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Circuit Breaker and Transformer Inspection and Maintenance: Probabilistic Models

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***Abstract*—Circuit Breakers and Transformers are two of the most common components in the power system. Catastrophic failure of these components will result in high cost associated with the loss of load and component replacement. Preventive maintenance may reduce these costs by extending the components' lifetime and increasing availability. However, too much maintenance may be costly while too little maintenance may result in catastrophic failure. Probabilistic models that will include the effects of maintenance on reliability are needed to perform cost benefit analysis and arrive at an optimal maintenance strategy.**

A probabilistic maintenance model introduced earlier for power transformer is proposed for circuit breaker uses in this paper. The model is based on data coming from a study of deterioration process, maintenance tasks, and inspection tests for circuit breaker.

***Index Terms*—Circuit Breakers, transformers, inspection, maintenance, probabilistic model.**

I. Introduction

FAILURE of circuit breakers and power transformers can greatly affects the power delivery. The "remaining life" of power apparatus and maintenance cost are two most important aspects, which affects the maintenance policies. Various maintenance strategies are reported in literature so far [1]. It was concluded that power apparatus service availability and replacement cost should be balanced in order to get an optimal maintenance strategy. Incipient failures have along term-accumulated effect, which may cause major failures if no related maintenance action is taken. In reference [2], failure, repair and maintenance sequences are described as Markov processes and optimal maintenance intervals are discussed in detail. Based on this concept, a maintenance model for transformer is presented in [3].

In this paper, a similar idea is applied to circuit breakers. In order to build the probabilistic model for estimating circuit breaker failure rate, the deterioration process, inspection tests, and maintenance actions are discussed. Then, a comparison between circuit breakers and transformers regarding operating conditions, inspection tests and maintenance actions is carried out. Finally, a circuit breaker maintenance model is proposed.

Oil filled and air blast circuit breakers are considered in this paper since most of the circuit breakers that are already in service are of the above type.

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II. Deterioration Processes of Circuit Breaker

A. 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.

B. 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 [4]. These conditions may result in binding of contacts.

C. Deterioration of Oil

Arc byproducts combine with moisture and oxygen in the oil and reduce the dielectric strength of the oil. Accumulation of these products contributes to the deterioration of oil [5]. If prolonged, this condition causes arcing in the insulation gradually developing into an internal fault.

D. 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. [5, 6].

III. Maintenance Actions

Various maintenance actions for power circuit breakers are summarized in reference [7]. In the proposed model, two different levels of maintenance actions are considered.

A. Basic Maintenance

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

B. Replacement

This includes 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.

IV. Inspection Tests

This section gives an idea about how various inspections can be done, and what is the information that can be obtained from those tests. Some of the possible inspection tests used in practice for a circuit breaker are mentioned below [8]. The inspection tests are grouped according to the order of components that are discussed in section II.

A. Operating Mechanism

Inspection tests, which give the performance of operating mechanism either directly or indirectly, are presented in this section.

1) Contact Travel Time Measurement

The motion of the breaker contacts can be determined with contact travel time measurement. It is a plot of position (distance) of contacts with respect to contact travel time, and can be obtained by a resistive transducer [9]. The transducer is usually mounted on a moving part of the breaker. The contact travel time measurements provide information about the operating components of the circuit breaker, which include mechanical links and interrupter contacts.

2) Vibration Analysis

Mechanical malfunctions, excessive contact wears, maladjustments, other irregularities and failures can be detected through vibration patterns [10]. Accelerometers mounted usually on the arcing chamber and operating mechanism, are used to record the vibrations. The recorded vibration patterns are converted into time/frequency patterns using signal-processing techniques. The time-axes of reference frequency pattern and test frequency pattern are aligned to indicate any changes in the condition of the operating mechanism. The presence of an abnormal event in the test signature will change the frequency, and the time at which this event occurs.

3) Control Circuit Monitoring

Portable test sets are generally used to monitor the control circuit. The circuit breaker is forced into operation and the control circuit signals are recorded [11]. The following are the typical control circuit signals that can be monitored in practice [12].

- Trip coil current
- Close coil current
- DC Supply voltage
- A, B auxiliary contacts
- X & Y Coils
- Trip initiation
- Close initiation

B. Contacts

Inspections related to circuit breaker contacts are mentioned in this section.

1) Contact Resistance Test

The resistance of the main contact can be measured with a portable double bridge (Kelvin) or a "Ducter" [7]. A DC current is injected in one phase of the breaker, and the breaker is forced into operation. The current and voltage over the contact are measured and the dynamic resistance curve is calculated. The condition of the contacts can be analyzed by comparing the measured resistance curve with previous measurements [9].

2) Contact Temperature Monitoring

Large changes in contact temperature may be due to broken contact fingers, excessive burning of the main contacts, material degradation, oxide formation, weak contact springs, improperly or not fully closed contacts etc. Optical sensors are used to measure the temperature of the contacts [4].

C. Inspection of oil

Oil sample can be taken and tested for its dielectric strength. The following are the inspections that can be done in practice [5].

- Color and visual inspection
- Interfacial tension (soluble contaminants measurement)
- Dissipation factor (measure of power lost as heat)

D. Partial Discharge

Insulation failures of circuit breakers can be detected by Partial discharge monitoring [13]. The test procedure and equipment for the partial discharge monitoring are discussed in detail in reference [14]. Various methods are reported in literature so far but the cost varies according to the test procedures and accuracy of results.

V. COMPARISON BETWEEN A 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. Suggested limits for service-aged insulating oils for both breaker and transformer are given in table I [5]. 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 II provides a comparison between the breaker and transformer characteristics.

VI. PROPOSED MAINTENANCE MODEL AND DESCRIPTION

A probabilistic model, based on the concept of representing the deterioration process by various stages [3, 15] is shown in Figure 1. 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.

TABLE I
SUGGESTED LIMITS FOR SERVICE-AGED OILS FOR TRANSFORMERS AND CIRCUIT BREAKERS [5]

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 ºC, % maximum	0.5	0.5	0.5	1.0
100 ºC, % 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

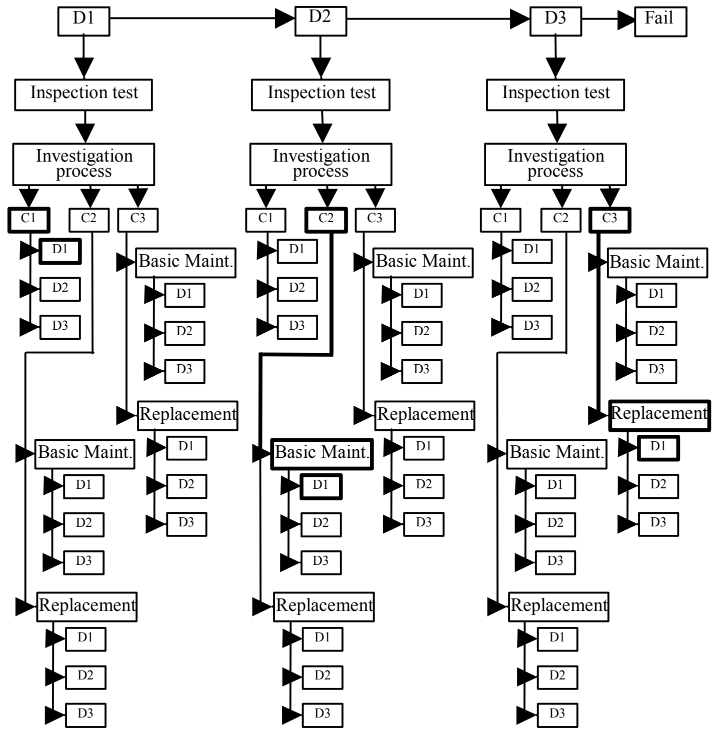

Fig 1. Proposed circuit breaker probabilistic maintenance model.

The model takes results from various inspection and maintenance tasks and the frequency of performing the tasks as inputs and gives the failure rates as output. The changes in the "mean time to failure" indicator can be observed by considering different inspection and maintenance actions. This model can help in obtaining optimum maintenance intervals such that both the component availability and the total cost are balanced. Various inspection tests and maintenance actions considered in the model are discussed next.

A. *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) *Contact Travel Time Measurement*

Condition of the circuit breaker can be obtained by comparing the test curve with the reference curve. Figure 2 shows various contact travel curves during the opening of a circuit breaker [4]. The solid lines indicate the reference curve and the dotted lines indicate the current observation. The following are the possible observations from the Figure 2.

- *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

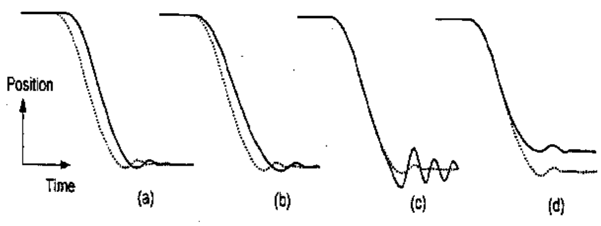

Fig. 2 Comparison of circuit breaker contact travel curves [4]

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. A detailed analysis of circuit breaker operations based on automated monitoring of control circuit is discussed in reference [12]. Table III shows some of the possible causes for the behavior of the measured signals [16].

Figures 3, 4, 5 and 6 show the sluggish trip latch, defective close coil, defective auxiliary switch and defective battery respectively.

The proposed criterion for the condition of control circuit is

Condition 1: within specification and will not require maintenance

TABLE II
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

Condition 2: caution stage; need more attention
Condition 3: final stage; need major replacement

TABLE III
ABNORMAL WAVE FORMS [16]

Signal Name	Signal Behavior	Figure	Possible Cause
Trip Coil Current	Dip delayed	Fig. 3	Binding or friction
Close Coil current	Excessive noise (distortion)	Fig. 4	Defective close coil
A&B Contacts	Abnormal noise on contacts	Fig. 5	Defective auxiliary switch
DC Voltages	DC Voltage unstable	Fig. 6	Defective substation battery or high impedance short

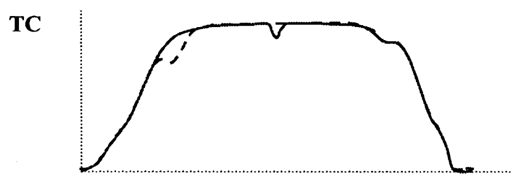

Fig. 3. Trip current dip delayed

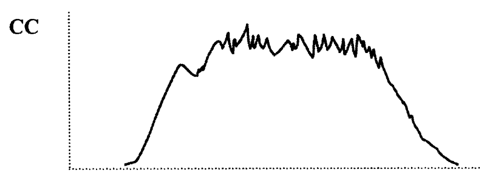

Fig. 4. Close current excessive noise

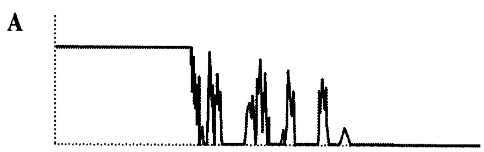

Fig. 5. Noisy transition when opening

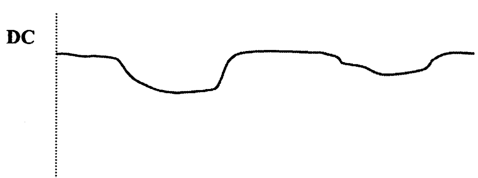

Fig. 6. DC Voltage unstable

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 [7].

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 [5].

TABLE IV
SUGGESTED LIMITS FOR CONTINUED USE OF SERVICE-AGED CIRCUIT BREAKER INSULATING OIL [5]

Test and method	Suggested limit
Dielectric strength kV minimum	25
Dielectric strength, kV minimum	
1 mm gap*	20
2 mm gap*	27
Dissipation factor (power factor), 25 ºC, % maximum	1.0
Interfacial tension, mN/m minimum	25
Color , ASTM units, maximum	2.0

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

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 IV. Criterion for recondition is excessive carbon in oil and reduced dielectric strength (dielectric strength drops below the accepted limit).

A detailed analysis of inspection tests and the collected data is needed for implementation of the model, and will be included in further work.

B. Investigation Process

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.

C. Maintenance Action

1) 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.

2) Basic Maintenance

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

3) Replacement

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

VII. CONCLUSION

A probabilistic maintenance model for circuit breakers is introduced. 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. Implementation of the model using Monte Carlo simulation is in progress. Maintenance cost and time to failure of each transformer and circuit breaker will be incorporated.

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