible to update the performance indices online as the new set of data come in, where is it is not possible in the case of existing approaches. It is observed that none of the existing approaches have utilized the control circuit data of circuit breaker to achieve the condition assessment of the breaker. In our approach, we have used control circuit data, which can be recorded by portable devices, to achieve the condition assessment. Also, the process of installing the portable devices and obtaining the condition based data is relatively easy and cost effective compared to the existing approaches, shown in the left hand side of the diagram.

C. Component Level Maintenance

This section explains the proposed approach for component level maintenance, specific to circuit breakers (CBs). Two tasks proposed for the research efforts in this dissertation as explained below.

Task 1: A probabilistic maintenance model developed earlier for transformer [24]-[25], employed from [23], will be extended to circuit breaker. Component aging process will be modeled in terms of deterioration stages. Sensitivity analyses of model parameters with respect to 'failure probability' and various costs will be carried. The cost analyses include cost of inspection, cost of maintenance and cost of failure. This task is more focused at giving a detailed analysis of deterioration process, inspection tests and various costs associated with the breaker, which helps in achieving task 2.This model finds its importance in long term planning, and hence may be used to allocate the budget properly among maintenance and inspection activities.

Task 2: A methodology is proposed to convert data from the breaker control circuit to health level of the circuit breaker by defining several performance indices. The performance indices reflect the behavior of various sub assemblies of circuit breaker. The methodology quantifies the effect of maintenance in terms of reduction in performance indices, which can be utilized instantly in reliability and risk analyses. Following steps are involved in the proposed methodology.

Step 1: Develop a history of CB control circuit signals

Step 2: Extract signal parameter timings using signal processing module

Step 3: Analyze the relationship between the parameters using scatter plots and fit probability distribution to each parameter

Step 4: Define performance indices using these distributions to assess the condition of the breaker

Step 5: As the new data arrives, update these distributions and performance indices using Bayesian updating approach.

D. System Level Maintenance

Optimal maintenance strategy at system level is very important objective in asset management. There is a need to formulate the system level optimization problem with inputs being the benefits of individual component maintenance. In this work, a risk based decision approach to optimize circuit breaker maintenance at system level is proposed. This approach utilizes the results of task 2 which is part of the expected contribution in component maintenance. The other inputs to the proposed risk based approach are budget, security and labor constraints.

E. Contribution

The contribution of this dissertation is to establish a link between the ‘condition-based data’ and ‘risk-based decision approach’ through a proposed probabilistic methodology for component maintenance. With reference to the top-down approach in Fig. 1, the starting point will be the available data. Task 1 and 2 will be achieved utilizing the history and condition monitored data. Further, risk based decision approach to achieve system level maintenance problem will be formulated on top of task 2.

Contribution of the proposed research is:

- Development component probabilistic maintenance model
    - The component’s age is modeled using several deterioration stages and impact of inspection and maintenance at each stage is introduced
    - Failure probability analysis is enhanced by utilizing condition based data

  - Cost analysis is made more comprehensive by including inspection, maintenance and failure cost
- Conversion approach from condition based data to performance indices such as probability of failure
  - Control circuit data to account for conditions of the breaker are utilized
  - Performance indices for various assemblies of breaker are defined
  - Bayesian updating approach to update performance indices is developed
- Formulation of the system maintenance optimization problem
  - The proposed conversion approach is applied to assembly of multiple breakers
  - Strategy objective to maximize risk reduction is defined
  - Optimization approach to meet budget, security and labor constraints is developed

F. Summary

Probabilistic maintenance model based on condition data is proposed to develop maintenance strategy at component level. The need for probability of failure analysis and cost analysis at component level is recognized. An approach to convert condition based data to health level of the breaker is proposed. This approach utilizes a history of control circuit data. System level risk based decision approach is formulated for an assembly of breakers based on the proposed approach of defining indices for the health stages of individual breakers.

CHAPTER IV

CIRCUIT BREAKER MONITORING TECHNIQUES, FAILURE MODES AND MAINTENANCE ACTIONS

A. Introduction

In order to develop models relating maintenance actions to the failure probabilities, it is essential to know the various monitoring techniques, failure modes and maintenance policies of a device. Furthermore, we should have an idea of which failure mode affects which measurement and, the related maintenance action. The following procedure includes some of the crucial steps in obtaining probabilistic maintenance models.

System Identification: The physical design of the device and, its basic components and their functions needs to be identified.

Phenomena Associated with the Device Operation: This gives the information regarding the deterioration processes associated with different components of the device.

Measurements: These are the available monitoring options for the particular device under consideration.

Failure Modes: Various failure modes and the related failure effects need to be understood.

Maintenance Actions: The available maintenance techniques are to be studied to be able to offer alternatives.

Relation between measurements, failure modes and maintenance: This is the crucial step in developing the maintenance models. It basically gives the relation between measurements, failure modes and maintenance techniques.

The above methodology can be applied to various power system components such as power transformers and circuit breakers. We have taken an example that centers on circuit breakers. Various monitoring techniques and failure modes for circuit breaker are arranged according to the proposed methodology as given below.

B. System Identification

Main components of a circuit breaker are its operating mechanism, contacts, control circuit and interrupting medium. The function of operating mechanism is to open or close the breaker contacts upon a command. As shown in Fig. 3 the operating mechanism consists of various components such as operating rod, springs, valves, latches, cams, rollers, bolts, washers etc.

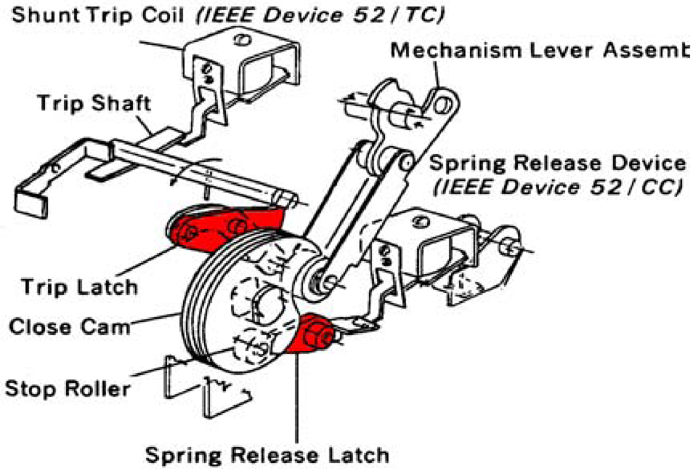

Fig. 3 The arrangement of operating mechanism and coils [16]

Contacts are metal parts and carry the load current when circuit breaker is in closed position. The electrical representation of the control circuit is shown in Fig. 4. Control circuit issues a command to the circuit breaker, and in turn the operating mechanism reacts and opens the breaker contacts. Contacts are located in interrupting chamber where arc extinction takes place. Air Blast and Oil circuit breakers are considered in this study.

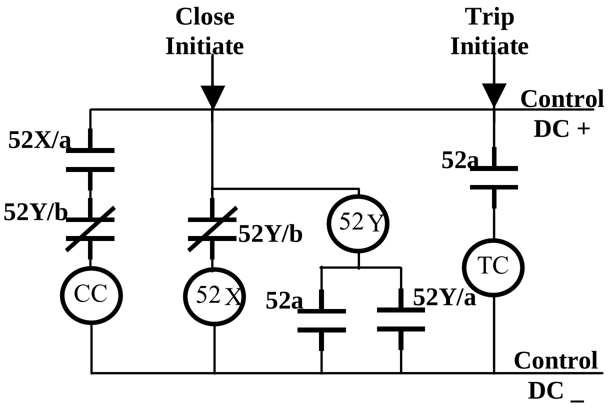

Fig.4 Electrical representation of circuit breaker control circuit [15]

C. Phenomenon Associated with the Device Operation

Most of the circuit breaker failures are associated with failure of operating mechanism. Operating mechanism consists of various moving components and all components should work in desired way in order to operate the breaker correctly. Hence, inspection and maintenance of the operating mechanism is necessary for proper operation of the breaker. Formation of oxides during the arc extinction results in deterioration of contacts and oil [5]. If proper maintenance of components is not scheduled, this deterioration may result in failure of the device.

D. Measurements

Preventive maintenance heavily depends on the information obtained from condition monitoring. Technology developments offer various condition monitoring techniques which directly (or indirectly) affects the existing maintenance policies. Data acquisition systems, signal processing techniques and expert systems made the condition monitoring techniques much more refined and accurate as well. A condition monitoring technique is usually designed for evaluating one unique condition, and the information collected to evaluate such condition can be called monitoring parameters. Condition monitoring is playing a major role in taking accurate maintenance decisions. It allows the maintenance crew to get a clear picture of the condition of the breaker, which in turn helps to come up with more optimal maintenance programs. This section presents some important monitoring parameters and groups them according to the subassemblies they belong to, such as operating mechanism, contact, control circuit, etc. as shown in Table I [5]-[6]. It is also possible to classify the monitoring parameters as electrical and non electrical measurements. The measurements such as vibration analysis, gas pressure etc can be treated as non electrical measurements whereas the control circuit, DFR recorder measurements etc. can be treated as electrical measurements. In our work, we used the electrical measurements, in particular the control circuit measurements for its relative importance and ease of obtaining the data.

Table I: Monitoring Parameters of Circuit Breakers

Operating Mechanism (Breaker Timing, vibration analysis)	
– Movement of release mechanism	– Full travel indication
– Stored energy pressure (such as air pressure)	– Mechanism travel and over travel
– Position of stored energy springs	– Ambient Temperature
Contact (Contact Resistance Test, Infrared monitoring of contact temperature)	
– Contact temperature	– Contact travel distance
– Contact erosion and interrupter wear	– Contact Resistance
Control Circuit (Circuit Breaker Signature Analysis)	
– Control circuit current	– X & Y relay timing
– Close coil current	– DC voltage
– Trip coil current	– Charging motor
– Auxiliary contact timing	– Heater
Arc extinction and insulating medium (air, oil, vacuum, SF6) (Partial discharge, oil condition)	
– Water content (Air)	– Vacuum-Integrity Over-potential (Vacuum)
– Temperature (All)	– Density (Gas, Oil)
– Relative humidity of compressed air	– Pressure (Air)
– Dielectric (Oil)	– Moisture (Gas)
– Insulating medium level (liquids)	– Partial discharge
– Color, purity (Gas, Oil)	
System (DFR recorder)	
– Number of breaker operation	– Primary voltage
– Power system disturbance	– Primary current
– Fault level, and condition	
Environment	
– Severe weather conditions (Temperature, moisture, dirt)	

E. Failure Modes

This section presents typical failure modes of circuit breakers. Circuit breaker failures and their effects are discussed in detail in references [6] and [11]. CIGRE working group A3.12 conducted a failure survey focusing on control system reliability on circuit breakers [26]. The study objective was to receive information on which failure modes, components and causes appear most frequently. Readers are advised to go through the mentioned references to know more about the failures of different varieties of CBs (e.g. Oil, Air Blast, SF_6 etc). In this report, failure modes are grouped according to their behavior. For example, all failure modes related to opening of circuit breaker are grouped into one section called “failures related to opening of the breaker”. The circuit breaker failure modes can be identified after regrouping them as shown in Table II.

Table II: Failure Modes of Circuit Breakers

Failures related to opening	• Fails to open on command • Opens but fails to remain open • Opens but fails to interrupt • Opens but fails to maintain open contact insulation • Opens without command
Failures related to closing	• Fails to close on command • Closes but fails to conduct current • Closes without command
Failures to conduct continuous or momentary current (while already used)	-
Failures related to insulation	• Insulation fails • Insulation to ground fails • Insulation between phases fails • External insulation across the interrupter fails • Internal insulation across the interrupter fails
Failures to contain insulating medium	-
Failures to indicate condition or position	-
Failure to provide for safety in operation	-

F. Maintenance Actions

Various maintenance actions for power circuit breakers are summarized in reference [27] and are grouped as follows,

1. Operating Mechanism
    - Clean all insulating parts from dust and smoke

- Clean and lubricate operating mechanism and apply suitable grease for the wearing surfaces of cams, rollers, bearings etc.
- Adjust breaker-operating mechanism as described in the manufacturer’s instruction book.
- Make sure all bolts, nuts, washers, cotter pins etc. are properly tightened.
- After servicing the circuit breaker, verify whether the contacts can move to the fully opened and fully closed positions or not.

2. Contacts
    - Check the alignment and condition of the contacts and make adjustments according to the manufacturer’s instruction book
    - Check if the contact wear and travel time meet specifications
3. Insulating Medium and Arc Extinction
    - Check for leaks and remove any water content. Check governor and compressor for required pressure
    - Recondition oil by filtering
    - In addition, replace the following components if necessary according to their condition: a) Arc chute and nozzle parts if damaged, b) Governors and compressors if worn or malfunctioning c) Contacts if badly worn or burned, and d) Oil if dielectric strength drops below an allowable limit and if any arc products are found in the oil.

G. Relationship between Measurements, Failure Modes and Maintenance Actions

This section presents how the measurements, failure modes and maintenance tasks are related [6].

1. Failure Related to Opening

Operating Mechanism: Improper operation of operating mechanism, inadequate lubrication of trip latch or trip mechanism, failure to travel complete distance, and mechanism linkage failure between operating mechanism and interrupters are some possible causes for the circuit breaker not opening on command. This failure mode also occurs if the temperature of breaker cabinet containing the mechanical parts falls below the required level. A failure mode is if circuit breaker opens on command but closes again due to either mechanism failure or loss of "hold open" energy (e.g., loss of air pressure on air blast circuit breaker requiring air pressure to hold contacts open). Failure of anti pumping scheme results in circuit breaker opening and then repeatedly closing and opening. Monitoring of these failure modes can be done by breaker timing tests (contact travel measurement) and vibration analysis techniques [5], [7].

Control Circuit: Defective trip coil, improper operation of trip circuit, external circuit failure including wiring, battery, and protection devices may cause the improper operation of circuit breaker. Monitoring trip coil continuity, control circuit continuity, X&Y control relay timing and dc voltage at circuit breaker are some possible monitoring options. Portable test sets are generally used to monitor the control circuit [13].

Insulating Medium: Due to the loss of insulating medium and or failure of interrupting mechanism, the circuit breaker opens but fails to interrupt the load or fault current. This unfolds into a major failure of circuit breaker. If breaker fails to provide required dielectric insulation of contacts immediately after the opening operation because of oil contamination, low gas pressure or density, dielectric stress exceed the circuit breaker capability, lightning etc, oil dielectric strength and gas pressure or density, are suitable measurements for this failure mode.

2. Failure Related to Closing

Operating Mechanism: Loss of stored energy, inappropriate lubrication, spring release mechanism worn, vibration of circuit breaker, pilot valve not secure etc. are responsible for the failures related to closing operation of the circuit breaker. Measurements for these failure modes are monitoring spring position, air pressure, timing between main contacts and close coil current, movement of release mechanism, contact travel and over travel, air pressure leaving pilot valve etc.

Control Circuit: Defective close coil or solenoid and control circuit failure may cause the breaker not to close on command. Circuit breaker closes with out command due to stray current in close circuit and ground on close circuit. Measurements for these failure modes include monitoring close coil circuit for possible increase in close current and for grounds, and monitoring other control circuit signals.

Contacts: Circuit breaker closes but fails to conduct current because of contacts burnt away (electrically eroded), mechanical linkage to contacts is broken or the overtravel inertia is lost preventing full contact closing. Power system disturbance recorder (including oscillographs and digital fault recorders) capturing primary current circuit, contact resistance test and infrared monitoring of contact for temperature are the measurements needed to detect this failure mode.

3. Failure to Conduct Continuous or Momentary Current (while already used)

Breaker does not conduct current due to resulting thermal damage to contact assemblies. This may be caused by high-resistance of contacts, ablation of contacts, broken or missing contacts, spring failure, bolted joints and sliding, rolling, or moving main contacts. Infrared monitoring of contact of temperature is one of the monitoring options available for this failure mode.

4. Failure Related to Insulation

This failure mode results in short circuit on power system or unintentional energization of components, phase to ground and phase-to-phase faults on the power system with possible safety hazard and economic damage.

Failure causes: Deterioration of interrupter exterior surfaces caused by partial discharge, loss of dielectric medium, loss of dielectric integrity of oil, loss of compressed air dielectric, excessive voltage applied to breaker, excessive temperatures of insulating materials, flashover caused by system transient events, ionization of surrounding insulating air caused by unusual service conditions, water infiltration, and foreign material.

Monitoring options: Monitor gas pressure or density, fluid level, periodic test of oil condition, monitor compressed air water content and temperature or relative humidity of compressed air, periodic insulation resistance and dielectric tests, monitor ambient air or component temperature, monitor overall component conditions using power system disturbance recorder, partial discharge monitoring, gas density monitor, etc.

5. Failure to Contain Insulating Medium

Failure of seals, gaskets, corrosion, erosion and porcelain rupture disk, result in loss of insulating medium to the environment. Measurements can be taken by monitoring insulating medium level (liquids), or pressure (air blast).

6. Failure to Indicate Condition or Position

Failure of insulation gas density switch; stuck, broken, or defective indicator; defects in auxiliary contacts, linkage, or wiring are the possible causes for this failure mode. Monitoring options are monitoring gas density variation, monitoring indication with signal to open and close circuit, primary current, control circuit current, and stored energy charging system operation.

7. Failure to Provide for Safety in Operation

This failure mode causes hazard to personnel. The possible causes of this failure are overpressure of porcelain interrupter, pneumatic or hydraulic fluids, spring charging system and failure of interlocks. Measurements can be taken by monitoring pressure relief valve, monitoring circuit breaker stored energy device condition remotely, and monitoring gas pressure/density.

H. Summary

Recent trend in maintenance approaches is to maintain the device according to its condition. Mathematical models, like probabilistic maintenance models, look promising but they demand an extensive relationship among condition monitoring techniques, failure probabilities, and maintenance tasks of the device. This chapter describes various circuit breaker condition monitoring techniques. Then it identifies typical failure modes and maintenance actions of circuit breaker. Finally, it describes the interplay between condition monitoring techniques, failure modes and maintenance actions. This information indicates that variety of components, techniques and failure modes is immense. Our approach was to use the control circuit data to obtain the condition based data. The main reason to select the control circuit data as monitoring parameter is that the data can be readily captured using small portable devices which are relatively cheap. Also data acquisition and signal processing techniques are well developed to process the condition based data.

CHAPTER V

PROBABILISTIC MAINTENANCE MODEL

A. Introduction

A model for power transformers is developed in [24] based on the concept of device-of-stages [23] and sensitivity analysis of the model parameters is carried in [25]. Utilizing the similar concepts, a probabilistic maintenance model for circuit breaker is proposed and discussed in this chapter. A brief discussion about the deterioration process, maintenance actions, and inspection tests of circuit breaker to is presented. A comparison is carried between transformer and circuit breaker among different aspects such as main components, deterioration process, operating mechanism, failure modes, inspection tests, maintenance actions etc. Such comparison helps in developing probabilistic maintenance model for circuit breaker based on maintenance models for transformers. Then, a probabilistic maintenance model for circuit breaker is proposed and discussed. The model parameters are indentified and a sensitivity analysis is carried to see the effect on model parameters on probability of failure and various costs. Some of the concepts regarding the sensitivity analysis are taken from [9] and repeated in this chapter to achieve the continuity of discussion of the proposed model. The proposed model finds its use in long term maintenance planning. The main purpose of this chapter is to provide a detailed discussion about the deterioration process, and inspection tests of circuit breaker, and how the inspection rate can affect the circuit breaker maintenance planning. This will help in understanding the concepts presented in later chapters.

B. Deterioration Process of Circuit Breaker

1. Deterioration of Operating Mechanism

This includes the deterioration of interrupter chamber, valves and various moving components. Moisture and corrosion of metal parts are some of the causes that are responsible for deterioration process of operating mechanism. As a result, the breaker may fail to operate.

2. Deterioration of Contacts

Oxidation of contacts results in formation of a thin oxide film over the contact surfaces. At higher temperatures these oxide materials will begin to soften and might result in a plastic deformation. Finally, contact erosion takes place due to the vaporization of electrodes during the current interruption process [5]. These conditions may result in binding of contacts.

3. Deterioration of Oil

The deposition of arc by-products when combined with moisture and oxygen in the oil, reduce the dielectric strength of the oil. Accumulation of these products contributes to the deterioration of oil [28]. If prolonged, this condition may cause arcing in the insulation gradually developing into an internal fault.

4. Deterioration Failure

Deterioration process results in deterioration failure, which is a long term-accumulated fault. It can happen mostly due to deterioration of contacts and oil, and break down of insulating materials such as bushings etc. [28], [11].

C. Maintenance Actions

Two maintenance actions (basic maintenance and replacement) have been proposed for the model.

1. Basic Maintenance

Operating Mechanism

- Clean and lubricate operating mechanism and apply suitable grease for the wearing surfaces of cams, rollers, bearings etc.
- Adjust breaker-operating mechanism as described in the manufacturer's instruction book
- Make sure all bolts, nuts, washers, cotter pins etc. are properly tightened
- After servicing the circuit breaker, verify whether the contacts can move to the fully opened and fully closed positions or not

Contacts

- Check the alignment and condition of the contacts and make adjustments according to the manufacturer's instruction book
- Check if the contact wear and travel time meet specifications

Insulating Medium and Arc Extinction

- Check for leaks and remove any water content. Check for governor and compressor for required pressure
- Recondition oil by filtering

2. Replacement

This situation causes the replacement of various components.

- Arc chute and nozzle parts if damaged
- Governors and compressors if worn or malfunctioning
- Contacts if badly worn or burned
- Oil if dielectric strength drops below an allowable limit and if any arc products are found in the oil

D. Inspection Tests

The following inspection tests are considered in developing the proposed model. Air blast and oil circuit breakers are considered in this study.

1. Breaker Timing Test

Condition of the circuit breaker can be obtained by comparing the test curve with the reference curve. The following are some possible observations that can be made from such measurements [11].

- *Contact separation occurred sooner than before*: contact wear
- *Faster circuit breaker stroke*: kinetic energy of the mechanism is above its upper limit
- *No damping at the end of the operation*: shock absorber failure
- *Reduction in total travel distance*: binding or stalling of the mechanism or insufficient stored driving energy

The proposed criterion for assessment of the condition of operating mechanism is:

Condition 1: satisfactory, test results follow the reference curve

Condition 2: caution stage, test results deviate slightly and need more attention

Condition 3: excessive wear and need complete overhaul or replacement

2. Control Circuit Monitoring

The recorded control signals are analyzed to find any abnormalities in the breaker operation. Sluggish trip latch, defective close coil, defective auxiliary switch and defective battery are some abnormalities that can be detected from monitoring control circuit signals [13].

The proposed criterion for the condition of control circuit is:

Condition 1: within specification and will not require maintenance

Condition 2: caution stage, need more attention

Condition 3: final stage, need major replacement

3. Contact Resistance Measurement

The possible causes for abnormal increase in contact resistance are deposition of foreign material in contacts, loose contacts and loose bushing connections [27].

The proposed criterion for the condition of contacts is

Condition 1: satisfactory

Condition 2: caution stage; need more attention

Condition 3: excessive wear and need complete overhaul

4. Inspection of Oil

Service-aged oils are classified into the following three conditions [28].

Condition 1: satisfactory

Condition 2: should be reconditioned for further use

Condition 3: poor condition; dispose

Suggested limits for oil in condition 1 are listed in Table III [28]. Criterion for recondition is excessive carbon in oil and reduced dielectric strength (dielectric strength drops below the accepted limit).

Table III: Suggested Limits for Service-Aged Oils for Transformers and Circuit Breakers [28]

Test and method	Transformer (Value for voltage class)			Circuit Breaker
	69 kV and below	69 – 230 kV	230 kV and above	Suggested limit
Dielectric strength[a] KV minimum				
1 mm gap*	23	28	30	20
2 mm gap*	40	47	50	27
Dissipation factor[a] (power factor),				
25 °C, % maximum	0.5	0.5	0.5	1.0
100 °C, % maximum	5.0	5.0	5.0	-
Interfacial tension, mN/m minimum	25	30	32	25

[a] Older transformers with inadequate oil preservation systems or maintenance, may have lower values

*Alternative measurements of 0.04 in and 0.08 in respectively for gaps

E. Comparison of Several Aspects between Circuit Breaker and Transformer

Circuit breaker is an electrical device that operates on command. Once the operating mechanism receives trip or close signal from a control circuit, it starts working and opens or closes the main contacts respectively. The overall performance of the breaker depends on the operating mechanism, which consists of various moving parts. Transformer is a device, which while in service, is always in an energized state. The insulating oil properties used in breaker and transformer are different and the. suggested limits are given in Table III [28]. Having an idea about the similarities and differences between the two devices, and knowing the maintenance model of the transformer will help in developing the maintenance model for the circuit breaker. Table IV provides a comparison between the breaker and transformer characteristics.

Table IV: Comparison between Circuit Breaker and Transformer

Comparison Aspect	Circuit breakers	Transformers
Main components	Contacts, interrupter, insulating medium, control circuit, mechanism which includes cam, latches, springs, bearings, coils, compressors, charging motors etc.	Winding, Cooling agent, for example, oil, gas, or air. Bushing, Tap changer
Operating mechanism	Stored energy in springs or gas pressure is used to move operating mechanism which either opens or closes the main contacts	Transforms voltage from one level to another preserving the same voltage frequency.
Deterioration process	Operating mechanism, oxidation of contacts and oil	Insulation paper in the winding, oxidation of oil.
Particles produced by aging process	Oxides, arc byproducts such as carbon, water, partial discharge	Sludge, Water, Fiber, Gases (CO, CO_2, etc.), Furfural, Partial Discharge
Failure Modes	• Fails to open on command • Fails to close on command • Fails to conduct continuous or momentary current (while already in use) • Fails to maintain the insulation • Fails to contain insulating medium • Fails to indicate condition or position • Fails to provide for safety in operation	• Thermal related faults • Dielectric related faults • Mechanical related faults • General degradation related faults
Inspection tests	• Contact travel time measurement • Vibration Analysis • Control circuit monitoring • Contact Resistance Test • Contact temperature monitoring • Dielectric strength • Partial Discharge	• Routine oil sampling test; dielectric strength, resistivity, acidity, moisture content. • Dissolved gas analysis • Furfural analysis • Partial discharge monitoring
Maintenance	• Basic maintenance: lubricating mechanism components, check for compressor pressure and dielectric strength of oil, adjusting all components and contacts as per manufacturer's instructions, check for control circuit connections • Replacement of contacts, interrupters, oil, damaged nozzles, springs, coils etc.	(For oil-immersed transformer) • Oil filtering (online/offline) • Oil replacement

F. Proposed Probabilistic Maintenance Model

A probabilistic maintenance model for circuit breaker is proposed in Fig. 5. The basic concept of the model is adapted from [23]. The entire life time of circuit breaker is represented by several deterioration stages.

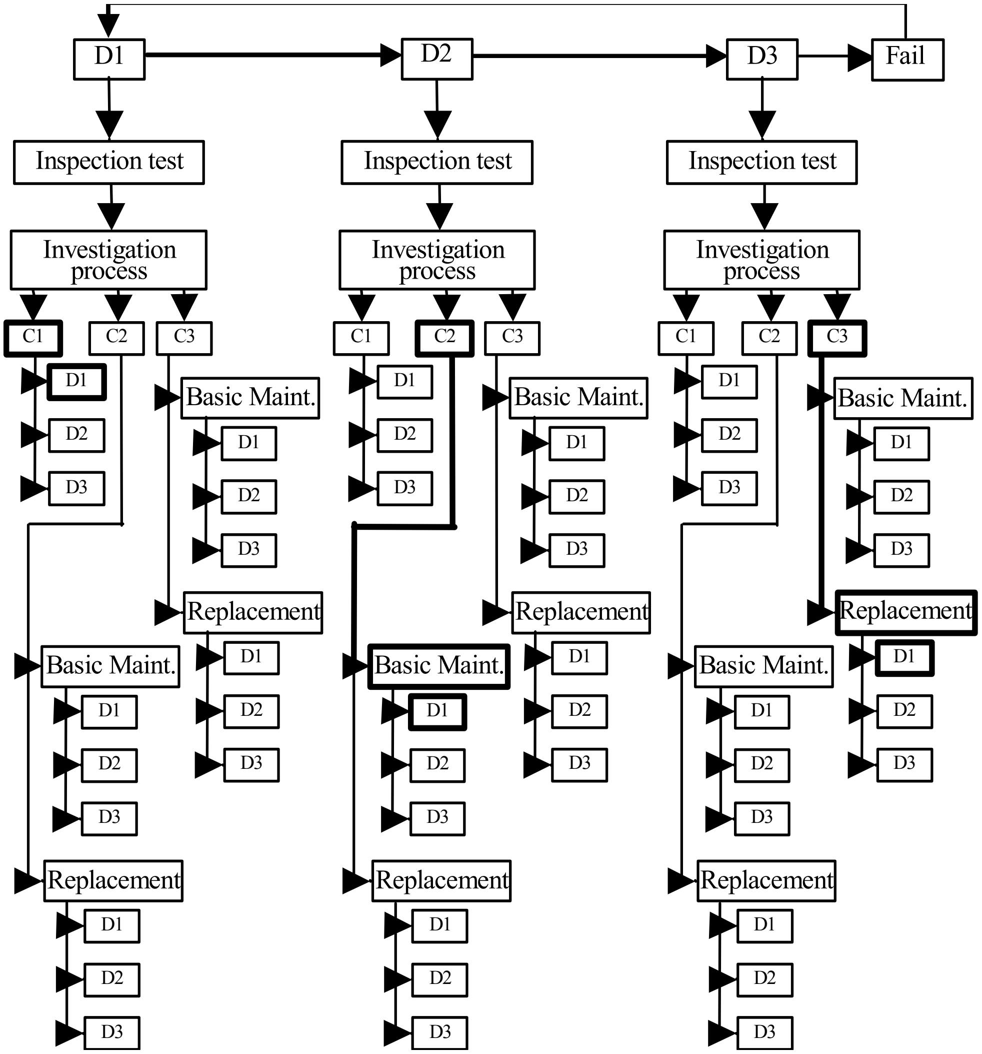

Fig. 5 Probabilistic Maintenance Model for Circuit Breaker

1. Model Description

Three deterioration stages, i.e., the initial stage (D1), minor (D2) and, major (D3) deterioration stages, followed by a failure stage are considered. Inspection test is implemented at each stage and the collected data is investigated to determine the condition of the breaker. In this model, three different levels of breaker condition are defined: C1- satisfactory and no maintenance is needed, C2- indication of abnormality or caution stage, needs further investigation or related maintenance and C3- Failure stage or poor condition, needs replacement. Further, the maintenance process is divided into three levels; (1) Do nothing, (2) Basic maintenance, and (3) Replacement. Once the suggested maintenance action is taken, the subsequent condition of the breaker is determined.

2. Investigation Process and Maintenance Actions

Information out of the inspection tests can be used to determine the condition of the device followed by the necessary maintenance action and rate of the next inspection. It is assumed that inspection is always followed by a maintenance action. Following are the three maintenance levels introduced in this model. These maintenance actions are already discussed in section C.

Do Nothing: The breaker is in satisfactory condition and no maintenance is needed. The probability that the system is set back to same stage is relatively high.

Basic Maintenance: This maintenance action increases the probability of going back to the previous stage.

Replacement: Replacement of damaged components brings the system back to its original stage i.e. beginning stage

G. Model Parameters

Table V shows the list and definition of parameters that are used in the circuit breaker maintenance model. The probabilities in model parameter 3 can be treated as equivalent transition rates from one stage to others. The equivalent model is introduced to clarify this point later. Parameters 1 and 3 can be approximated from the historical data of a physical circuit breaker condition [23]. Whereas, parameter 2, which is the inspection rate of each stage can be varied to achieve high reliability with minimum cost. Therefore, this parameter is of the most concern in the analysis. Following section presents the simulation results from MATLAB. Model parameters that are used in the simulation are listed in appendix.

TABLE V: List of Model Parameters and Definitions

Model parameters	Definition
1. Mean time in each stage	It is defined as mean time the device spends in each stage. The inverse of the mean time is the transition rate of the corresponding stage in the deterioration process.
2. Inspection rate of each stage	It is defined as the rate at which the inspection is done. The inspection may be followed by the maintenance.
3. Probabilities of transition from one state to others	These parameters are the probabilities of transition from one state to others. These probabilities include: • The breaker conditions after the inspection process • Transfer from any breaker condition to a given stage • Basic maintenance or replacement • Transferring to each stage after the maintenance

H. Sensitivity Analysis

As discussed in the previous section, the parameter of interest is the inspection rate in each stage. Let, i1 = inspection rate of stage 1 (per year)

i2 = inspection rate of stage 2 (per year)

i3 = inspection rate of stage 3 (per year)

From the Fig.3, it can be seen that the inspections which lead back to D1 will not reduce the failure probability; whereas those inspections that lead to D2 and D3 result in degradation. Thus with the assumption that, D1 is exponential distribution, the effect of inspection always results in degradation. It is possible to relax the assumption of exponential distribution by representing the D1 by three sub-stages. The reasons are discussed in detail in [25].

1. Impact of Inspection Rate on Failure Probability

Fig. 6-8 shows the effect of increasing the inspection rate on probability of failure. Following observation can be made from the simulation results.

- In Fig 6, for the small values of i1, the failure probability decreases. However, as the i1 increases beyond a number, which can be called as too much inspection, the failure probability increases.
- Fig 7 and 8 show that the probability of failure decreases with increasing inspection rates, i2 and i3 respectively.

In summary, the simulation results suggest that inspection rate of D1 helps in decreasing the probability of failure; however too much inspection results in increasing failure probability. In this model, the maintenance in stage 1 can result in the system transition to stage 3. Therefore, it is likely that too much maintenance can result in higher failure probability due to problems introduced by maintenance.

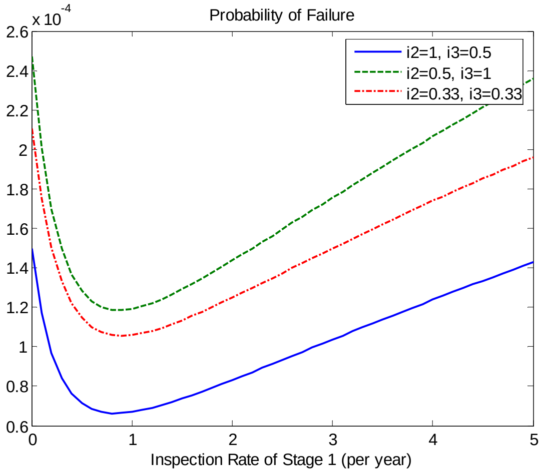

Fig 6 Failure probability vs. inspection rate of stage 1

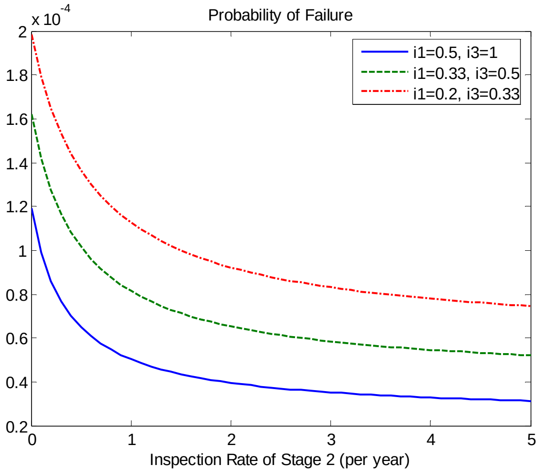

Fig 7 Failure probability vs. inspection rate of stage 2

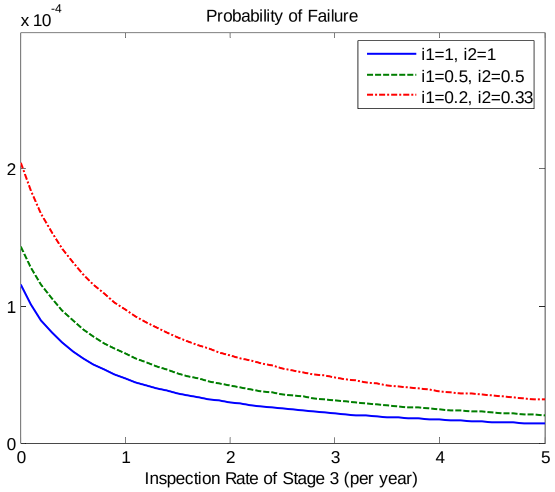

Fig 8 Failure probability vs. inspection rate of stage 3

2. Impact of Inspection Rate on All Associated Costs

Costs associated with the maintenance model are inspection cost, basic maintenance cost, replacement cost and failure cost. Assumed cost parameters are listed in appendix. This analysis will give insight into all the associated costs. The simulation results, showing the relation between inspection rate and associated costs, are shown in Fig. 9-17. The following observations can be made out of the simulation results.

- Failure cost decreases exponentially and then increases as the inspection rate of D1 increases and decreases exponentially as the inspection rate of D2 and D3 increases. This scenario can be observed in Fig 9, 12 and 15 respectively.
- Maintenance cost first decreases and then increases with inspection rate of D1. Where as it increases and stays at constant value at higher inspection rate of D2 & D3. Fig. 10, 13 and 16 shows the variation of maintenance cost with inspection rate of D1, D2 and D3 respectively.
- The optimal region of inspection rate of D1 that will minimize the total cost is 0.5-1 per year.
- Maintenance of the device at its stage D1, beyond the optimal region is not useful.
- Fig. 14 and 16 shows that the total cost is minimal at high inspection rate of D2 and D3 respectively.

Finally, results suggest that small inspection rate of D1 and high inspection rate of D2 and D3 will lead to cost effective maintenance. The model helps in allocating the available resources towards maintenance of the device and finds its importance in long term planning purposes.

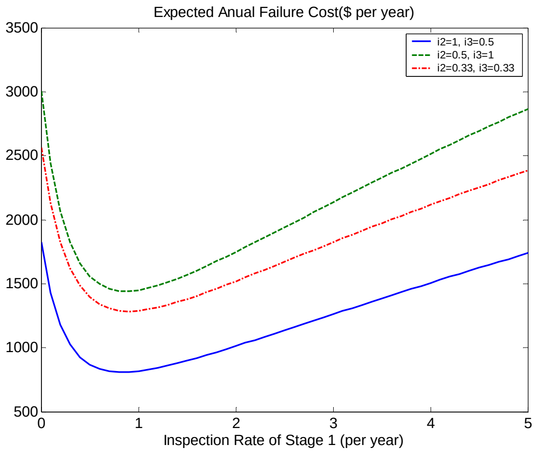

Fig 9 Failure cost vs. inspection rate of stage 1

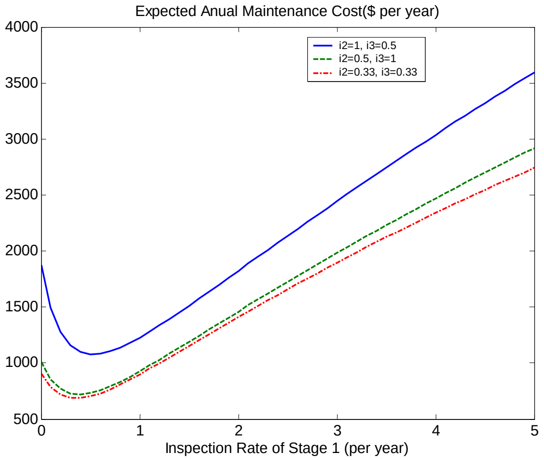

Fig 10 Maintenance cost vs. inspection rate of stage 1

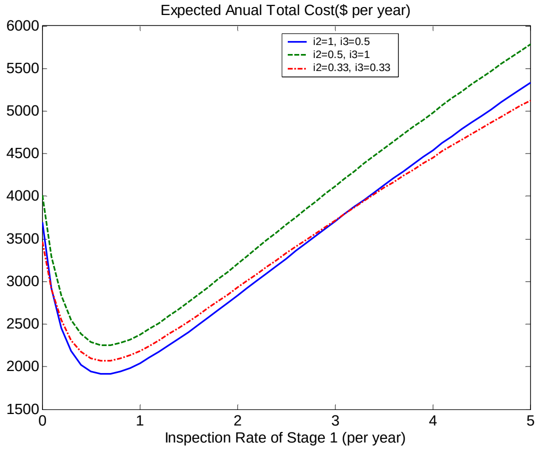

Fig 11 Total cost vs. inspection rate of stage 1

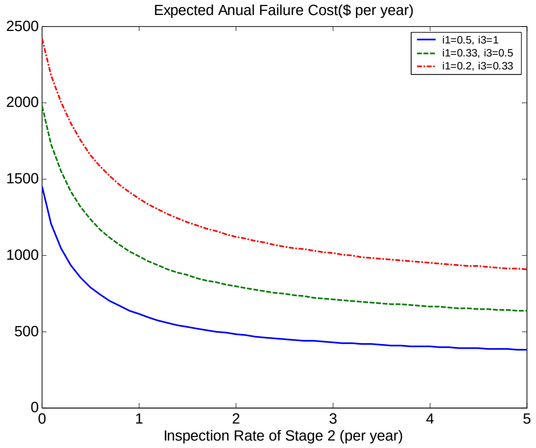

Fig 12 Failure cost vs. inspection rate of stage 2

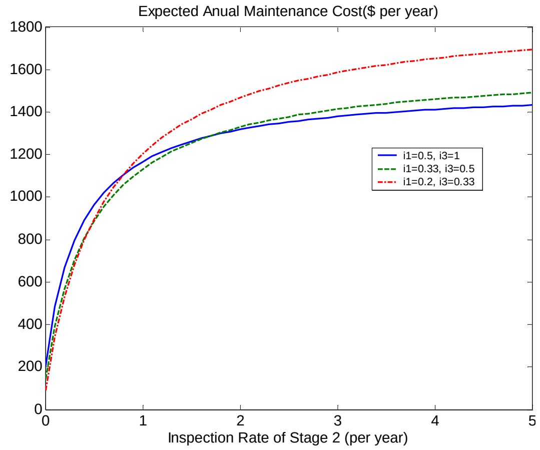

Fig 13 Maintenance cost vs. inspection rate of stage 2

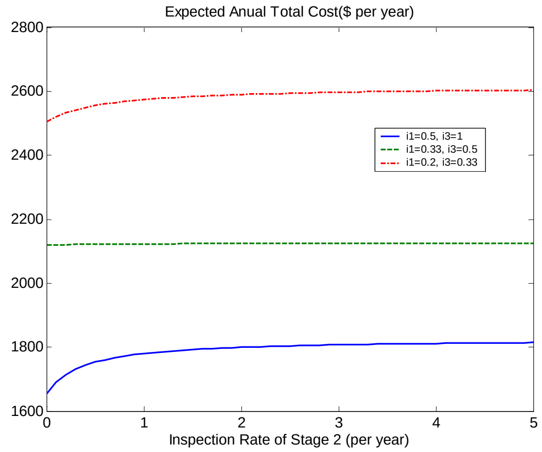

Fig 14 Total cost vs. inspection rate of stage 2

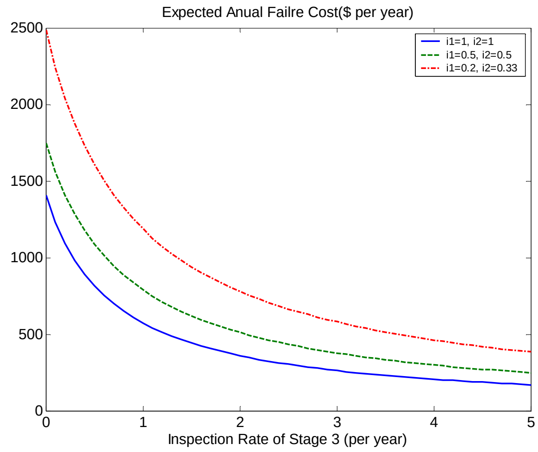

Fig 15 Failure cost vs. inspection rate of stage 3

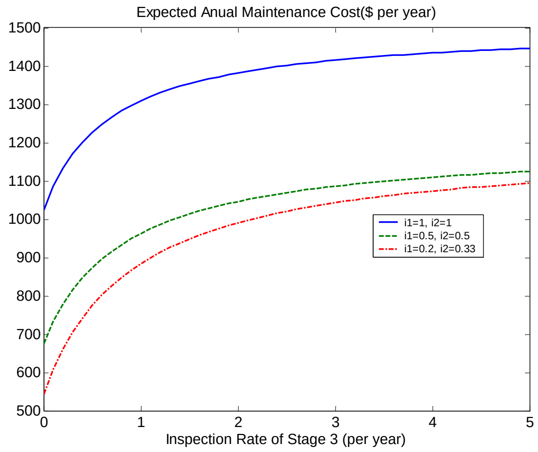

Fig 16 Maintenance cost vs. inspection rate of stage 3

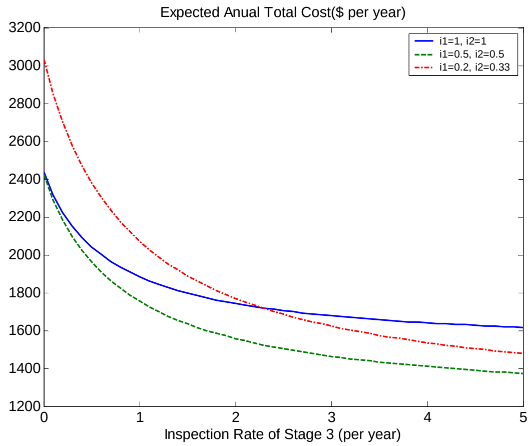

Fig 17: Total cost vs. inspection rate of stage 3

3. Equivalent Model for Mathematical Analysis

In order to check the validity of the maintenance model presented in Fig. 5, it is necessary to introduce an equivalent model. Fig. 18 shows the equivalent model with 3 discrete stages representing the deterioration process of the breaker. Assume that maintenance is implemented at every inspection, maintenance and inspection rate of each stage is considered to be an equivalent repair rate. Let,

D1: stage 1

D2: stage 2, minor deterioration

D3: stage 3, major deterioration

F: failure stage

y_1 = mean time in stage 1 (year)

y_2 = mean time in stage 2 (year)

y_3 = mean time in stage 3 (year)

μ_{21} = repair rate from stage 2 to 1 (/year)

μ_{32} = repair rate from stage 3 to 2 (/year)

μ_{31} = repair rate from stage 3 to 1 (/year)

μ_F = repair rate (/year).

Transition rate from stage 1 to 3 (λ_{13}) is introduced to describe an imperfect inspection of stage 1. This accounts for the probability that inspection of stage 1 might cause the system to transit to stage 3.

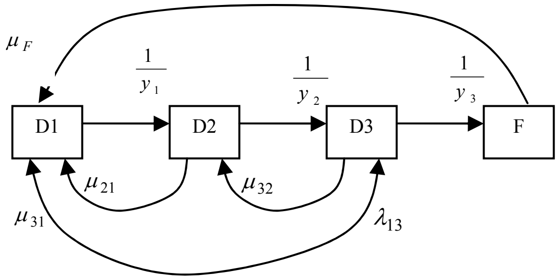

Fig. 18 Equivalent maintenance model

The mathematical analyses are presented in the next section using the steady state probability calculations [25]. The analyses cover both the probability of failure and cost analysis. The mathematical equations will be used to verify the simulation results presented in previous sections. Steady state probability calculations are presented in Appendix A.

Probability of Failure Analysis: Probability of failure can be expressed as the function of Mean Time to First Failure (MTTFF) and the repair rate (μ_F). Let T_0 = life time without maintenance and T_E = extended life time with maintenance. Then,

$$T_0 = y_1 + y_2 + y_3 \tag{1}$$

$$\begin{aligned} T_E &= (\mu_{21}\mu_{31} + \mu_{21}\mu_{32} + \mu_{21}\lambda_{13} + \mu_{32}\lambda_{13}) y_1 y_2 y_3 + \mu_{21} y_1 y_2 \\ &\quad + \mu_{31} y_2 y_3 + \mu_{31} y_1 y_3 + \mu_{32} y_2 y_3 + \lambda_{13} y_1 y_3 \end{aligned} \tag{2}$$

$$MTTFF = \frac{T_0 + T_E}{1 + \lambda_{13} y_1 + \lambda_{13}\mu_{21} y_1 y_2} \tag{3}$$

$$P_F = \frac{T_R}{T_R + MTTFF}, \tag{4}$$

$$T_R = \frac{1}{\mu_F} \tag{5}$$

As mentioned in section G, the model parameter that is of interest, is the inspection rate at each stage. Following subsections are devoted to analyzing the relationships between the inspection rate of each stage and the probability of failure.

Inspection Rate of Stage 1: Increasing inspection rate of stage 1 increases the repair rate from stage 1 to stage 3 (λ_{13}). This results in decreasing failure probability as the denominator is higher than the numerator of (4). However, at higher inspection rate of stage 1, the numerator becomes more predominant than the denominator and hence the failure probability may increase. This result is observed in Fig 6. It is quite reasonable that if the device is in good condition, too much maintenance may decrease the life time.

Inspection Rate of Stage 2: Inspection rate of stage 2 results in increasing repair rate from stage 2 to 1, μ_{21}. Assuming that this repair rate is very high,

$$P_F \approx \frac{T_R \lambda_{13}\mu_{21} y_1 y_2}{T_R \lambda_{13}\mu_{21} y_1 y_2 + (\mu_{31} + \mu_{32} + \lambda_{13})\mu_{21} y_1 y_2 y_3} \tag{6}$$

It can be easily seen that the failure probability decreases with increase in repair rate (μ_{21}). This scenario is observed in Fig 5.

Inspection Rate of Stage 3: Inspection rate of stage 3 increases the repair rates from stage 2 to 3 (μ_{32}) and 1 (μ_{31}) respectively. These rates appear in the denominator of (4) and hence decrease the failure probability. This result is verified in Fig 6.

Cost Analysis: The cost analyses include failure cost, maintenance cost, and total cost. Maintenance cost in this analysis includes inspection cost based on the assumption of the equivalent model that maintenance is implemented at every inspection. These equations will explain the simulation results in Fig 8-17.

The transitional probability matrix and resulting steady state probability are derived in appendix. Let,

FC = repair cost after failure (dollar/time)

MC = maintenance cost (dollar/time)

P(i) = steady state probability of stage i; i=1,2, or 3

C_F = expected annual failure cost (dollar/year)

C_M = expected annual maintenance cost (dollar/year)

C_T = expected annual total cost (dollar/year)

T_R = repair time (year)

Failure Cost Analysis: The expected failure cost per year is, C_F = FC × frequency of failure which is equal to

$$C_F = FC \times (P_F \mu_F) = \frac{FC}{T_R + MTTFF} \tag{7}$$

It can be observed that without any maintenance, $C_F = FC/(T_R + T_0)$ is the highest possible value. If we assume that $\lambda_{13} << \lambda_{12}$ and $\lambda_{13} << \lambda_{23}$, then MTTFF will be higher and C_F will decrease as we increase repair rate of any stages (μ_{12}, μ_{31} or μ_{32}). On the other hand, if λ_{12} and λ_{13} are close to each other ($\lambda_{12}/\lambda_{13} \approx 1$), then MTTFF is possibly small. If MTTFF is small relative to T_R, then C_F will converge to, $C_F = FC/T_R$.

From Probability of failure analysis, P_F always decreases with maintenance as long as the probability of transferring from stage 1 to 3 is not high which is usually true. Therefore, failure cost will reduce to a constant value as inspection rate of any stage increases. This conclusion is verified by simulation results in Fig 9, 12, and 15.

Maintenance Cost Analysis: The expected maintenance cost per year is, C_M = MC × frequency of maintenance, which is equal to

$$C_M = MC \times (P(1)\lambda_{13} + P(2)\mu_{21} + P(3)(\mu_{31} + \mu_{32})) \tag{8}$$

Maintenance cost depends on repair rate of stage 2 and 3, if the probability of transferring from stage 1 to 3 is very small. In such case, it will increase from zero to some constant value. This is verified by simulation results in Fig 13 and 16. However, when inspection rate of D1 increases (probability of transferring from stage 1 to 3 is higher), maintenance cost could increase to infinity. It might be possible that the breaker condition gets even worse with every inspection and maintenance. Also, note that the maintenance cost includes the cost of inspection, which will increase with each inspection, resulting in increasing maintenance cost. This is verified by the simulation result in Fig 10.

Total Cost Analysis: Total cost analysis gives an overall picture of relation between frequency of inspection rates and the associated cost. It can be observed from (7) and (8) that the failure cost dominates total cost at small inspection rates while maintenance cost dominates total cost at high inspection rate. The optimal value of the total cost will be the region with low inspection rate of stage 1 and high inspection rate of stage 2 and 3. The simulation results in Fig 10, 14 and 17 supports this conclusion.

I. Summary

A probabilistic maintenance model for circuit breakers is introduced. The deterioration process is modeled by representing the breaker age by different stages. Inspection and maintenance is introduced at each stage. Information collected during inspection tests is analyzed and the condition of the breaker can be defined. Maintenance action is taken according to the condition of the breaker. Sensitivity analysis of the probabilistic maintenance model is done to see the effect of model parameters. The analysis covers the probability of failure, failure cost, maintenance cost and total cost. Equivalent mathematical model is corroborated to verify the simulation results. The simplified mathematical model provides some insight into the complexity of the proposed model. The model finds its importance in long-term planning and allocation of resources over the life time of the breaker.

CHAPTER VI

MODEL TO ASSESS CIRCUIT BREAKER PERFORMANCE USING CONDITION-BASED DATA

A. Introduction

This chapter proposes a methodology to utilize the condition-based data to develop probabilistic approaches to quantify the effect of device maintenance for circuit breakers. This results in definition of performance indices, which leads to development of optimized, system level, risk-based maintenance strategies. The work presented in this chapter makes the methodology practical so that it can be applied in real time using field condition-based data. The proposed approach can be easily extended with few modifications to other devices such as power transformers.

B. Proposed Model to Assess Performance of Breaker

The proposed methodology is shown in Fig. 19, and has the following steps:

(i) develop a history of CB control signals and extract timings of each signal parameter using signal processing module

(ii) analyze the relationship between the parameters using scatter plots and fit probability distribution to each parameter

(iii) define performance indices using these distributions to assess the condition of the breaker

(iv) as the new data arrives, update the distributions and performance indices using Bayesian updating approach. The methodology is explained in detail in the following subsections.

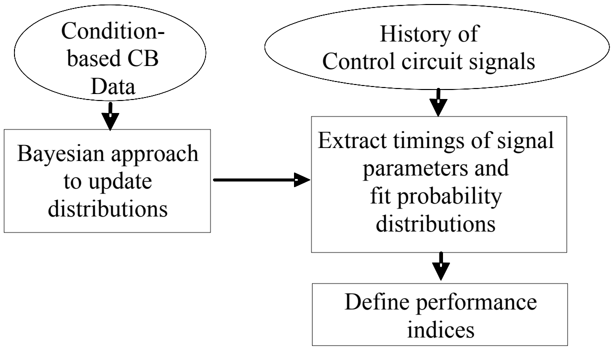

Fig. 19 Model to assess the condition of breaker

C. Condition Monitoring Data of Circuit Breaker

1. Control Circuit of Circuit Breaker

According to a failure survey conducted by CIGRE working group A3.12, the failure percentage of the control circuit is rated second to the operating mechanism among all the circuit breaker assemblies [21]. The condition-based data from the control circuit is used in this work, as it allows assessment of the performance of control circuit and the operating mechanism as well. The condition monitoring techniques are relatively easy to develop since the secondary control circuit is readily accessible for on-line monitoring. The electrical representation of CB control circuit is given in Chapter IV.

2. Signals that Reflect the Operating Mechanism Status

There are portable test devices available on the market to collect and display the control circuit signals which are analog and/or digital waveforms [13]. A low cost circuit breaker monitor (CBM) development for acquisition and automated analysis of condition-based data both offline and online is reported in [14]-[15]. The collected waveforms represent a "signature" of the circuit breaker. An ideal representation of such signature during the open and close operation is shown in Fig. 20 and 21 respectively. A full list of recorded signals and the corresponding timing parameters are provided in Table VI. Signal processing and expert system modules are developed for extracting the exact timings of the signal parameters for both open and close operations [16]-[17].

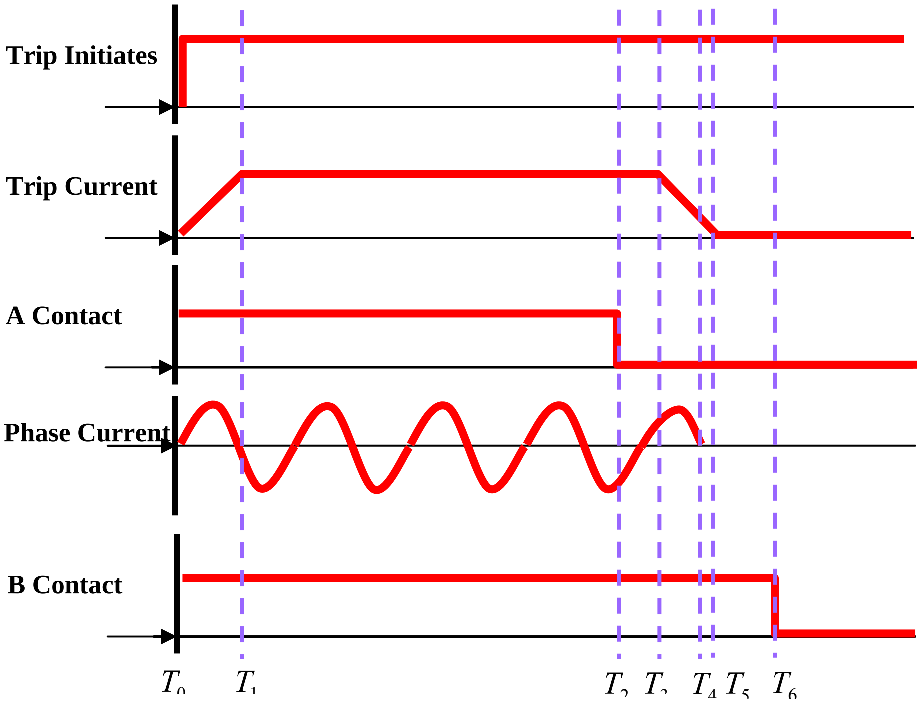

Fig. 20 Trip event and opening of circuit breaker

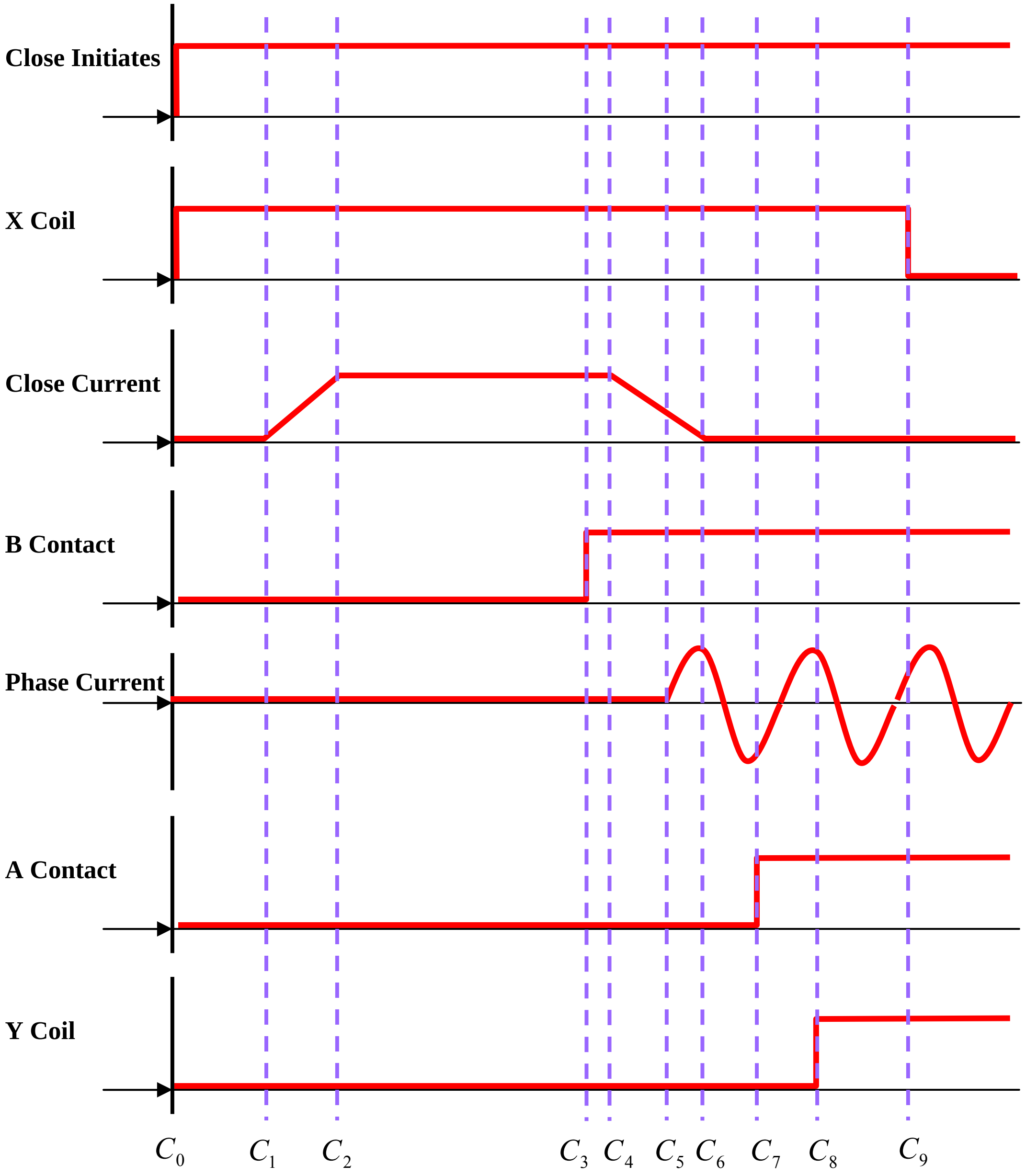

Fig. 21 Close event and closing of circuit breaker

Table VI: Waveform Abnormalities and Signal Parameters [16]

Event	Event Description	Signal
1	Trip or close operation is initiated (Trip or close initiate signal changes from LOW to HIGH)	T1
2	Coil current picks up	T2
3	Coil current dips after saturation	T3
4	Coil current drops off	T4
5	B contact breaks or makes (a change of status from LOW to HIGH or vice versa)	T5
6	A contact breaks or makes	T6
7	Phase currents breaks or makes	T7
8	X coil current picks up	T8
9	X coil current drops off	T9
10	Y coil current picks up	T10

D. Probability Distribution

1. Scatter Plot Analysis

Before fitting a distribution to each parameter, understanding the dependency between the parameters is needed. This can be done through scatter plot analysis [29]. One of the most common patterns is a linear relationship between the two variables. A simple linear regression model is appropriate to represent the response variable Y in terms of X, such as $Y = \beta_0 + \beta_1 X + \varepsilon$. Some times the response variable Y linearly depends on more than one variable, say X_1 and X_2. In this case, Y can be represented as, $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$. This situation can get complex if a co-linearity exists between the predictive variables X_1 and X_2. Such cases can be dealt by a technique called ‘Principle Component Analysis’ (PCA) [29]. In simple terms, PCA orthogonally transforms X_1, X_2 into Z_1, Z_2 respectively such that there is no correlation among Z_1 and Z_2. Now Y can be expressed as $Y = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \varepsilon$, where β_0, β_1, and β_2 are different.

2. Statistical Measure Definitions

A normal distribution is assumed for all signal parameters for the purpose of illustration. Fig. 22 shows the probability distribution of signal parameter t_2 alone. To proceed, define upper and lower limits for each timing parameter such that if new value of 't_i' falls in this range, then those parts of the breaker which cause the occurrence of time instant 't_i', operate properly. For example, if t_2 falls out of the limits, it means that there is some problem associated with close coil. The shaded area between the lower and upper limits is the probability that the breaker will operate properly.

In general, probability that breaker operates correctly with respect to 't_i' is defined as, $p(t_i) = \Pr(l_i \le t_i \le u_i)$, where, l_i is the lower limit and u_i = upper limit. These probabilities are used to define performance indices for various assemblies of circuit breaker.

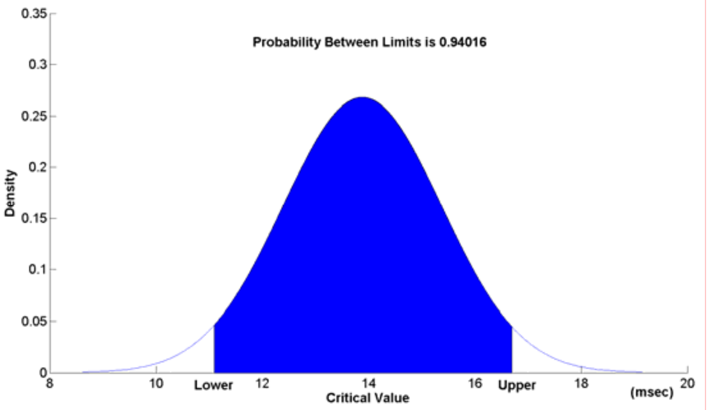

Fig. 22 Probability distribution of parameter 't_2'

E. Condition Assessment

1. Performance of Trip and Close Coils

A sample representation of trip coil current and close coil current is shown in Fig. 23 and 24 respectively. After the trip or close initiate is active, the coil current makes a gradual transition to a nonzero value at time ‘t_2’. The time instant ‘t_3’ corresponds the time at which the operating mechanism starts moving with the help of trip or close coil energy. The coil current starts dropping down to zero at time ‘t_4’. The trip and close coil current signals should be fairly smooth except for the dips at the beginning and end of the waveform. Possible abnormalities associated with trip and close coil include: pick up delayed, dip delayed, drop-off delayed, etc. These abnormalities can be addressed by probabilities $p(t_2)$, $p(t_3)$ and $p(t_4)$ corresponding to the timing parameters, t_2, t_3 and t_4. These time instants should occur with in the tolerance limits to assure proper operation of trip and close coils. The performance index related to trip coil is defined as ‘the probability that trip coil fails to operate properly’,

$$p_f(\mathrm{TC}) = 1 - p(t_2)p(t_3)p(t_4) \quad (1)$$

Similarly, the probability that ‘the close coil fails to operate correctly’ is defined as,

$$p_f(\mathrm{CC}) = 1 - p(t_2)p(t_3)p(t_4) \quad (2)$$

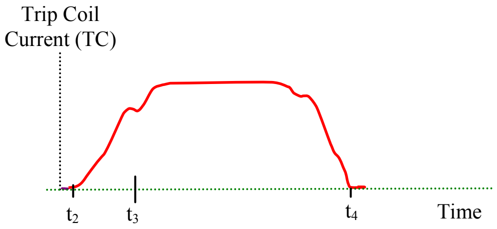

Fig. 23 Trip coil current

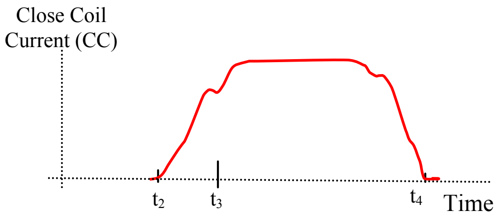

Fig. 24 Close coil current

2. Performance of Auxiliary Contacts

As the breaker opens or closes its main contacts, it also changes the status of the auxiliary ‘a’ and ‘b’ contacts as shown in Fig. 25 and 26. Some possible abnormalities associated with operation of “a” and “b” contacts are: delay in transition, premature transition, unstable contacts, noise and contacts bounce. If the timings t_5 and t_6 fall with in their tolerance limits, we can say the auxiliary contacts operate normally. The performance index related to auxiliary contacts can be defined as, the ‘probability that auxiliary contacts fails to operate properly’,

$$p_f(\mathrm{AB}) = 1 - p(t_5)p(t_6) \tag{3}$$

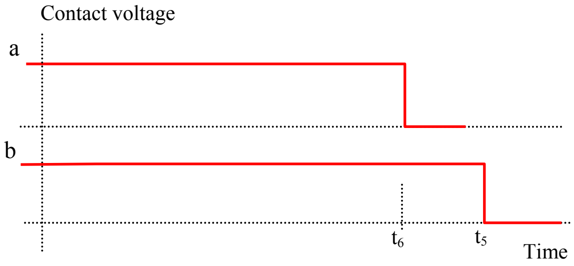

Fig. 25 “a” and “b” auxiliary contacts transition during open operation

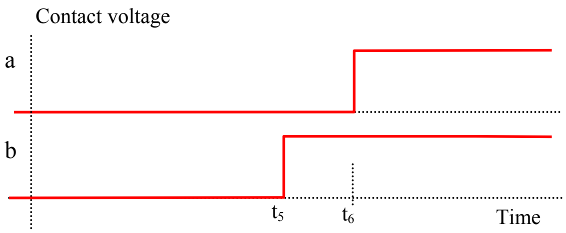

Fig. 26 “a” and “b” auxiliary contacts transition during close operation

3. Performance of Operating Mechanism

The time period between the instant at which the TC (CC) rises (t_2) and the instant at which the dip occurs (t_3) is the ‘free travel time’ that equals to $|t_3-t_2|$. This free travel time reflects the performance of the trip (close) latch mechanism. The timings t_2 and t_3 need to fall in the tolerance limits for the breaker to have normal free travel time. Any violation reflects an improper operation of trip (close) latch mechanism. The corresponding performance index is defined as the ‘probability that free travel time is abnormal’,

$$p_f(FT) = 1 - p(t_2)p(t_3) \tag{4}$$

The coil current also needs to correlate with the event of “a” or “b” contact. The time period between the dip and the operation of “a” for open operation (“b” for close operation) is the mechanism travel time which is equal to $|t_6-t_3|$ for open ($|t_5-t_2|$ for close) operation [16]. For normal ‘mechanism travel time’, the timings t_3 and t_4 need to fall in corresponding tolerance limits. Any violation of these timings can be reported as abnormal operation of breaker. The corresponding performance index is defined as the ‘probability that the mechanism travel time is abnormal’,

$$p_f(\mathrm{MT}) = 1 - p(t_3)p(t_6) \quad \text{(Open)} \tag{5}$$

$$p_f(\mathrm{MT}) = 1 - p(t_3)p(t_5) \quad \text{(Close)} \tag{6}$$

4. Performance of Breaker

In addition to the performance of individual components of breaker, an over all performance of the breaker may be assessed. If none of the timings (t_2-t_6) is violated, we can say that breaker operates properly. In other words, if any of these timings fall out side the corresponding tolerance limits, we can say that the breaker fails to operate properly. This quantity can be defined as 'probability that the breaker does not operate properly' and is estimated as,

$$p_f(\mathrm{Br}) = 1 - \prod_{i=2}^{6} p(t_i) \tag{7}$$

Note that this probability is different from the actual failure probability of the breaker, the calculation of which involves consideration of historical data including failures. A summary of all performance indices for both open and close operation is given in Table VII.

Table VII: Performance Indices

Operation	Performance Index	Performance
open	p_f(TC)	Trip Coil
	p_f(AB)	Auxiliary 'a' and 'b' contacts
	p_f(FT)	Trip latch mechanism
	p_f(MT)	Operating Mechanism
	p_f(Br)	Breaker as a whole
Close	p_f(CC)	Close coil
	p_f(AB)	Auxiliary 'a' and 'b' contacts
	p_f(FT)	Close latch mechanism
	p_f(MT)	Operating Mechanism
	p_f(Br)	Breaker as a whole

F. Bayesian Updating Approach

1. Background

A brief discussion of the Bayesian approach is given below. The posterior distribution, due to Bayes' theorem is expressed as [30],

$$p(\theta|y) = \frac{\pi(\theta)L(y|\theta)}{\int_{\Theta}\pi(\theta)L(y|\theta)d\theta} \tag{8}$$

where, $\pi(\theta)$ is the prior distribution and $L(y|\theta)$ is likelihood function. The denominator of the above equation is a constant for a given 'y', and hence the equation can be written as,

$$p(\theta|y) \propto \pi(\theta)L(y|\theta) \tag{9}$$

Efficient Markov Chain Monte Carlo (MCMC) algorithms such as Gibbs Sampler can be used to draw samples from the posterior distribution and any posterior inference can be based on the samples-thus obtained. The likelihood in (9) is the joint likelihood of entire data ($y_1 \ldots y_n$), as shown in Fig. 27.

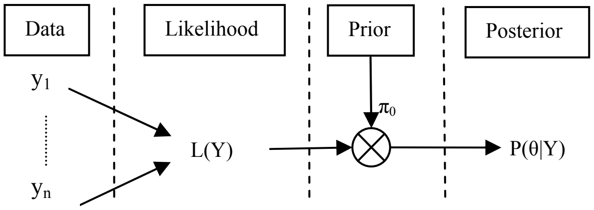

Fig. 27 Flow chart of Bayesian approach

2. Sequential Bayesian Updating Approach

The Bayesian approach discussed in previous sections is often suited for offline analysis, i.e. entire data is available at the time of computation. In other words, as the new data point arrives, it will be appended to the already existing data and the whole data set is used in constructing the joint likelihood to estimate posterior distribution. This might demand extra storage capacity on computer and processing time in MCMC simulations, especially if the data set is either huge or gets accumulated enough. It would be more realistic if one can analyze the condition-based data and be able to update the performance indices online. This can be achieved by Sequential Bayesian approach shown in Fig. 28. In this approach, as the new data points comes in, the likelihood will be formed with that data point alone, and the current prior will be the posterior of previous data set as explained in Fig. 26. In this way, one doesn't have to deal with huge data sets, as the information of the data will be captured by prior.

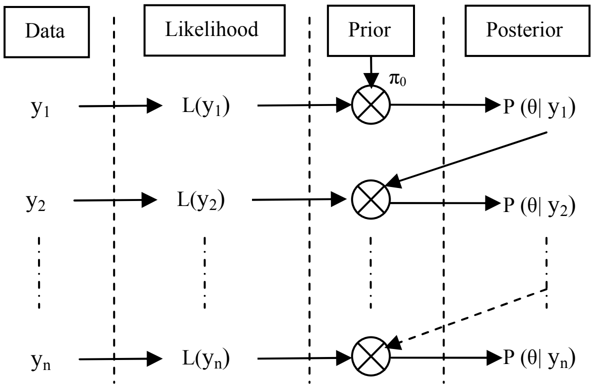

Fig. 28 Sequential Bayesian approach

G. Quantification of Maintenance

The proposed methodology can be used to quantify the effect of maintenance. The procedure is to measure the new data after a maintenance action. Then update the timing distributions and performance indices, and compare with that of previously calculated indices. Any difference can be reported as the direct result of that particular maintenance action. This way, it is possible to quantify the effect of maintenance and hence to develop system level optimized risk-based maintenance strategies.

H. Example

A brief example of the whole process is presented in this chapter. Detailed case studies are presented in Chapter VIII. Assume that y_1-y_5 represents the signal parameters for the data set under consideration and scatter plot analysis reveals that the parameters y_1, y_2, y_3 and y_4 are independent, and a linearly increasing relationship between parameters y_4 and y_5 as shown in Fig. 29. A normal model is proposed based on the data and scatter plot analysis.

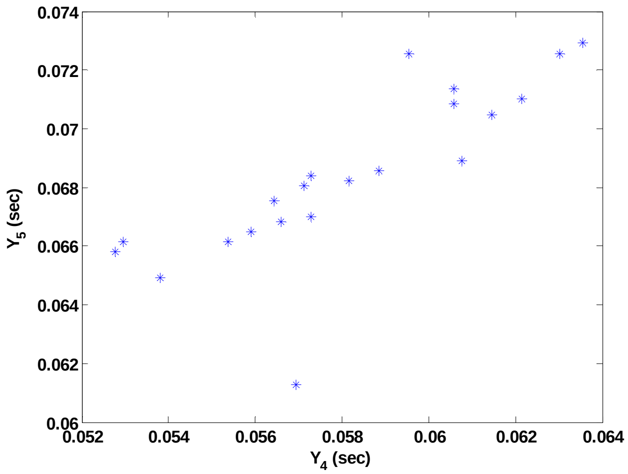

Fig. 29 Scatter plot of Y_4 and Y_5

Let y_{ij} is the j_{th} observation of i_{th} variable and ‘n’ is the sample size,

$$y_{ij} \sim N(\mu_i, \sigma_i^2), \; \forall j, \; i = 1,2,3,4 \tag{10}$$

where μ_i and σ_i^2 are sample mean and variance. Since there is a linear relationship between y_4 and y_5, y_5 is expressed as,

$$y_{5j} = \beta_0 + \beta_1 y_{4j} + \varepsilon_{5j}, \ \ \forall j \tag{11}$$

$$y_{5j} \sim \ N(\beta_0 + \beta_1 y_{4j}, \sigma_5^2), \tag{12}$$

where σ_5^2 is the error variance and, β_0 and β_1 are constants.

The parameter set of the problem is given in (13). Assuming non informative prior for all σ_i^2 and uniform prior for all other parameters, the prior, likelihood function and joint posterior distributions are given by (14), (15) and (16) respectively.

$$\Theta = [\mu_1, \mu_2, \mu_3, \mu_4, \sigma_1^2, \sigma_2^2, \sigma_3^2, \sigma_4^2, \sigma_5^2, \beta_0, \beta_1] \tag{13}$$

$$p(\theta) \propto \prod_{i=1}^{5} \frac{1}{\sigma_i^2} \tag{14}$$

$$L(Y|\Theta) = \prod_{j=1}^{n} \left[\prod_{i=1}^{4} \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(y_{ij}-\mu_i)^2}{2\sigma_i^2}} \left(\frac{1}{\sqrt{2\pi\sigma_5^2}} e^{-\frac{(y_{5j}-(\beta_0+\beta_1 y_{4j}))^2}{2\sigma_5^2}} \right) \right] \tag{15}$$

$$p(\theta|_Y) \propto \left(\prod_{i=1}^{5} \frac{1}{\sigma_i^2} \right) \prod_{j=1}^{n} \left[\prod_{i=1}^{4} \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(y_{ij}-\mu_i)^2}{2\sigma_i^2}} \left(\frac{1}{\sqrt{2\pi\sigma_5^2}} e^{-\frac{(y_{5j}-(\beta_0+\beta_1 y_{4j}))^2}{2\sigma_5^2}} \right) \right] \tag{16}$$

It is difficult to compute the normalizing constant that makes the above posterior distribution a density. Hence, Markov Chain Monte Carlo (MCMC) technique is used to estimate the posterior distribution of the parameters [30]. The MCMC algorithm using Gibbs sampler involves estimation of conditional and marginal distributions and they are given below.

Conditional Distributions:

$$\mu_i \Big|_{\theta,y} \sim N(\bar{y}_i, \sigma_i^2 / n), \; i = 1,2,3,4 \tag{17}$$

Retaining those terms that involve β_0 in the likelihood function (15) and after rearranging, conditional distribution for β_0 is given by,

$$\begin{aligned} &\beta_0 \Big|_{\beta_1,\sigma_5^2,y} \sim N(\bar{a}, \sigma_5^2 / n), \\ \textit{where,} \quad &\bar{a} = \frac{1}{n}\sum_{j=1}^{n}(y_{5j} - \beta_1 y_{4j}) \end{aligned} \tag{18}$$

Retaining those terms that involve β_1 in the likelihood function (15) and after rearranging, conditional distribution for β_1 is given by,

$$\begin{aligned} &\beta_1 \Big|_{\beta_0,\sigma_5^2,y} \sim N(D/C, \sigma_5^2 / C), \\ \textit{where,} \quad &C = \sum_{j=1}^{n} y_{4j}^2, \quad D = \sum_{j=1}^{n}(y_{5j} - \beta_0) y_{4j} \end{aligned} \tag{19}$$

Marginal Distributions:

$$\sigma_i^2 \,|_y \; \sim \; Inv - \chi^2(n-1, s_i^2), \qquad i = 1,2,3,4 \tag{20}$$

Retaining those terms that involve σ_5^2 in the likelihood function (15) and after rearranging, marginal distribution for σ_5^2 is given by,

$$\begin{aligned} &\sigma_5^2 \,|_y \; \sim \; Inv - \chi^2(n, K/n), \quad \textit{where} \\ &K = \sum_{j=1}^{n}(y_{5j} - \beta_0 - \beta_1 y_{4j})^2 \end{aligned} \tag{21}$$

The algorithm implementation has the following steps:

- start with initial vector of parameters, θ_0
- draw σ_i^2 , i = 1,2,3,4 from marginal distributions (20)

- draw σ_5^2, from marginal distribution (21)
- draw β_0 from conditional distribution (18)
- draw β_1 from conditional distribution (19)
- draw μ_i, $i = 1,2,3,4$ from conditional distributions (17)
- new set of parameters, θ_1 is available
- repeat the above steps up to a predefined length

The above procedure is implemented in MATLAB. Table VIII shows posterior mode and 95% Highest Posterior Density (HPD) region for all the parameters under consideration. 95% HPD region means that the sample values of the parameters fall under this interval with a probability of 0.95. As the new data comes, it is possible to update the parameter distributions using the Bayesian approach described above. The posterior distribution of parameters is shown in Fig. 30.

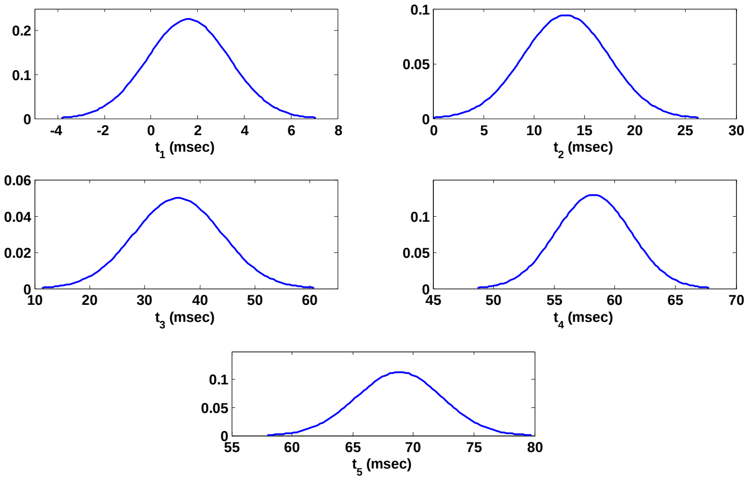

Fig. 30 Updated probability distributions of parameters

Table VIII: Mode and 95% Highest Posterior Density Regions

PARAMETER	MODE	95% HPD REGION
μ_1	0.0016	(0.0014, 0.0018)
μ_2	0.0130	(0.0125, 0.0134)
μ_3	0.0359	(0.0352, 0.0368)
μ_4	0.0582	(0.0578, 0.0585)
σ_1^2	0.0173E-05	(0.0093, 0.0325)E-05
σ_2^2	0.0094 E-05	(0.0502, 0.1818) E-05
σ_3^2	0.3517 E-05	(0.1886, 0.6552) E-05
σ_4^2	0.0520 E-05	(0.0278, 0.0949) E-05
σ_5^2	0.0148 E-05	(0.0079, 0.0277) E-05
β_0	0.0249	(0.0248, 0.0251)
β_1	0.7476	(0.7432, 0.7511)

As explained in earlier subsection, various performance indices can be computed using the updated distributions. The performance index, $p_f(AB)$, depicting the performance of auxiliary contacts is shown in Fig. 31. It can be observed from the figure that two records are abnormal. Except that, we can conclude that the auxiliary contacts are working properly. More detailed case studies are presented in Chapter VIII which gives insight into all computed performance indices.

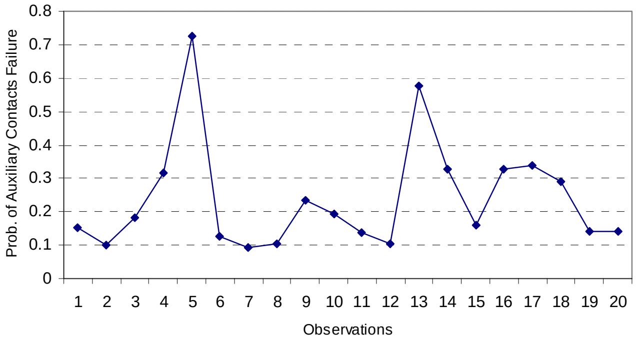

Fig. 31 Probability that the auxiliary contacts fail to operate normally

I. Summary

An attempt was made to link the control circuit data to the health of the breaker. Portable test devices are available to capture circuit breaker signals during its operation and signal processing modules are used to extract the exact timings of signal parameters. Probability distributions are fitted to these signal parameter timings and scatter plot analysis is carried to see the interdependency between among the parameters. Statistical measures such as, performance indices are defined for various assemblies of breaker. These indices can be readily used in risk calculations to develop system level maintenance strategies. The quantification of maintenance is achieved by comparing the performance indices before and after a particular maintenance action.

CHAPATER VII

RISK BASED SYSTEM LEVEL MAINTENANCE STRATEGY

A. Introduction

Cost-effective maintenance scheduling of power system equipment is critical, especially with present economic scenario of power industry. Apart from long-term maintenance policy, asset planners need to come up with revised short term maintenance strategies mainly due to the shrinking budget allocations for various reasons. The problem may be formulated as follows: if it is the same availability of labor crews, and labor hours, and the given budget is constrained, how the maintenance decisions need to be revised. The problem is particularly prominent if one needs to assign maintenance tasks for part of a system, say a substation with few circuit breakers and transformers. A risk-based decision approach is proposed which suits best this kind of situation. In this approach, the classic definition of 'risk' term is adopted, which is the product of event probability and event consequence. Risk based approaches have been proposed earlier, but this work differs in the way the 'event probability' and 'consequences' are defined and calculated. Condition monitoring devices can be used to get informed about the equipment condition up to date, which plays major role in this approach. The 'Event probability' is updated after a specified maintenance action and risk is recalculated, and the difference is the direct result of that maintenance activity. The proposed approach is implemented on a set of circuit breakers in a substation.

B. Proposed Approach

The proposed approach for risk based system level maintenance strategy is shown in Fig. 32, and has the following steps.

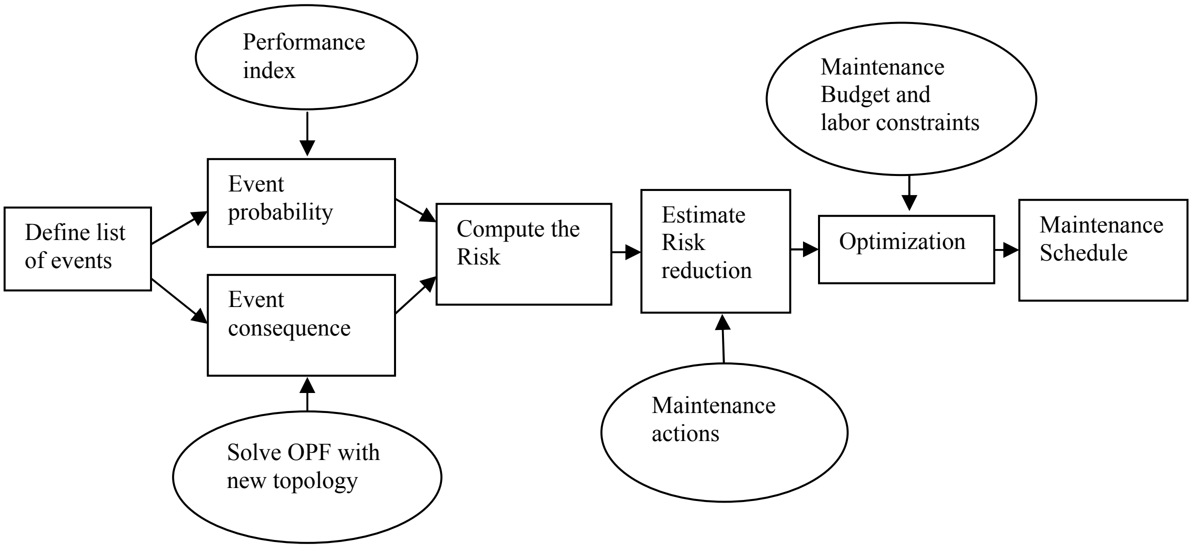

Fig 32 Proposed approach for risk based system level maintenance strategy

- Identify the list of events such as fault on bus bar, line or circuit breaker or combination
- Estimate the probability of each event
    - Event probability is combination of failure probabilities of bus bar, line and circuit breaker (according to the definition of the event)
    - Failure probability of bus bar and line is taken from the literature

  - Failure probability of circuit breaker is estimated using the developed ‘probabilistic methodology’ through performance indices
- Estimate the Consequence of each event
  - Due to loss of line, load, generator and circuit breaker
  - OPF is used to estimate the consequence
- Compute the risk associated with each event as the product of probability and consequence
- Define a maintenance action for circuit breaker and estimate change in performance index, and hence change in event probability. This change will eventually reflect in risk as well
- Compute the risk reduction associated with each event
- Formulate the objective function as, maximizing risk reduction, subject to constraints: budget and labor
- Identify the set of breakers that require immediate attention and amount of budget to be spent

The proposed approach is discussed in detail in the following subsections.

1. Concept of Risk

This section presents a brief literature about the usage of risk concept, followed by definitions used in this paper. The term ‘risk’ is very general and can be applied to many areas including finance and power industry. The risk analysis usually includes the process of risk identification, risk management, and hedging, a process of risk mitigation. In finance sectors, risk analysis involves the trade off between the risk and the return. It is used in evaluating the risk associated with bonds, futures, new projects, etc. [31]. The risk concept has been extended to several areas of power industry as well. These areas include but not limited to: energy trading, contracts, operations, bidding, risk based planning, asset management techniques, risk based overload and voltage security assessment, maintenance scheduling of power system equipment, etc [32]-[44]. This work proposes a risk based approach for maintenance of transmission system equipment such as circuit breakers. In all of the above references, the underlying quantitative definition of risk associated with an event, is 'the product of probability and consequence of the event'. Following are the definitions used to define the risk in this work.

<u>Event, E:</u> 'Failure of a component or group of components to operate properly'. Components can be line, breaker or bus bar.

<u>Event probability, p(E):</u> 'Probability that a component or group of components fail to operate properly'.

<u>Event consequence, Con(E):</u> 'Impact of failure of a component or group of components on the system'.

Now, the risk associated with each event is defined as,

$$Risk(E) = p(E) \times Con(E) \tag{1}$$

Following sections show how to estimate the event probability, consequence and the event risk.

2. Event Probability

The event probability is the product of failure probabilities of components involved in that event. The failure probabilities of line and bus are taken from the literature. Where as, the failure probability of circuit breaker is estimated from the proposed methodology for maintenance quantification, as explained in Chapter VI. The performance index, 'probability that the breaker fail to operate properly', $p_f(Br)$ is utilized as failure probability of breaker in estimating the event probability.

3. Event Consequence

Consider the example system as shown in Fig. 33. The system consists of a load, generator and three lines protected by breaker-and-half scheme.

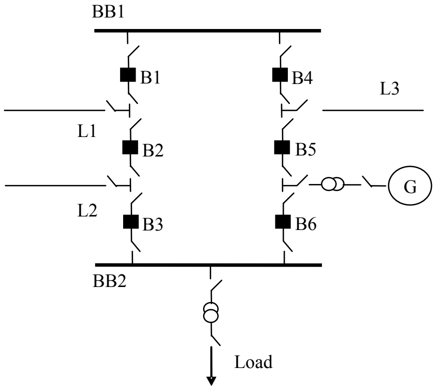

Fig 33 Breaker-and-half scheme

To illustrate the impact of the event on the system, two different scenarios are considered; single and multiple contingencies. Single contingency involves fault on bus bar, line, or breaker. Multiple contingency involves failure of more than one component.

Consider the single contingency; a fault on bus bar BB2. The breakers B3 and B6 should open to isolate the faulted bus bar. This results in loss of load for the duration until the bus bar is restored. Failure of any of these breakers leads to multiple contingency. If B3 fails to open, B2 and the breaker on the other side of the line L2 will open, resulting in loss of that line. Similarly, failure of B6 results in loss of generator.

Consider the other single contingency, which is a fault on line L2. In this case, breakers B2, B3 and the breaker on the other side of the line will open to isolate L2. Multiple scenarios will occur if any of those breakers fail to open.

In conclusion, for both scenarios, the event consequence term can be divided into four components: (i) loss of load, (ii) loss of line, (iii) loss of generator, and (iv) repair cost.

Loss of Load: The loss of load has a direct impact on customers connected to the system. One way to estimate the impact of loss of load is to use the composite customer damage function (CCDF). It is a measure of the interruption cost for a mix of customers at a bus [45]. The CCDF gives the interruption cost in \$/MW for a particular duration of time. The consequence due to loss of load is computed as:

$$\mathrm{Con}_{\mathrm{load}} = \text{Interruption cost (\$/MW)}*\text{Loss of load (MW)} \qquad (2)$$

Loss of Generator: When there is a loss of generator, other generators in the system will share the load of the lost generator. There might be additional cost with this situation, if running the other generators is expensive. The impact of this scenario is calculated by running the OPF without considering the generator. Any additional cost ($/hr) is the impact of loss of that particular generator. The consequence is computed as:

$$\text{Con}_{\text{gen}} = \text{Add.cost (\$/hr)*Switching time(hr)} \tag{3}$$

Loss of Line: If a line is out of service, the system configuration is changed. The load flow is recalculated according to the new topology of the system. If the system is secure enough, the power flow is redistributed without overloading the other lines. In this case, loss of line results in switching of one or more components to put the line back in the system. If the system is not secure which means, redistribution of power flow causing any lines to become overload, load curtailment occurs.

The optimal power flow (OPF) is used to estimate the impact of loss of line. The OPF is run without considering the line, and the cost of power generation ($/hr) is compared with that of the base case. Any additional cost ($/hr) is the result of loss of line. The consequence of loss of line due to switching action is computed as:

$$\text{Con}_{\text{line}} = \text{Add.cost (\$/hr)*Switching time (hr)} \tag{4}$$

The consequence of loss of line due to load curtailment is computed as:

$$\text{Con}_{\text{line}} = \text{Interruption cost (\$/MW)*Loss of load (MW)} \tag{5}$$

Repair Cost of Breaker: This includes the repair/maintenance cost of the components involved in the event. Also, it includes any cost to clear the fault including the labor cost. Following are the costs that are assumed in this study.

The maintenance cost of breaker = \$1000.

The repair cost of bus bar and faulted line = \$1000 each.

The total consequence is the summation of consequences due to: loss of load, loss of line & generator and repair cost.

$$\mathrm{Con(E)} = \mathrm{Con}_{\mathrm{load}} + \mathrm{Con}_{\mathrm{line}} + \mathrm{Con}_{\mathrm{gen}} + \text{Repair cost} \tag{6}$$

4. Event Risk and Risk Reduction

Now, the risk associated with each event can be computed as given in (1). The risk associated with each event can be reduced by using maintenance actions. One can come up with better maintenance policies based on the reduction in risk of each maintenance activity. Recall that the event probability is nothing but the product of failure probabilities of components involved in that event. Since the failure probabilities of line and bus are taken from literature, the only way to achieve a reduction in event probability is by effecting the failure probability of breaker which is the performance index, p_f(Br). The proposed methodology in Chapter VI quantifies the effect of maintenance and captures the reduction in failure probability of breaker, and hence the reduction in risk. Also, it is possible to estimate the future value of the index, pf(Br) with that of the existing knowledge and the difference in the two values can be treated as the change in the event probability, p(E). In either case, the risk reduction is computed as,

$$\Delta Risk(E) = \Delta p(E) \times Con(E) \tag{7}$$

5. Optimization

Once we have the risk levels associated with each event and risk reduction due to suggested maintenance actions, the next step would be to identify the most critical components. The critical components are nothing but those possess higher risk. The objective of risk based approach is not only to identify higher risk components but also to identify the components which offer higher reduction due to suggested maintenance action. Hence, it would be more appropriate to consider the risk reduction in formulating the objective function of the optimization problem. If we have few events under consideration, one can make decision by simply looking at the risk and risk reduction with each event. The situation becomes more complicated if we have huge number of events, and the best approach in that case would be formulate an optimization problem as follows,

$$\begin{aligned} & Max \quad \sum_{i=1}^{N} \Delta R_i x_i \\ & ST: \quad \sum_{i=0}^{N} c_i x_i \le C \\ & \qquad x = 0 \ or \ 1 \qquad \forall i \end{aligned} \tag{8}$$

Where,

i : index on breaker
N : Total number of breakers
ΔR_i : Risk reduction by maintaining breaker ‘i’
c_i : Maintenance cost of breaker ‘i’
C : Total budget

This optimization problem is classical knap-sack problem and can be solved with the existing dynamic programming methods [46].

C. Example

This section presents an illustration of the whole approach. The Fig. 34 shows substation configuration of the test system under consideration. The details of the test system are given in Chapter VIII. Consider the single contingency: a fault on bus bar BB2 to which the load is connected. Breakers B3, B6 and B8 will open to isolate the bus bar BB2 and hence the fault. This activity is associated with a loss of 100 MW load. The duration of the loss of load is equal to the time it takes to clear the fault and restore the bus bar BB2. If any of these breakers fail to open, it will results in multiple contingencies. Table IX lists all the events considered, components involved in each event, the change in topology of the system with each event and the event probability.

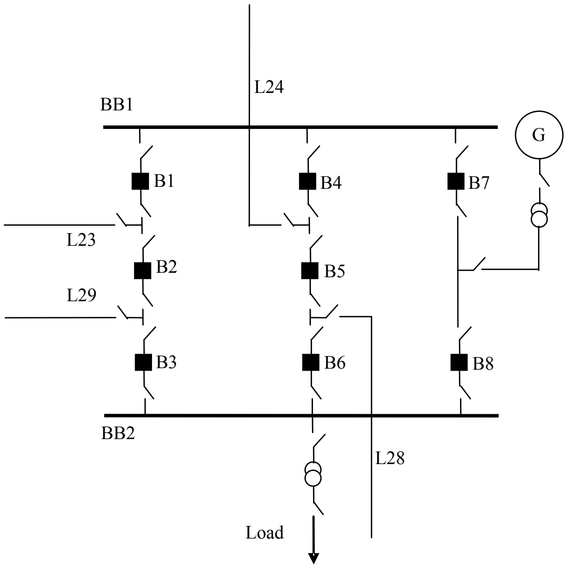

Fig. 34 Breaker-and-half scheme substation configuration [30]

Table IX: List of Events and Event Probability

Event #	Definition	Change in system topology	Probability, p(E)
E1	BB2, B3 fails	Loss of line L29	2.25E-04
E2	BB2, B6 fails	Loss of line L28	1.95E-04
E3	BB2, B8 fails	Loss of generator G	2.25E-04
E4	BB2, B3, B2 fail	Loss of lines L23, L29	1.01E-04
E5	BB2, B6, B5 fail	Loss of lines L24, L28	7.64E-05
E6	BB2, B8, B7 fail	Loss of generator, G	1.01E-04
E7	BB2, B3, B6 fail	Loss of lines L28, L29	8.79E-05
E8	BB2, B6, B8 fail	Loss of line L28, G	8.79E-05
E9	BB2, B8, B3 fail	Loss of line L29, G	1.01E-04

Table X: Consequence of Loss of Line and Generator

Event #	Loss of line or generator	Switching time (hrs)	Add. Cost of OPF $/hr	$\text{Con}_{(\text{line+gen})}$ $
1	L29	1	337.74	337.74
2	L28	1	54.44	54.44
3	G	1	0.83	0.83
4	L23+L29	2	313.48	626.96
5	L24+L28	2	97.33	194.66
6	G	1	0.83	0.83
7	L28+L29	2	347.47	694.94
8	L28+G	2	55.5	111
9	L29+G	2	337.77	675.54

Consequence due to loss of load is estimated by composite customer damage function and is give as, $Con_{load}(E) = 3850 \times 100 = 385000\$$. The consequence due to loss of line and generator are computed together by running OPF with new topology and comparing with that of the base case solution, and is shown in Table X. The maintenance cost of breaker and the repair cost of the bus bar is assumed to be $1000. The total consequence is the summation of consequences due to: loss of load, loss of line &

generator and repair cost which is, Con(E) = Con_{load} + $\text{Con}_{(\text{line+gen})}$ + Repair cost. The probability, consequence and risk associated with each event are given in Table XI. It is observed that the consequence is almost comparable for all events. However, the event probability is what makes the difference and leads to different risk levels.

Table XI: Event Risk

Event #	Probability, p(E)	Consequence, Con(E)	Risk
1	2.25E-04	387337.7	87.04
2	1.95E-04	387054.4	75.66
3	2.25E-04	387000.8	86.96
4	1.01E-04	388627.0	39.24
5	7.64E-05	388194.7	29.67
6	1.01E-04	388000.8	39.18
7	8.79E-05	388694.9	34.15
8	8.79E-05	388111.0	34.09
9	1.01E-04	388675.5	39.25

Since there are only few events, one can make decisions by simply looking at the risk levels and there is no need for optimization. It can be seen from the Fig. 35 that events E1, E2, and E3 possess higher risk compared to others. Since breakers B3, B6 and B8 are involved in those events, they should be given importance in maintenance planning. The probabilities are same for events E1 and E3, but the consequences are different and hence the risk levels. The consequence of event E1 is higher than that of E3. This suggests that the breaker B3 should be given the highest importance followed by B8 and B6 in that order.

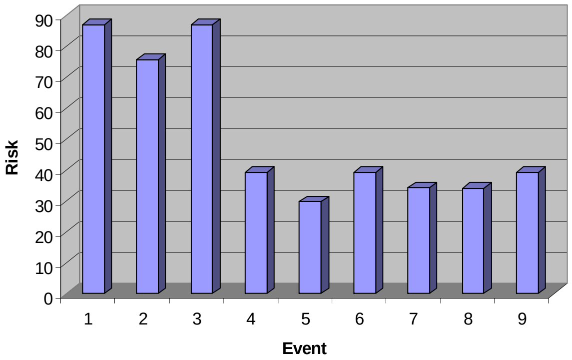

Fig. 35 Risk associated with each event

An illustration is presented on how the risk reduction can be computed and used for planning purposes. Using the probabilistic methods, it is possible to predict the future data point with some confidence level and hence the event probability and risk level. Fig. 36 shows the reduction in risk level with each event for the data under consideration. It is interesting to note from Fig. 36 that the amount of risk reduced by maintaining the breaker B6 is less compared to breakers B3 and B8. The breakers B3 and B8 can be given more importance than B6, if one wants to spend money according to the reduction in risk level. For the test system under consideration, it can be concluded from Fig. 32 and 33 that, breakers B3 and B8 are more important followed by B6 than others and should be given priority in budget allocation.

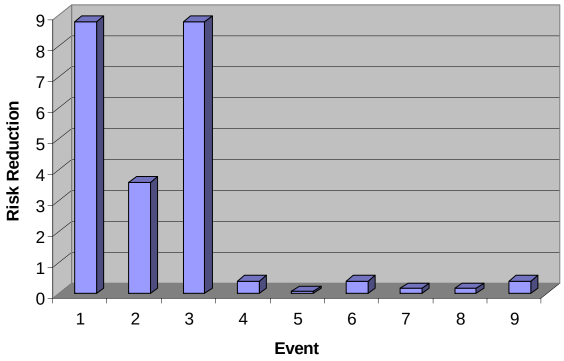

Fig.36 Risk reduction with each event

D. Summary

This chapter presented a risk-based optimization approach for system level maintenance applications. The proposed approach utilizes the methodology discussed in Chapter VI in estimating the event probability. Event consequence due to loss of load, line and generator are computed. It is possible to reduce the risk by suggested maintenance actions and the reduction in risk can be computed by estimating the reduction in event probability with help of the proposed methodology for maintenance quantification. A brief illustration of the whole process is presented. A detailed case study is presented in Chapter VIII.

CHAPTER VIII

CASE STUDIES

A. Objective of Testing and Evaluation

This chapter has been devoted to testing the proposed concepts in this dissertation. The main objective of the testing is to evaluate the performance of the proposed concepts and their capability for practical application. The first contribution of this dissertation, a probabilistic maintenance model for circuit breaker, is tested by carrying a sensitivity analysis in Chapter V. The major contribution of this dissertation is presented in Chapter VI, which is a new methodology to assess the condition of the circuit breaker using control circuit data by defining performance indices for CB assemblies. Based on this concept, a risk based approach is proposed in Chapter VII for optimizing system maintenance, which is the final contribution of this dissertation. These two concepts that are presented in Chapters VI and VII will be tested in this chapter. Table XII lists the case studies that are considered in this dissertation.

Table XII List of Case Studies

Methodology to assess condition of breaker (Chapter VI)	Case study I	CB control circuit data during open operation
	Case study II	CB control circuit data during close operation
	Case study III	Approximation to the Bayesian approach in case studies I and II
Risk based maintenance optimization	Case study IV	Bus 16 of IEEE Reliability Test System

B. Model to Assess Performance of Circuit Breaker

1. Case Study I

This case study is to test the performance of the proposed methodology to assess the condition of the breaker using control circuit data taken from group of similar circuit breaker at different times during open operation. The type of breaker and the data is given in appendix A. The data set consists of 19 records taken during opening of circuit breaker under consideration. Only those timing parameters, which are relatively important and sufficient to make conclusions about breaker, are considered in this study. The sequence of occurrence of timing of parameters during opening is: t_2-t_3-t_6-t_4-t_5. The parameters are renamed as, y_1-y_5 in that order. The lower and upper tolerance limits for each timing parameter are shown in Table XIII. These are the expert system settings developed as part of automated circuit breaker analysis developed at Texas A&M University.

The scatter plot analysis of the parameters is shown in Fig. 37. The off diagonal plots show the dependency of each parameter with other parameters. It is observed from the figure that, parameters y_1, y_2 and y_3 show no particular relationship with any other parameters and hence can be treated as independent. A linear relationship is observed between y_3 and y_4, and can be expressed as, $y_4=\beta_0+\beta_1 y_3+\varepsilon_4$. The parameter y_5 is linearly dependent on both y_3 and y_4 and can be represented by a multiple regression model. Since there is a linear dependency between y_3 and y_4, principle component analysis explained in previous section can be used to represent y_5 and the modified representation is given by, $y5 = \beta_0 + \beta_1 y_3 + \beta_2 y_4 + \varepsilon_5$.

Table XIII: Tolerance Limits for Open Operation [17]

Event	Lower (msec)	Upper (msec)
t_2	0	2
t_3	13.6	18.6
t_4	26.4	35.4
t_5	28.7	38.7
t_6	22.4	32.4

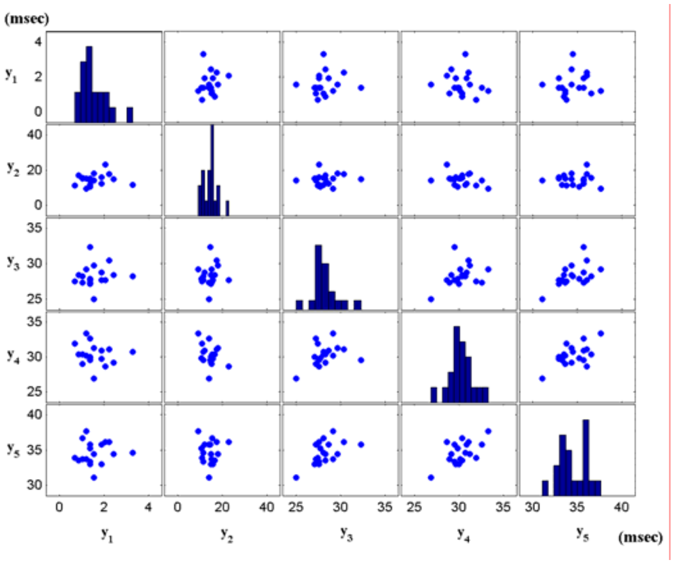

Fig. 37 Scatter plot analysis of timing parameters (open)

Model Formulation: Let j = 1, 2, 3, 4, 5, be the index over parameter; n be the total number of observations; Y: (n×j) be the data set; the likelihood function and covariates using multiple linear regression set-up are given below.

$$Y_j \sim N(X_j\beta_j, \sigma_j^2 I), \text{ for j = 1, 2, 3, 4, 5} \tag{1}$$

$$X_j = J, \text{for } j = 1,2,3 \tag{2}$$

$$X_4 = [J \quad Y_3] \tag{3}$$

$$X_5 = [J \;\; Y_3 \;\; Y_4] \tag{4}$$

where, J = [1, …, 1]^T of dimension (n×1), β_j is the parameter vector of interest, σ_j^2 is the measurement variance. In a Bayesian frame work, all the unknown parameters are considered as random variables and the uncertainty in the parameters is expressed in terms of prior distribution. For the sake of analytical tractability and the computational efficiency, we elicit conjugate priors for all the unknown parameters in, given by:

$$\beta \sim N(\mu, \Sigma) \tag{5}$$

$$\frac{1}{\sigma^2} \sim \Gamma(a, b) \tag{6}$$

where μ, Σ, a, b are prior parameters that are assumed to be known or set in a way to express lack of knowledge about the parameters of interest. The posterior conditional distributions required in the Gibbs sampling stage are given below.

$$\begin{gathered} \beta\big|_{Y,\sigma^2,\mu,\Sigma} \sim N(\Lambda(X^T Y \sigma^{-2} + \Sigma^{-1}\mu), \Lambda) \\ \text{where,} \quad \Lambda = ((X^T X)\sigma^{-2} + \Sigma^{-1})^{-1} \end{gathered} \tag{7}$$

$$\left.\frac{1}{\sigma^2}\right|_{Y,\beta,\mu,\Sigma} \sim \Gamma(a + (Y - X\beta)^T J, b + n) \tag{8}$$

MCMC simulation is carried out to estimate the posterior distribution of the parameters of interest. WinBUGS, an open source platform is used for performing MCMC simulations [47]. We used diagnostic tools available such as Gleman-Rubin statistic to monitor the convergence of the MCMC chains. We threw-away the first thousand samples as burn-in and thinned down the subsequent samples by a factor of ten to reduce the correlation in the samples. After burn-in and thinning, we obtained five thousand samples based on which all the posterior inferences were drawn.

The computed performance indices for each data point are shown in Fig. 38. It is observed that all indices follow decreasing pattern as the new data point comes in. The indices $p_f(\mathrm{TC})$, $p_f(\mathrm{FT})$ and $p_f(\mathrm{MT})$ have probabilities lying above 0.6, suggesting abnormal behavior of respective assemblies. The mechanism travel time is the difference between t_6 and t_3, in which the time instant t3 related to trip coil current and time instant t_6 related to auxiliary 'a' contact. So, it is necessary to check which timing parameter is responsible for high values of index $p_f(\mathrm{MT})$.

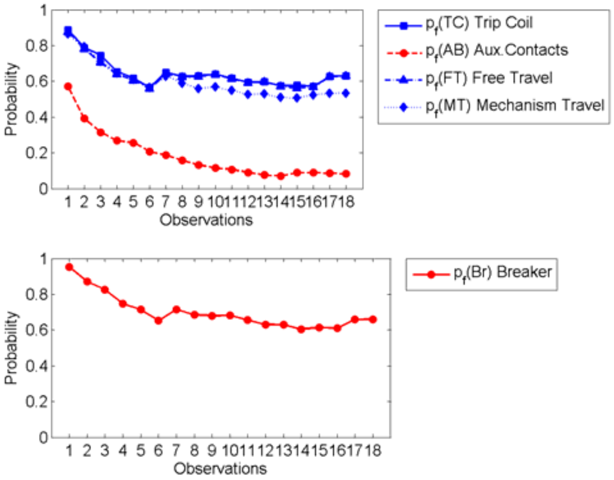

Fig. 38 Performance indices for CB opening

As we have already seen the auxiliary contacts are functioning well, which means that t_5 occurs with in the tolerance limits. Hence the problem is with t_3, because of improper operation of trip latch mechanism. The performance index $p_f(\mathrm{Br})$, which depicts the performance of breaker as a whole, also has probabilities lying above 0.6 because of abnormal operation of trip coil, trip latch and operation mechanism.

2. Case Study II

The data in this case study is developed by the same set of breakers as in case study I, but during close operation. The data set consists of 23 records taken during closing of circuit breaker under consideration. The sequence of timing parameters occurrence during closing is: t_2-t_3-t_4-t_5-t_6. Rename the parameters as, y_1-y_5. The lower and upper tolerance limits for each timing parameter are shown in Table XIV.

Recall that the model formulation will change according to the dependency among the observed timing parameters; we need to first start with the scatter plot analysis. The scatter plot analysis of the parameters is shown in Fig. 39. It is observed that, parameters y_1, y_2 y_3 and y_4 show no particular relationship with any other parameters and hence can be treated as independent. A linear relationship between y_4 and y_5 and, y_5 can be used to expressed as $y_5=\beta_0+\beta_1 y_4+\varepsilon_5$.

Table XIV: Tolerance Limits for Close Operation [17]

Event	LOWER (MSEC)	Upper (msec)
t_2	0	5.5
t_3	9.8	16.4
t_4	26	43.4
t_5	49.9	67.5
t_6	62	75.8

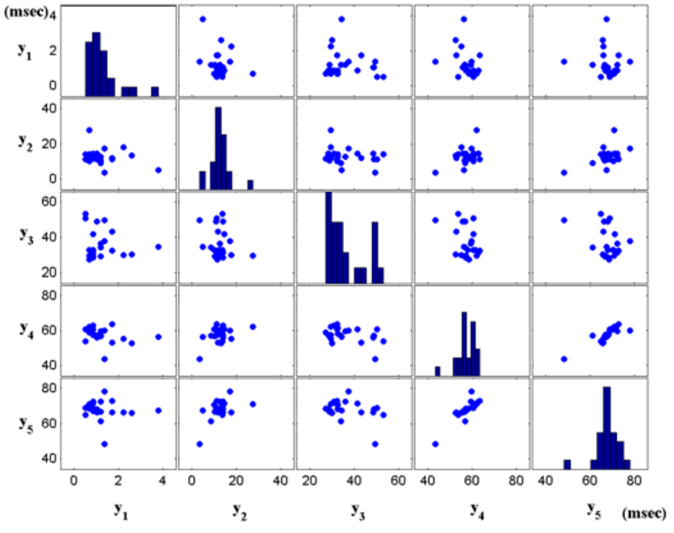

Fig. 39 Scatter plot analysis of timing parameters (close)

Model Formulation: The model formulation presented in earlier section can be used for the data under consideration. The likelihood is expressed by (1). The covariate matrix X in (1) changes as below:

$$\mathrm{X}_j = \mathrm{J}, \text{for } j = 1,2,3,4 \tag{9}$$

$$\mathrm{X}_5 = [\mathrm{J} \quad \mathrm{Y}_4] \tag{10}$$

The prior distribution is given by (5) and (6), and the posterior distribution is given by (7) and (8). The computed performance indices for each data point are given in Fig. 40. It can be observed that the index $p_f(\mathrm{AB})$ lies below 0.5 except for one record which has a probability of 1. This situation can be interpreted as follows. Due to the abnormal operation of auxiliary contracts at that instant, one of the quantities $p(\mathrm{t}_5)$ and $p(\mathrm{t}_6)$ are either zero or close to zero. Hence the index $p_f(\mathrm{AB}) = 1 - p(t_5)p(t_6)$, is either 1 or close to

1. Except that one observation, we can conclude that the auxiliary contacts are working properly as the index $p_f(\mathrm{AB})$ has very low probabilities compared to other indices.

The other indices follow almost the same pattern and a decreasing trend can be observed as more observations come in. The indices lie in the range of 0.6 to 0.8 for most of the records suggesting improper operation of close coil and close latch mechanism. The performance index, $p_f(\mathrm{Br})$ also lies above 0.6 meaning the breaker is not operating properly.

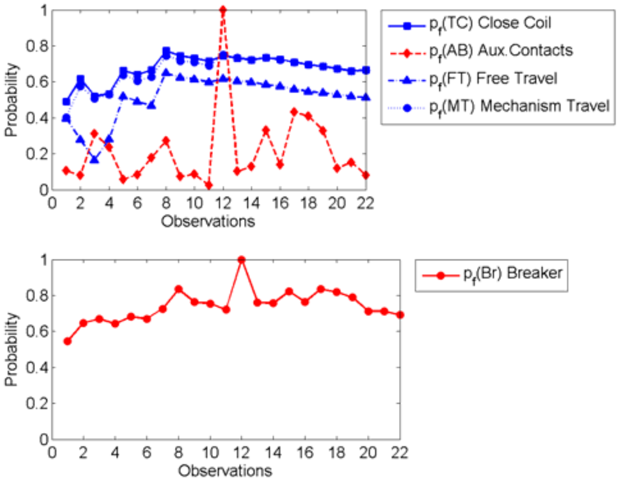

Fig. 40 Performance indices for CB closing

3. Case Study III

The case study III is presented to test the practical application of the proposed methodology in case studies I and II. An approximation to the Bayesian approach, called sequential Bayesian approach, is presented in Chapter VI for calculation of performance indices on-line as the filed data arrives. This is a tremendous improvement form the conventional Bayesian approach which utilizes the whole data and might be bit time consuming. The computed performance indices for both case studies are shown in Fig. 41 and 42. It can be seen that all indices follow the same pattern as obtained using the Bayesian approach in Chapter VI, and hence the obtained conclusions about the performance of breaker can still hold. Such a sequential approach is very suitable for on-line posterior-inferences as it makes use of the posterior distribution already obtained instead of the previously obtained data.

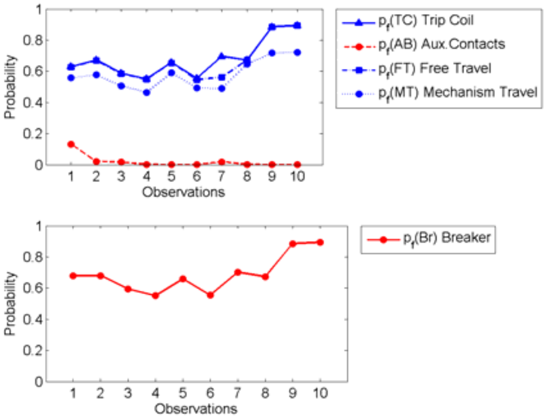

Fig. 41 Performance indices (open)

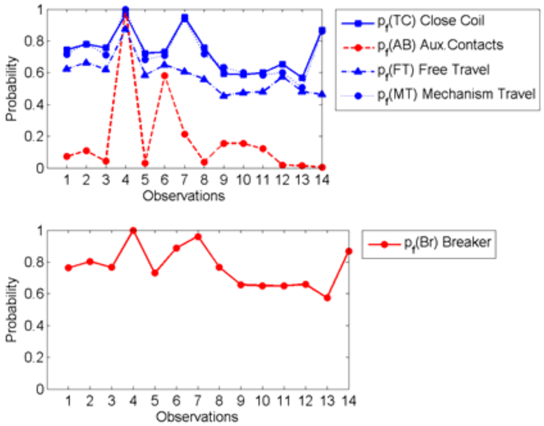

Fig. 42 Performance indices (close)

In order for this approach to be computationally attractive and to be put in a recursive frame work (as shown in Fig. 28), we require that prior and posterior distribution be from the same family of distributions such as normal distribution for mean parameters and inverse gamma distribution for variances. In our analysis we approximate the marginal posterior distribution with a normal distribution. The accuracy of this approximation is given in Fig. 43.

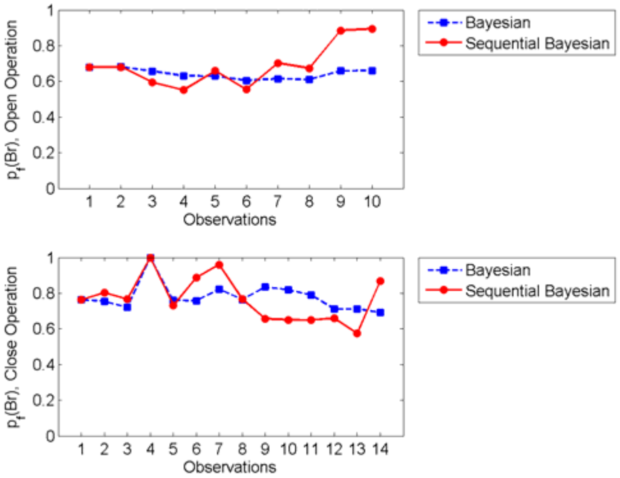

Fig. 43 Comparison of index p_f(Br) between Bayesian and Sequential Bayesian approach for both open and close operation

4. Discussion of Results

A summary of the analysis from case study I is shown in Table XV. From the analysis it can be concluded that the trip coil, trip latch mechanism, and operating mechanism of the breaker are not functioning well and need immediate attention. However, the auxiliary contacts of the breaker are working properly. A summary of the analysis from case study II is shown in Table XVI. It is observed from the Table that the close coil, close latch mechanism and operating mechanism need some maintenance because of their abnormal operation.

Table XV: Summary of Analysis for Open Operation

Performance Index	Observations	Maintenance action required?
pf(TC)	Abnormal behavior of trip coil current.	Yes
pf(AB)	Auxiliary contacts are operating properly	No
pf(FT)	Abnormal free travel times. Improper operation of trip latch mechanism	Yes
pf(MT)	Abnormal mechanism travel times. Improper operation of operating mechanism.	Yes
pf(Br)	Improper operation of breaker as a whole	Yes

Table XVI: Summary of Analysis for Close Operation

Performance Index	Observations	Maintenance action required?
pf(CC)	Abnormal behavior of close coil current.	Yes
pf(AB)	Auxiliary contacts are operating properly	No
pf(FT)	Abnormal free travel times. Improper operation of close latch mechanism	Yes
pf(MT)	Abnormal mechanism travel times. Improper operation of operating mechanism.	Yes
pf(Br)	Improper operation of breaker as a whole	Yes

Case study III evaluated the accuracy of the approximation to the Bayesian approach, and is shown in Fig. 38. The upper subplot shows the index, p_f(Br) for open operation. It can be seen that except for the last observation, both follows the same pattern and same values. The lower subplot shows the same index for close operation. In this case also, the index computed in both Bayesian approaches follows the same pattern and of almost the same values. Further, the index values lie above 0.6 for all cases, and hence there is no pay-off in the obtained conclusions about the breaker performance. In summary, Sequential Bayesian approach can be utilized as approximation to the Bayesian approach, such that it can be used for computing performance indices online.

C. Risk Based Maintenance Optimization

1. Case Study IV

Consider the IEEE 24 Bus Reliability Test System [48] to illustrate the proposed concepts in Chapter VII. Fig. 44 shows the substation configuration of bus 16, which has 4 lines protected by breaker and half scheme, a generator of capacity 155MW and a load of 100MW. The substation has a total of 8 breakers (B1-B8), and the objective is to find out which breaker needs immediate attention and how to spend a fixed pool of money towards the maintenance of these breakers. A total of 15, covering all possible scenarios and corresponding definitions are listed in Table XVII. There are 42 events associated with these 15 scenarios and are given in Table XVIII. The events include single and double contingencies. The next step is to estimate the probability and consequence of each event and hence risk associated with each event.

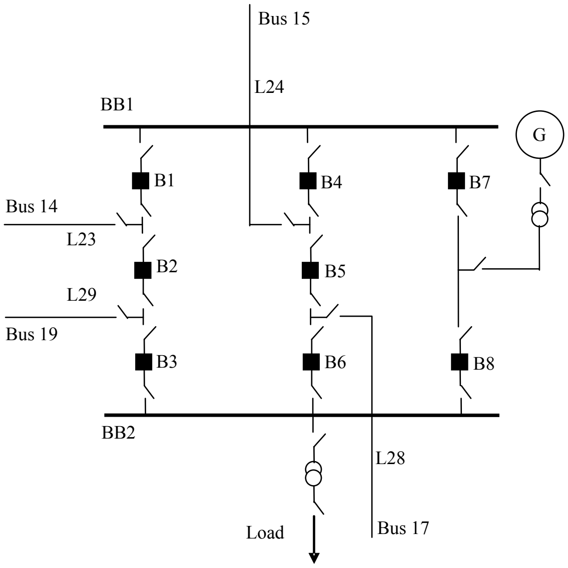

Fig. 44 Substation configuration of Bus 16, IEEE RTS [48]

Table XVII: List of Scenarios

Scenario #	Definition
S1	Fault on BB1
S2	Fault on BB2
S3	Fault on Line 23
S4	Fault on Line 24
S5	Fault on Line 28
S6	Fault on Line 29
S7	Fault on Generator
S8-S15	Fault on Breakers B1-B8 respectively

Table XVIII: List of Events Associated with All Scenarios

Event #	Definition	Event #	Definition
E1	Fault on BB1	E22	Fault on G, B7 fails
E2	Fault on BB1, B1 fails	E23	Fault on G, B8 fails
E3	Fault on BB1, B4 fails	E24	Fault on B1
E4	Fault on BB1, B7 fails	E25	Fault on B1, B2 fails
E5	Fault on BB2	E26	Fault on B1, B4 fails
E6	Fault on BB2, B3 fails	E27	Fault on B1, B7 fails
E7	Fault on BB2, B6 fails	E28	Fault on B2
E8	Fault on BB2, B8 fails	E29	Fault on B2, B3 fails
E9	Fault on L23	E30	Fault on B3
E10	Fault on L23, B1 fails	E31	Fault on B3, B6 fails
E11	Fault on L23, B2 fails	E32	Fault on B3, B8 fails
E12	Fault on L24	E33	Fault on B4
E13	Fault on L24, B4 fails	E34	Fault on B4, B5 fails
E14	Fault on L24, B5 fails	E35	Fault on B4, B7 fails
E15	Fault on L28	E36	Fault on B5
E16	Fault on L28, B5 fails	E37	Fault on B5, B6 fails
E17	Fault on L28, B6 fails	E38	Fault on B6
E18	Fault on L29	E39	Fault on B6, B8 fails
E19	Fault on L29, B2 fails	E40	Fault on B7
E20	Fault on L29, B3 fails	E41	Fault on B7, B8 fails
E21	Fault on G	E42	Fault on B8

The control circuit data is utilized to estimate the failure probability index of each circuit breaker [10]. The estimated failure probability of breakers B4, B5, B6 is 0.3909 and for the remaining breakers is 0.4494. For the purpose of illustration, the bus bar failure probability is assumed to be 0.0005. The reliability data for lines and generator is taken from [45]. Now, the event probability is computed as the product of failure probabilities of components involved in that event. A switching time of 1 hr is assumed for each component in computing the consequence term [45].

2. Discussion of Results

The probability, consequence and risk associated with each event are given in Table XIX. It is observed from the table that, the risk associated with events which involve faults on breakers, is more significant. This is because of the higher probability of these events compared to other events. The risk levels associated with events, which include faults on lines, are very less. It can be seen from the Fig. 45 that events E30, E42, and E38 possess higher risk in that order, compared to others. Since breakers B3, B6 and B8 are involved in those events, they should be given importance in maintenance planning. Further, events E29, E31, E32, E37, E39 and E41 possess significant risk as well. These events involve combination of breakers B2, B3, B5, B6, and B7. This higher risk is because breakers B3, B6 and B8 are involved in those events. This can be verified by looking at the low risk levels of events E28, E36 and E40 that involve breakers B2, B5 and B7 alone respectively. It can be concluded that breakers B3, B6 and B8 are very crucial and needs immediate attentions compared to other breakers.

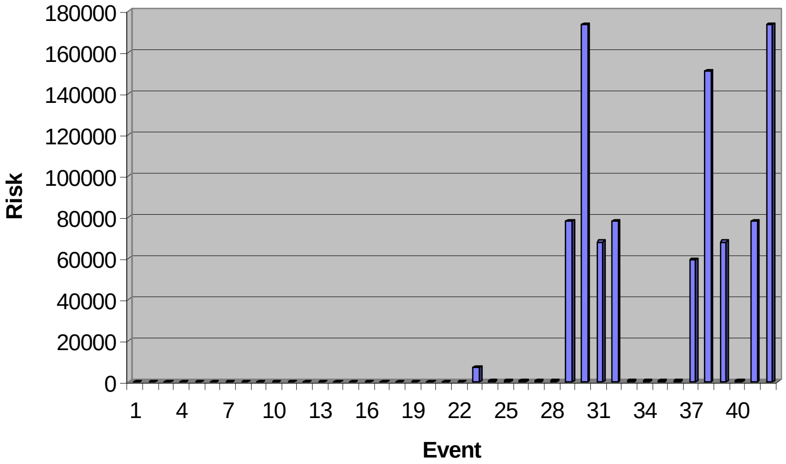

Fig. 45 Risk associated with each event

Table XIX: Event Probability, Consequence and Risk

Event #	Probability, p(E)	Consequence, Con(E)	Risk, R(E)
E1	0.0005	1000.00	0.50
E2	0.000225	2464.31	0.55
E3	0.000195	1994.07	0.38
E4	0.000225	2463.32	0.55
E5	0.0005	386000.00	193.00
E6	0.000225	387337.70	87.03
E7	0.000195	387054.40	75.64
E8	0.000225	387000.80	86.95
E9	0.000494	1464.31	0.72
E10	0.000222	2464.31	0.54
E11	0.000222	2936.04	0.65
E12	0.000429	994.07	0.42
E13	0.000168	1994.07	0.33
E14	0.000168	2985.22	0.50
E15	0.000442	1103.12	0.48
E16	0.000173	2985.22	0.51
E17	0.000173	387054.40	66.87
E18	0.000416	2832.30	1.17
E19	0.000187	2936.04	0.54
E20	0.000187	387337.70	72.41
E21	0.0400	1463.32	58.53
E22	0.0180	2463.32	44.33
E23	0.0180	387000.80	6966.01
E24	0.4494	1464.31	658.06
E25	0.2020	2936.04	593.08
E26	0.1757	2945.98	517.60
E27	0.2020	3969.82	801.90
E28	0.4494	1936.04	870.05
E29	0.2020	387627.00	78300.64
E30	**0.4494**	**386337.70**	**173620.18**
E31	0.1757	387694.90	68118.00
E32	0.2020	387675.50	78310.45
E33	0.3909	994.07	388.58
E34	0.1528	2985.22	456.14
E35	0.1757	2926.90	514.25
E36	0.3909	1985.22	776.02
E37	0.1528	387194.70	59163.34
E38	**0.3909**	**386054.40**	**150908.68**
E39	0.1757	387111.00	68015.40
E40	0.4494	1463.32	657.61
E41	0.2020	387000.80	78174.16
E42	**0.4494**	**386000.80**	**173468.77**

One very important concept in risk analysis is that there might few events which offer same risk levels but with different event probabilities and event consequences. In general terms, an event with high probability and low consequence might possess the same risk level as that of an event with low probability and high consequence. Technically these two events should be treated differently. This concept is visualized in Fig. 46. The plot environment shows the event probability, consequence and risk curves. The events are represented by stars close to the risk curves showing their risk levels. Most of the events fall around or under the risk level of 2500 with a probability and consequence varying in a wide range. It is also observed that these events can be neglected in compared to the higher risk levels such as 175000.

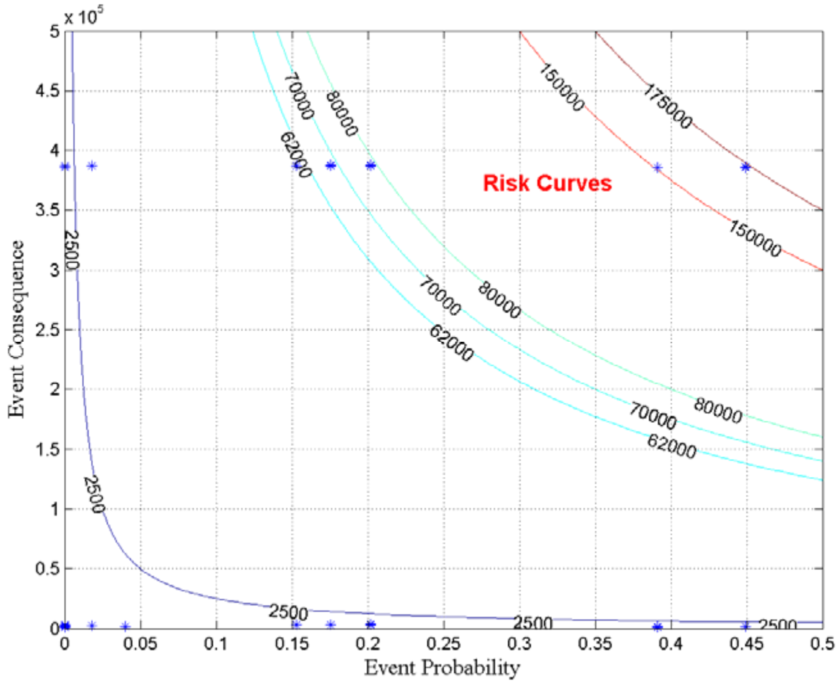

Fig. 46 Risk curves

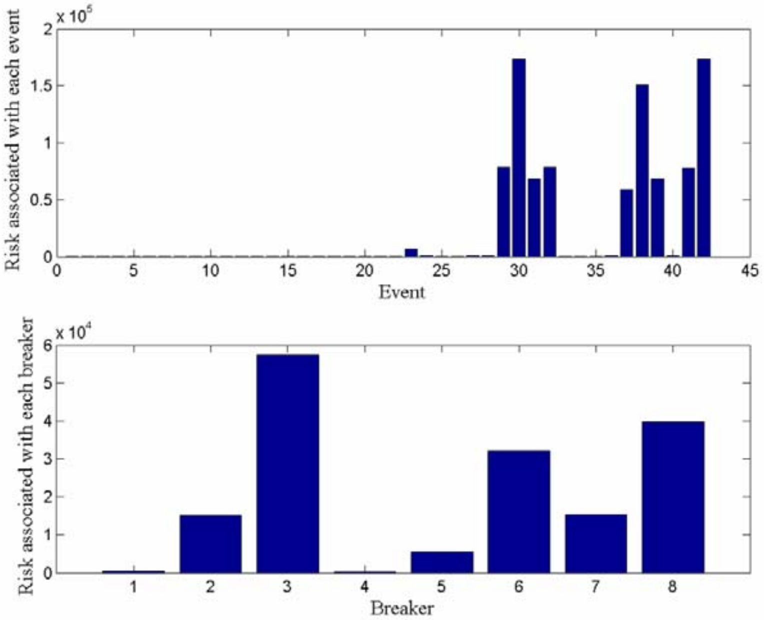

Fig. 47 Risk associated with each event and breaker

The other events that possess higher risk almost have the same probability and consequence and hence there is no need to treat them separately in this study. One may wish to explore the multi-objective formulations such Pareto Optimization technique to deal with probability and consequence separately [49]-[50].

Since the final objective is to identify critical circuit breakers, the events are regrouped in such a way that the risk possessed by each breaker is readily available. This can be seen in Fig. 47, the upper plot of which shows the risk of each event, where as the lower plot shows the risk associated with each breaker. One can readily conclude that Breaker 3 is very critical.

The risk associated with each event can be reduced by using maintenance actions. One can come up with better maintenance policies based on the reduction in risk of each maintenance activity. Again, the risk reduction can be captured by the maintenance quantification model proposed in Chapter VI. The model quantifies the effect of maintenance and captures the reduction in failure probability of breaker, and hence the reduction in risk. The risk reduction is computed as,

$$\Delta Risk(E) = \Delta p(E) \times Con(E) \tag{11}$$

An illustration is presented on how the risk reduction can be computed and used for planning purposes. Using the probabilistic methods, it is possible to predict the future data point with some confidence level and hence the event probability and risk level. Fig. 48 shows the reduction in risk level with each event for the data under consideration. It is interesting to that the amount of risk reduced by maintaining the breaker B6 is less compared to breakers B3 and B8. The breakers B3 and B8 can be given more importance than B6, if one wants to spend money according to the reduction in risk level.

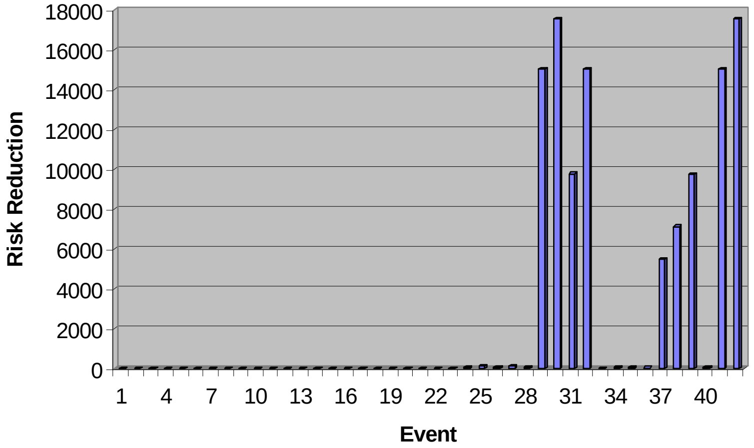

Fig. 48 Risk reduction with each event

For the test system under consideration, it can be concluded from Fig. 47 and 48 that, breakers B3 and B8 are more important followed by B6 than others and should be given priority in budget allocation. The optimization result also confirms with the visual study results of Fig. 46 and 47.

D. Summary

In conclusion, four case studies are considered to evaluate the performance of the proposed concepts. Case studies I and II are to test the proposed methodology to assess the performance of the breaker utilizing condition based data. Case study III is to see the accuracy of the approximation to the Bayesian updating approach. Based on the observed results, it is concluded that the approximation holds good in assessing condition of the breaker. Finally, case study IV is proposed to test the risk based maintenance optimization approach to achieve system level maintenance.

CHAPTER IX

CONCLUSIONS

A. Summary of Achievements

This dissertation is proposing maintenance models for circuit breakers, both at component level and system level. The achievements of this dissertation are summarized as below.

Chapter II has explored the existing approaches for maintenance strategies of power system transmission system equipment such as transmission lines, transformers and circuit breakers. The approaches have been classified into component level and system level. The hazard rate models, Markov models and Probabilistic maintenance models have been developed to estimate the component failure probability. They model the entire life time of component into several deterioration stages. These models come under the category of component maintenance. System level maintenance strategies such as RCM approach, Asset Management Planner, RCAM approach, etc. exist in literature with objective being different.

Chapter III has been dedicated to problem formulation. A concept of top-down approach is introduced to better understand the problem that is being addressed in this dissertation work. The chapter also presents the proposed dissertation approach and dissertation goals. In brief, the dissertation goals are to develop: (i) probabilistic maintenance model for circuit breaker (ii) maintenance quantification model using control circuit data of circuit breaker (iii) risk based system level decision approach.

Chapter IV has been devoted to explain the physical phenomenon associated with circuit breaker. This chapter serves as background information before proposing maintenance models for circuit breaker. Various inspection tests, maintenance actions and failure modes of circuit breaker are presented and the relationship among them is explored. A comparison among several aspects between transformer and circuit breaker has been carried to better understand how different both devices are from maintenance point of view. This comparison helps even in extending the existing transformer maintenance policies to circuit breakers.

Chapter V has proposed probabilistic maintenance model for circuit breakers. The model is built on the concept of representing the component into several deterioration stages. Inspection and maintenance are introduced at each stage. Model parameters are identified and sensitivity analysis is carried to see the effect of model parameters on probability of failure and associated costs. Cost analysis includes failure cost, maintenance cost, inspection cost and total cost.

Chapter VI has proposed a maintenance quantification model using condition based data of circuit breaker. Control circuit data is utilized to develop a methodology to convert the data into performance indices of several assemblies of breaker. Portable devices can be used to capture the control circuit signals during the breaker operation and the exact timings of signal parameter are extracted using signal processing modules. History of such control signal timings is developed and a probability distribution is fitted to each timing parameter. Performance indices for various assemblies of circuit breaker are defined based on the probability distributions. As the new data arrives, the performance indices are updated using Bayesian updating technique. Also, to make the approach suitable to handle data on-line, an approximation to the Bayesian approach called, sequential Bayesian approach is introduced.

Chapter VII has proposed a risk based system level decision approach. A brief discussion about concept of risk is presented. In general terms, the risk associated with an event is expressed as, the product of event probability and consequence associated with that event. The idea of risk based approach is to identify events with higher risk levels and the components involved in those events should be given importance in budget planning. Some events possess higher probability, lower consequence and some events possess lower probability and higher consequence, yielding same risk levels. It is necessary to distinguish such events and should be treated separately. The event probability is estimated from the performance indices developed in Chapter VI. The event consequence has four components: (i) loss of load (ii) loss of line (iii) loss of generator (iv) repair cost. The optimal power flow (OPF) is used to estimate the consequence of loss of line and generator; where as composite customer damage function (CCDF) is used to estimate the consequence of loss of load.

Chapter VIII has been dedicated to test the proposed maintenance quantification model and proposed risk based decision approach. Two case studies have been implemented to test the maintenance quantification model. The case study I is the control circuit data observed on a group of similar circuit breakers over the time during operation. The case study II is the control circuit data observed on the same breakers as in case study I during close operation. Performance indices have been calculated as the new data arrives, utilizing Bayesian approach. Also, sequential Bayesian approach is implemented for both test cases and the results have been compared. The sequential Bayesian approach makes the methodology more suitable for online calculation of performance indices. The proposed risk based decision approach has been implemented on substation configuration at bus 16 of IEEE Reliability Test System. The results have been discussed in detail.

B. Research Contributions

The major contributions of this dissertation are in the area of circuit breaker maintenance and application of the component maintenance models to develop system level maintenance strategies. First, a probabilistic maintenance model is proposed to get insight into the deterioration process, inspection tests and various costs associated with circuit breaker maintenance. Then, a probabilistic methodology is proposed to convert the condition based data of breaker into performance indices. These performance indices reflect the condition of various assemblies of circuit breaker. These indices are used to develop risk based system level maintenance strategies and this is how the component and system level maintenance strategies are connected. In accordance with the dissertation goals mentioned in Chapter III, the contributions of this dissertation are as follows.

The first contribution, probabilistic maintenance model for circuit breaker, models the components age by several deterioration stages followed by a failure stage. Inspection and maintenance is introduced at each stage. Sensitivity analysis is carried to see the effect of change in inspection rate at each stage on the failure probability and several costs associated with breaker. The cost analysis includes failure cost analysis, inspection cost analysis, maintenance cost analysis and total cost analysis. An equivalent mathematical model is developed to validate the sensitivity analysis results by corroborating with mathematical equations. The proposed model finds its use in long term maintenance planning. Also, it provides an understanding of phenomenon associated with circuit breaker in detail, which helps in achieving further tasks in this dissertation.

The second and major contribution is a new methodology to achieve maintenance quantification for circuit breaker utilizing condition based data. The control circuit data of circuit breaker is utilized in this work. The importance of control circuit data and the relative ease of measuring and extracting the timing instants are discussed in Chapter VI. A history of such signal timings has been developed and probability distribution is fitted to each timing parameter. Scatter plot analysis is carried to see the dependency among the parameters. The condition assessment of different assemblies is achieved by defining performance indices based on probability distributions. These performance indices are updated using Bayesian approach as the new data arrives. In order make the methodology for practical application, such as on-line estimation of indices, an approximation to the Bayesian approach called ‘sequential Bayesian approach’ is introduced and implemented. The proposed methodology is tested on two test cases. The estimated indices can be readily used in risk analysis calculations and this is how the component maintenance strategy leads to the system level maintenance strategy, explained in the following section.

The final contribution of this dissertation is a risk-based decision approach for maintenance planning of group of circuit breakers. It is a system level maintenance strategy aiming at maintenance of those components which possess higher risk. Identification of events is the starting point in the proposed approach. Event probability is computed using the performance indices developed as part of the dissertation contributions. Event consequence is divided into four parts namely loss of load, loss of line, loss of generator and repair cost. Consequence due to loss of load is computed using composite customer damage function. Consequence due to loss of line and generator is estimated using OPF. Then risk associated with each event is computed and events which higher risk levels are identified. The component involved in these events needs to be given importance. Also, reduction in risk due to maintenance action is computed and events that offer higher risk reduction can be given importance. The approach is implemented on bus 16 of IEEE reliability test system.

C. Suggestions for Future Work

The probabilistic maintenance model analyzes the performance of the breaker at component level. It is necessary to develop system level optimized maintenance policies based on the probabilistic maintenance model. It can be achieved by formulating an optimization problem with objective being reduction in total operating cost subject to security, maintenance and labor constraints. This task might get complex as a system might consist of various breakers from different manufacturer and type. This involves the modeling of different breakers separately at component level before proceeding to system level optimization.

In the proposed probabilistic methodology, the control circuit data is used to assess the performance of the breaker by defining performance indices based on probability distributions of the timing parameters. A normal distribution is assumed for the purpose of illustration. It is necessary to extend the model to deal with data driven distributions. In this case the model formulation becomes very complex and extremely difficult to implement the Bayesian approach. But once it is achieved, the proposed methodology can be readily used to deal with data from any type of the breaker and becomes very handy for industrial applications.

The proposed risk based optimization problem for system level maintenance applications can be further improved by considering additional constraint which is the availability of the component for maintenance purposes can be added to make this risk based approach more practical. This becomes a multiple stage knap-sack optimization problem and dynamic programming concepts such as branch and bound algorithm, are required to solve the optimization problem. Further, this study can be extended by considering the other power system equipment such as transmission lines and power transformers. This task involves the estimation of failure probability and consequence due loss of lines and transformers which is a complex process. Also, risk reduction due several maintenance actions needs to be estimated and this makes the extension of the proposed method a bit laborious. Once achieved, this approach might be very useful in the present scenario of industry where the maintenance budget is really shrinking.

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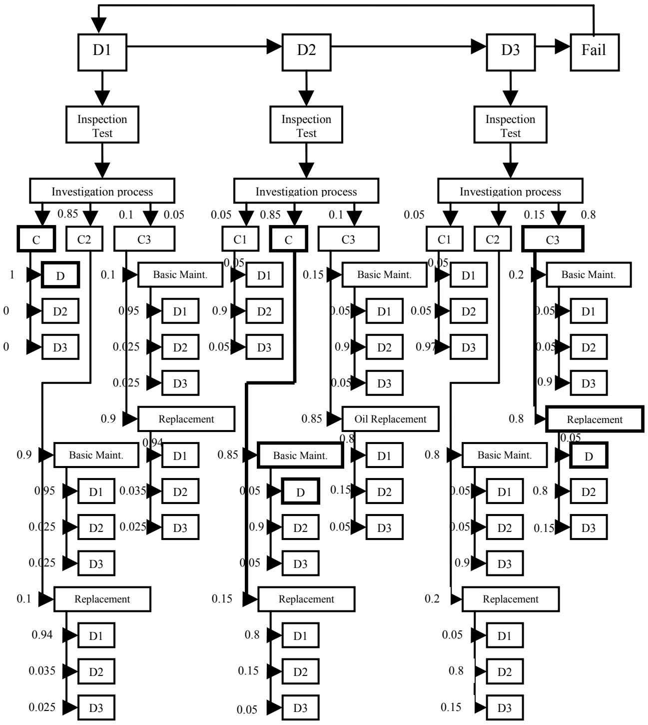
APPENDIX A

Model parameters for circuit breaker maintenance model:



Cost parameters for circuit breaker maintenance model:

Inspection cost = 100 $

Basic maintenance cost = 1,000 $

Replacement cost = 10,000 $

Failure cost = 100,000 $

Mean time in D1 = 12 years

Mean time in D2 = 9 years

Mean time in D3 = 4 years

Steady state probability calculations:

Using frequency balance approach, steady state probability is calculated from

$$P = \begin{bmatrix} 1 & 1 & 1 & 1 \\ \frac{1}{y_1} & -\left(\mu_{21} + \frac{1}{y_2}\right) & \mu_{32} & 0 \\ \lambda_{13} & \frac{1}{y_2} & -\left(\mu_{31} + \mu_{32} + \frac{1}{y_3}\right) & 0 \\ 0 & 0 & \frac{1}{y_3} & -\mu_F \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

$$\begin{aligned} \det(P) &= -\frac{\mu_F}{y_1 y_2 y_3}\left[\frac{1}{\mu_F}\left(1 + y_1\lambda_{13} + y_1 y_2 \mu_{21}\lambda_{13}\right) + MTTFF\left(1 + y_1\lambda_{13} + y_1 y_2 \mu_{21}\lambda_{13}\right)\right] \\ &= -\frac{\mu_F}{y_1 y_2 y_3}\left(T_R + MTTFF\right)\left(1 + y_1\lambda_{13} + y_1 y_2 \mu_{21}\lambda_{13}\right) \end{aligned} \tag{2}$$

$$MTTFF = \frac{T_0 + T_E}{1 + \lambda_{13} y_1 + \lambda_{13}\mu_{21} y_1 y_2}, \tag{3}$$

$$T_0 = y_1 + y_2 + y_3\,, \tag{4}$$

$$\begin{aligned} T_E = {} & (\mu_{21}\mu_{31} + \mu_{21}\mu_{32} + \mu_{21}\lambda_{13} + \mu_{32}\lambda_{13}) y_1 y_2 y_3 + \mu_{21} y_1 y_2 \\ & + \mu_{31} y_2 y_3 + \mu_{31} y_1 y_3 + \mu_{32} y_2 y_3 + \lambda_{13} y_1 y_3 \end{aligned}, \tag{5}$$

$$T_R = 1/\mu_F \tag{6}$$

Then, the steady state probabilities are

$$P = \frac{1}{\left(T_R + MTTFF\right)} \begin{bmatrix} \dfrac{y_1 + y_1 y_2 \mu_{21} + y_1 y_3 \mu_{31} + y_1 y_2 y_3 \mu_{21}\mu_{31} + y_1 y_2 y_3 \mu_{21}\mu_{32}}{\left(1 + \lambda_{13} y_1 + \lambda_{13}\mu_{21} y_1 y_2\right)} \\ \dfrac{y_2 + y_2 y_3 \mu_{31} + y_2 y_3 \mu_{32} + y_1 y_2 y_3 \lambda_{13}\mu_{32}}{\left(1 + \lambda_{13} y_1 + \lambda_{13}\mu_{21} y_1 y_2\right)} \\ y_3 \\ T_R \end{bmatrix} \tag{7}$$

APPENDIX B

Table A: Summary of Test Records Taken from CB Control Circuit during the Open Operation

Manufacturer and Type: GE VIB-15.5-20000-2					
Date	t_2 (msec)	t_3 (msec)	t_4 (msec)	t_5 (msec)	t_6 (msec)
2/12/2002	2.257	17.708	31.076	36.111	30.382
2/13/2002	1.215	9.375	33.333	37.674	29.167
2/13/2002	1.389	14.062	32.639	35.764	27.257
2/19/2002	1.389	14.757	29.514	35.764	32.292
2/21/2002	1.042	15.625	30.382	36.632	28.125
2/21/2002	1.563	18.056	31.250	34.375	29.687
2/21/2002	0.868	16.840	30.382	33.507	28.299
3/05/2002	2.083	23.090	28.646	36.111	27.604
3/05/2002	1.910	15.972	29.687	32.986	27.604
3/05/2002	2.431	14.931	29.167	34.375	28.299
6/10/2002	1.389	10.590	29.861	35.243	27.778
6/10/2002	1.215	15.278	30.208	33.681	29.167
6/10/2002	1.389	15.104	30.035	32.986	27.083
6/10/2002	1.389	11.458	29.514	33.333	27.604
6/11/2002	1.042	15.278	28.993	33.681	27.257
6/11/2002	1.563	14.062	26.910	31.076	25.000
6/11/2002	0.694	11.111	31.944	33.854	27.431
6/11/2002	3.299	11.458	30.729	34.549	28.125
6/11/2002	1.910	12.153	30.903	35.764	28.646

Table B: Summary of Test Records Taken from CB Control Circuit during the Close Operation

Manufacturer and Type: GE VIB-15.5-20000-2					
Date	t_2 (msec)	t_3 (msec)	t_4 (msec)	t_5 (msec)	t_6 (msec)
2/12/2002	1.2150	10.417	28.993	56.597	66.840
2/12/2002	0.8680	12.500	32.639	58.160	68.229
2/13/2002	1.0420	14.236	48.785	55.903	66.493
2/13/2002	1.7360	11.979	43.229	52.951	66.146
2/19/2002	1.3890	17.361	37.500	59.896	78.130
2/21/2002	3.8190	4.8610	34.375	56.424	67.535
2/21/2002	0.6940	11.632	27.257	58.854	68.576
2/21/2002	0.5210	11.285	50.521	60.764	68.924
2/21/2002	0.6940	27.604	29.514	62.153	71.007
3/05/2002	2.2570	17.882	29.687	55.382	66.146
3/05/2002	0.8680	11.458	29.514	57.292	67.014
3/05/2002	0.8680	14.236	28.299	57.292	68.403
3/05/2002	1.2150	8.8540	34.028	56.944	61.285
6/10/2002	0.5210	13.889	53.299	53.819	64.931
6/10/2002	8.6800	14.583	41.493	60.590	71.354
6/10/2002	2.6040	13.194	30.208	52.778	65.799
6/10/2002	1.7360	11.285	32.292	63.542	72.917
6/11/2002	0.8680	14.236	31.076	63.021	72.569
6/11/2002	0.6940	10.243	32.465	60.590	70.833
6/11/2002	0.6940	13.889	32.639	61.458	70.486
6/11/2002	1.0420	11.111	48.958	57.118	68.056

VITA

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