RELIABILITY STUDY OF CIRCUIT BREAKERS

(A CASE STUDY PHCN OSOGBO WORK CENTRE EQUIPMENT OFFICE)

BY

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DEDICATION

I dedicated this presentation to God almighty who has given me the privilege, opportunity and strength when embarking on this work. To my beloved parents Mr. and Mrs. Iselewa, Mrs Shade Foluso, Dayo, Gbenga, Ola, comfort and to all well wishers.

DECLARATION

I, Iselewa Oluwaseyi declare that this work was done by me and never been presented elsewhere for the award of a degree. I also hereby relinquish the copyright to the Federal University of Technology, Minna.

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May God bless you All.

ABSTRACT

Circuit breakers are crucial components for power system operation, since it forms one of the major elements of a protection system which contribute to the detection and removal of faults in the switchgear.

In this study, the performance of various types of circuit breakers was examine in Osogbo PHCN equipment centre. It was observed that, the three circuit breaker dominant in Oshogbo PHCN; The SF6 (sulphur hexaflouride) circuit breaker VCB (Vacuum circuit breaker) and OCB (oil circuit breaker) based on the result and analysis carried out the SF6 breaker has higher rate of performance in terms of number of operations with a minimum failure rate.

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CHAPTER ONE

INTRODUCTION

1.1 Reliability of High Voltage Circuit Breaker

Circuit breaker design is governed by several factors such as, current capability, interruption time, and means of reset. Circuit beakers began to appear as soon as electric power distribution was developed on an industrial scale. This was around the later part of the 19th century or the early part of the 20th century. Improvements in the first half of the 20th century centered on current handling capacity (for a given size) and reduced interruption time. Interruption tie prior to 1962 was about 45 cycles, or about 0.75 seconds. In the 1960s, two cycle circuit breakers were available. Shorter interrupted time results in less stress on other components of the power grid. [1]

In the sixties, circuit breakers were manually reset. In the case of electrical power distribution, this could mean hours before power was restored. Many of the breakers used today will attempt to automatically reset in the event of lightning strikes or other short term overloads. Household circuit breakers tend to be manual reset for reasons of low cost and safety. The trend in power distribution is to efficiently monitor and control circuit breakers from a central location. Power utilities today use sophisticated circuit breakers that can report their status over power lines, telephone lines, or by wireless means. Many utilities can monitor the status the grid and circuit breakers over the internet. Technicians at a central facility can monitor where breakers have tripped and attempt to reroute power through other segments of the grid. They can also reset the breakers remotely, significantly simplifying the task of restoring power. Of course downed power lines and failed equipment still require linemen in the field to repair the damage.

The knowledge of circuit breaker operation and performance is essential to an understanding of protective relaying. It is the coordinated action of both that results in successful fault clearing. The circuit breaker isolates the fault by interrupting the current at or near a current zero. Electric power transmission networks are protected and controlled by high voltage breakers. The definition of "high voltage" varies but in power transmission work is usually thought to be 72,500V (72.5kV) or higher, according to a recent definition by the International Electro technical Commission [2] (IEC) high voltage breakers are nearly always solenoid-operated, with current sensing protective relays operated through current transformers. In substations, the protection relay scheme can be complex, protecting equipment ands buses from various types of overhead or ground earth fault etc.

The purpose of protection in any electrical power system is to ensure isolation of the protected circuits as quickly as possible in the event of abnormal operating conditions of the system, such as faults or system disturbances. There abnormal conditions may result from failures of the components of the circuit or may be caused by nature. Failures can result from deterioration of insulation, overvoltage, overloading while the natural occurrences that will require quick isolation are flash over either to the ground due to the undergrowth in the case of transmission lines, or between phases due to atmospheric conditions or lightning strikes during thunder storms. Such faults, depending on the type, can be associated with currents whose magnitudes can be of large multiples of the normal load or much lower. It is therefore important to provide protection against different types of fault that can occur. Non fast clearance of the fault can lead to the following:

a) Excessive damage or destruction of faulty plant.

b) Damage to healthy plant due to the passage of excessive currents causing overheating and mechanical stressing. It should be noted that most HV plants are only rated for the passage of full short circuits currents for 1sec.

c) Partial or complete system collapses due to generators failing out of synchronism giving rise to large power oscillations leading to operation of protective devices particularly those associated with the generator prime movers and transmission lines. We have seen all these happen on the power holding company of Nigeria (PHCN) system. The best way of ensuring good performance of any protective scheme is to carry out periodic maintenance checks on the scheme. During such routine maintenance checks, all functions of the scheme should be checked and confirm that the entire scheme still operates as designed.

1.2 Statement of the Problem

Protective schemes are expected to be reliable and should have minimum failure rates. They are not supposed to operate frequently but expected to respond and give maximum performance whenever they operate to matter how infrequent this may be. On the average, they are not expected to operate more than twice or so a year but in spite of this “inactivity”, their reliability should remain very high. Since circuit breakers play a crucial role in switching for the reasons of both the routine network operation, protection of other devices in power systems and to ensure regular supply of power.

Therefore, this study will look into the performance of the various types of breakers available in PHCN Osogbo Transmission Station and a way of improving the circuit breaker maintenance (management).

1.3 Purpose of the Study:

The purpose of the study is to examine the performance of various types of circuit breakers, their applications and ways of improving circuit breaker maintenance/management.

Specifically, the study focuses on:

i. Reliability of the circuit breakers

ii. Maintainability of the circuit breakers

iii. Availability of the circuit breakers

iv. Efficiency of circuit breakers

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CHAPTER TWO

LITERATURE REVIEW

2.0 Concept of Reliability of Circuit Breaker

With the continuous development of production technology, equipment replacement, the traditional periodic maintenance has been unable to meet the current forms of production. The development of reliable technology, equipment maintenance provides a method and theoretical support. Reliability-centered maintenance methodology based on reliability, maintenance program development steps, on the SFE method to discuss the overhaul of circuit breakers. Determine the maintenance object; of the maintenance object failure mode analysis; according to different failure modes to determine the appropriate maintenance mode.[3]

making full use of the inherent reliability of the device itself, in the "prevention-oriented" plan preventive maintenance system, developed on the basis of a modern maintenance mind. The maintenance of thinking of the basis of reliability theory, by the specific factors affecting equipment reliability analysis and testing, application logic, decision analysis method, a scientific method to develop the maintenance and repair of the content to determine a reasonable equipment maintenance cycles, minimum equipment life cycle costs and make full use of equipment reliability. Its maintenance ideas include the following: first, the inherent reliability of equipment by the equipment design and manufacturing decisions. Second, to minimize unnecessary equipment maintenance work. Thirdly, a continuous collection and analysis equipment in the use of fault data. [4]

Circuit breaker in accordance with voltage levels, actuator, producers and other standard classification. Reliability index according to the statistics available to the reliability of sorting various types of circuit breakers can be used as a basis for the fundamental overhaul of preference. Classification is the study of the initial decomposition of the object to form a more specific object of study.

In accordance with voltage levels Category: In the SF6 circuit breaker used in 35 KV, 110 KV, 220 KV two voltage levels, the voltage level is divided into three categories, with the P1, P2, P 3, said. Reliability index (a, b, c, d ...) [P1] = [a1, b1, c1, d1 ...]; [P2] = [a2, b2, c2, d2 ...]; [P3] = [a3, b3, c3, d3 ...]

By calculating the [P1] - [P2], [P1] - [P3], [P2] - [P3] initially identified three voltage levels of the SF6 circuit breaker reliability, sorting, and to determine the repair should focus on what voltage level of equipment. [3]

In accordance with the manufacturer Category: in each voltage level in a number of manufacturers of equipment, different quality of the equipment of different manufacturers have different inherent reliability of equipment for each voltage level can be divided into several categories according to manufacturers Q1, Q2, Q3, Q4 ... use ibid methods to determine the reliability of different manufacturers equipment to sort, identify the equipment concerned. [4]

In accordance with actuator type Category: SF6 circuit breaker body is an important component of circuit breakers is also part of one of the highest failure rate. SF6 circuit breakers are commonly used actuator spring bodies, hydraulic mechanism, pneumatic body. Is divided into three categories, with I1, I2, I3, said. Ibid method used can determine the reliability of the different actuator sort. [3]reposted elsewhere in the paper for free download http://www.hi138.com.

2 .1 Breaker Failure Mode Analysis

Failure mode analysis is the "reliability-centered," the basis for the repair, maintenance goal is to determine fault for the device functionality, the maintenance is in order to dispose of failure modes in order to eliminate the root causes of failures.

Operating agencies (including driving part) failure: mainly spring operating mechanism type of institutions and hydraulic equipment. Gas sector applications small, permanent body is only in recent years, development of applications, but the number is running out. In recent years, judging from the operation, hydraulic institutional deficiencies and the failure rate of the highest failure rate of spring body is relatively minimal. From scheduled maintenance workload in terms of working hours spent on maintenance, hydraulic organization, Spring body at least. In recent years 110kv and below voltage level of circuit breaker, the spring bodies have gradually replaced the magnetic body and a large number of applications, replacing a number of hydraulic mechanisms, because of its low maintenance and no leakage by the maintenance, operating personnel welcome. [3]

The circuit breaker equipment failures Ontology: Ontology equipment failures include porcelain vase is damaged, loose joints, parts damage and foreign body jam and so on, installation and maintenance of poor quality, the wrong parts installed, the phenomenon of missing equipment. Such as the check valve, safety valve films, locking nut and a small installation or wrong installation or installation not in place, internal seriously dirty, there is no foreign body removal, etc., circuit breakers in poor quality parts, such as the insulator strength is not enough, the poor quality seals, casing insulation deterioration, such as casting failed. [4]

The insulation fault can be divided into internal insulation failures and external insulation failure: one inside the insulation fault hazards in general greater than the external insulation failure. Mainly by the insulation fault within the casing and the current transformer damp due to water, oil quality deterioration, oil shortage, crack, damage, main causes of failure such as insulation down. External insulation failure is mainly due to insulator contamination, leakage shorter distances, so that circuit breakers included, external over-voltage flashover occurs, discharge, explosion accidents. [5]

Breaking and Closing performance failures: The complete and reliable grid operation breaking, Closing the important task is the work of circuit breaker performance and circuit breakers in operation is the most severe test. The failure occurs mainly due to the equipment circuit breaker obvious defects, if the organization's sub-closing velocity and time of serious non-compliant, interrupter assembly quality problems and design and manufacturing flaws, e.t.c [6]

The failure of conductive properties of bad: bad because of electrical conductivity in the normal operating loads, circuit breakers fever exception. The main reason is the assembly, maintenance during the process is incorrect, resulting in dynamic and static contact their connections and lack of contact pressure or contact area is too small or contact at screw loose, soft link breaking and other equipment on the causes. However, in general due to the actual load is normally much lower than the rated load, but also in the process requirements easy to get assurance and control, so the fault was relatively small. [7]

2.2 Reliability Equations

2.2.1 For the system connected in series or the breaker connected in series, failure of one component leads to the failure of the entire system.

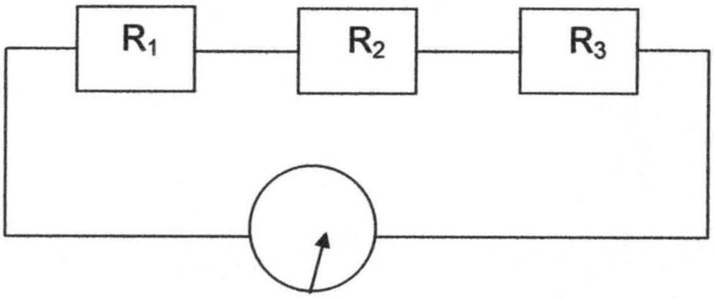

Fig 2.1: OCC

Where R_1 – SF_6 sulphur hexafluoride gas circuit breaker

R_2 - VCB Vacuum circuit breaker

R_3 – OCB Oil circuit breaker

OCC – operating circuit counter which counts the number of switching operations.

Probability of survival = product of individual probabilities of survival of the components.

$$R = R_{1.} R_{2.} R_{3.}$$

2.2.2 For the device to be connected in parallel; the whole device will fail if all of them fail.

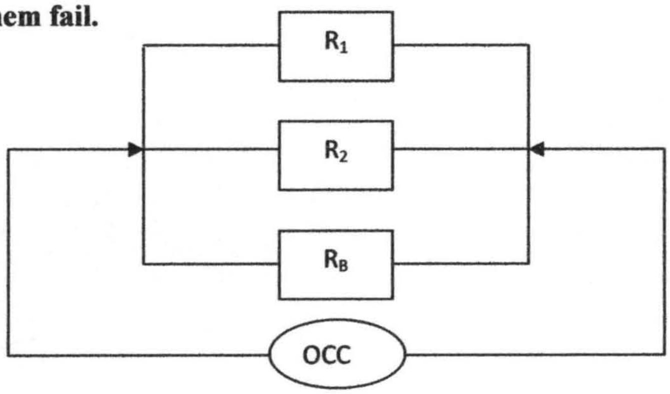

Fig2.2

$R_T = [1 - (1 - R_1)(1 - R_2)(1 - R_3)]$………………..

$R_1 = SF_6$

R_2 = VCB

R_3 = OCB

OCC = Operating Circuit Counter

2.3 ELECTRICAL CHARACTERISTICS OF A CIRCUIT BREAKER

There are 15 electrical signals generated during either tripping or closing of the breaker. 11 of them are analogue, while other 4 are status signals. The most important signals are Trip Event and Close Event [7]. These signals, generated by the protection relay, initiate some other signals (some generated during tripping, some during closing only), and as a result tripping or closing of the circuit breaker occurs. Figure 2.3 shows simplified control of the circuit of the circuit breaker.

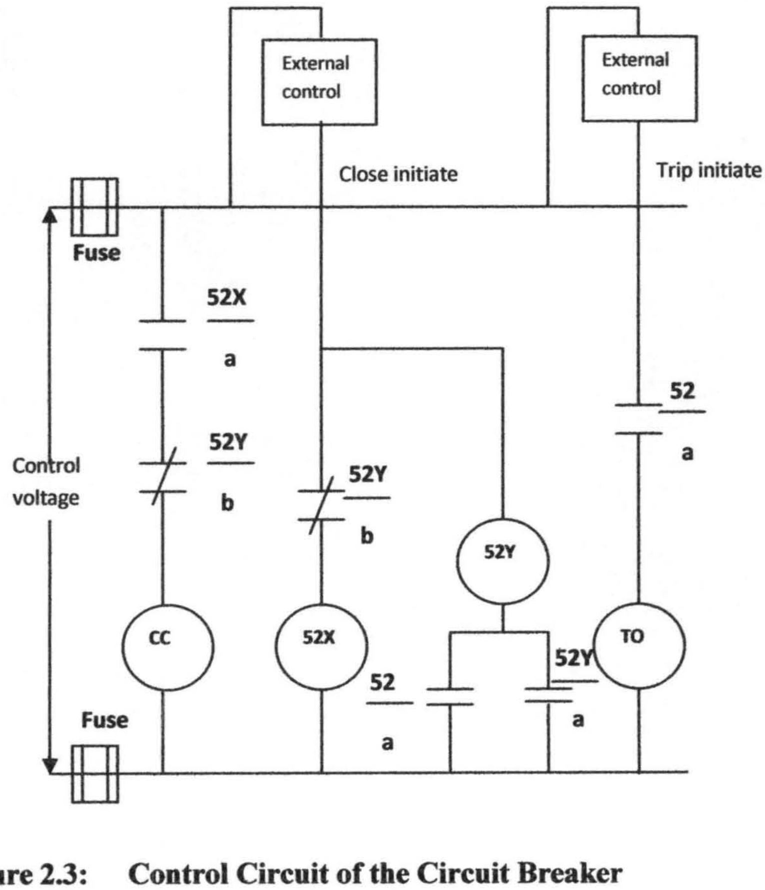

Figure 2.3: Control Circuit of the Circuit Breaker

Substation RTU is wired to CB auxiliary contact (52a and/or 51b), which are used to track circuit breaker status. They operate when the breaker mechanism changes state. The 52a and 52b contact signals represent the voltage across auxiliary switches that specify the open or close status of the circuit breaker contact 52a opens when the breaker opens and closes when the breaker closes. It is also called "a contact" contact 52 has opposite logic: it opens when the breaker closes and closes when the breaker opens. It is also called "b contact"

Signals, not mentioned in the figure 2.3, which change their values as a result of tripping or closing, are:

1. Control DC- analog signal
2. Light wire- analog signal
3. Yard DC- analog signal
4. A contact - analog signal
5. B contact - analog signal
6. Close coil current - analog signal
7. Trip coil current #1 - analog signal
8. Trip coil current #2 – analog signal
9. Phase A current - analog signal
10. Phase B current - analog signal
11. Phase C current - analog signal
12. Close event - status signal
13. Trip event - status signal
14. X coil - status signal

Table 2.1 circuit breakers signals with descriptions

Signal Name	Channel	Type	Analog or Status	Nominal Range	How it relates to the circuit (fig 2.2)
Control Voltage	Voltage	Contact	A	125V ± 15V	Provides Pos/Neg voltage for contacts
Light wire	Voltage	Contact	A	125V ± 15V	ON/OFF indicator
Aux contact B	Voltage	Contact	A	125V ±15V	Establishes Connection from light to Neg
Yard DC	Voltage	Contact	A	125V±15V	Runs CB motor
Aux. contact A	Voltage	Contact	A	125V ±15V	Indicates breaker status
Close coil current	Current	Shunt	A	<10A	Used to physically close the CB
Trip 2 coil current	Current	Shunt	A	<10A	Used to physically open the CB
Phase A Current	Current	Shunt	A	<10A	Used to physically open the CB
Phase B Current	Current	Shunt	A	5A	Indicates breaker status
Phase C Current	Current	Shunt	A	5A	Indicates breaker status
Close initiate	Event	Contact	S	125V ±15V	Initiates a close operation
Trip initiate	Event	Contact	S	125V ±15V	Initiates a tip operation

'X' Coil	Event	Coil	S	125V $\pm$ 15V	Close all 52X contacts Establishes a path from POS to 52CC
'Y' Coil	Event	Coil	S	125V $\pm$15V	Opens all 52Y contacts Interrupts 52CC and X coil current

2.4 Fault Clearance

In the case of a fault on Line1, protective relay(s) should send trip signals to CB1, CB2 and corresponding breakers on the other side of the line. They should open and disconnect faulted line1 from the rest of the circuit corresponding sequence of opening for this case is shown Fig2.4

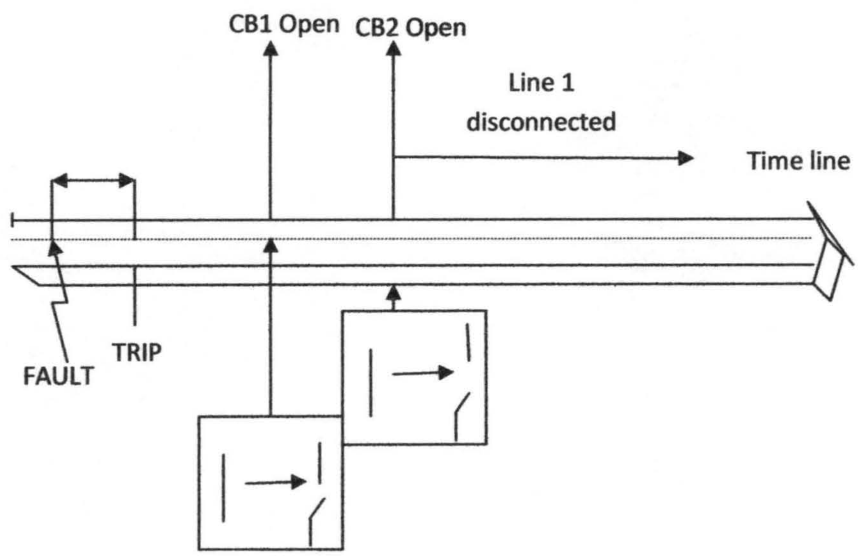

Fig.2.4: sequence of opening corresponding breakers in case on line 1

The CBM device sends event files to the client application in substation. Events are processed. If both breakers in this case are successfully opened and events on breakers CB1 and CB2 open between TRIP times, we consider Line 1 opening successful. If one of the breakers gets stuck software will inform the user and the breaker failure logic is executed. Tolerance time depends of the type of breaker. For example, tolerance time for short circuit fault on SF_6 gas type is 3s.

2.5 Auto Reclose

Circuit breakers start an opening sequence after they get trip command from protective relays. The relays observe whether fault is present. If they recognize the fault they send the trip signal to corresponding breakers according to the zone of protective. After some time circuit breaker assumes that fault is cleared and it will try to reclose itself automatically. Typical sequences occurring because of a fault present somewhere on a transmission line is shown on Fig2.5

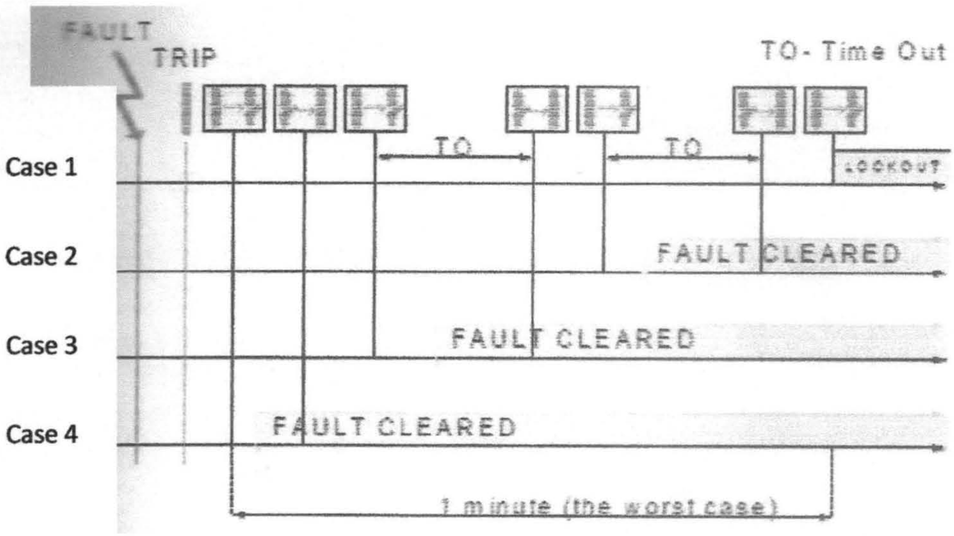

Fig.2.5: Trip and reclose sequences on a single breaker

Process of reclosing can be repeated a couple of times as Fig. 2.5 shows and it is initiated in order to determine whether fault, which caused opening of breaker, is still present. The sequence consists of three stages:

TRIP EVENT (fault is present)

CLOSE EVENT (to see if the fault is gone)

TRIP EVENT AGAIN (if the fault is still present)

If a fault is still present it will be given some time to be cleared, this time is called TIME OUT time. TIME OUT usually depends on type of breaker and the voltage level. The reclosing of the breaker consists of two stages:

CLOSE EVENT (to see if the fault is gone)

TRIP EVENT AGAIN (if the fault is still present)

In the case where fault is present after a reclosing, breaker will wait for the time out to pass and initiate reclosing again. If after selected number of attempts of reclosing, fault is still present, lockout take place. There will be no more attempts to reclose automatically the breaker again.

2.6 HIGH VOLTAGE SF_6 CIRCUIT BREAKER FUNDAMENTALS

Circuit breakers can be considered as the "last line of defense" in the context of providing protection from, and mitigating the effects of, faults on electrical power networks. They are designed to withstand the most severe stresses experienced by any equipment on a power system and thereby protect other equipment from overstress, particularly under fault conditions. As such, critical attention is placed on the specification, design, production, testing and application of circuit breakers. While various other measures are implemented in power systems to mitigate both the occurrences and consequences of faults on the system, including redundant primary and secondary systems, ultimately there is a dependence on the successful operation of the nominated circuit breaker to interrupt current flow as quickly and reliably as possible for any specific switching case.

Within the context of the research described in this thesis report, it is important to provide summary description of the fundamental aspects that describe modern high voltage (SF6) circuit breakers. Any controlled fault interruption concept will be highly dependent on the behaviour of the circuit breaker to which it is to be applied. Understanding how such circuit breakers function and how their behaviour is influenced by various aspects inherent to their specific application, is fundamentally important to the development of an appropriate and viable control scheme.

Any form of detailed analysis of the design and behaviour of high voltage circuit breakers, even if only restricted to those using SF6 gas as an interrupting medium, constitutes a major research area in itself; that is *not* the primary focus of this chapter. This chapter is intended to identify those aspects of high voltage SF6 circuit breaker design and behaviour that have direct bearing on the development of a scheme to facilitate controlled fault interruption.

Consistent reference has been made to SF6 circuit breakers in the above paragraphs. The focus on

SF6 circuit breakers is primarily due to the fact that the vast majority of high voltage circuit breakers produced today, and over the past 15-20 years, utilize SF6 gas as the primary insulation and interruption medium, due in no small part to the excellent dielectric and thermal properties of SF6. Nevertheless there remain large populations of non-SF6 transmission circuit breakers still in use on power systems; using either mineral oil or high pressure (dry) air as interrupting mediums [8].

Some of the circuit breaker principles described in this chapter may be equally relevant to such older interrupter designs, but the reader should be aware that the specific functionality and performance of a high voltage breaker is highly dependent, not only on its design, but on the type of interrupting medium.

It should be noted that in the context of discussing "high voltage" circuit breakers, the work conducted in this research project and described herein has been focussed primarily on "transmission" level circuit breakers and fault cases. In this context, "high voltage" implies voltages in the range of 72kV to 800kV. In principle, much of what is described herein could be applied to "medium voltage" or "distribution" level systems in the range of 6.6kV to 36kV, however the type of interrupters should then be expanded to cover vacuum interrupters, which in several respects behave somewhat differently than SF6, minimum-oil or dry-air interrupters (due to differences between low pressure and high pressure gaseous arc interruption processes. [9] [10]

The exclusion of medium voltage systems from this research project is in no way intended to imply an inherent lack of technical feasability nor interest in applying controlled fault interruption techniques at this level, but rather simply a need to restrict the specific project boundaries to a practical scope.

Also it is *not* intended to block consideration of the potential use of some aspects of the proposed controlled fault interruption scheme to possible "future" high voltage interruption techniques; for example solid-state / power electronic based interrupters. However such concepts are still largely experimental in respect of medium (or high) voltage applications and it is reasonable to expect that SF6 will remain the dominant interruption medium for transmission level high voltage circuit breakers for the immediate, if not long term, future.

The issues outlined in the following summary are by practical necessity very brief. A detailed analysis of high voltage alternating current circuit breakers involves combining a diverse range of disciplines ranging from arc physics to high voltage engineering and power system analysis to mechanical engineering. References are provided within the following text from which a deeper analysis of various aspects of circuit breaker design and performance can be obtained for the interested reader. [11]

2.7 TYPES OF CIRCUIT BREAKERS

2.7.1 Oil Circuit Breakers

These are the oldest type of circuit breakers. The separating contacts of the breakers are made to separate within an insulating oil, which has better insulating properties than air. The insulating properties of the oil can be used at high voltages and for high breaking capacities. Oil circuit breakers have the virtues of reliability, simplicity and relative cheapness. The oil circuit breakers can be divided into:

1. Bulk oil circuit breakers: using a large quantity of oil, also called the dead tank type, because the tank is held at ground potential. Such breakers are available in all classifications of voltages and interrupting rating for indoor and outdoor applications.
2. Low oil circuit breakers: which operate with a minimum amount of oil, so that is why sometimes called minimum oil circuit breakers or small-oil circuit breakers. These circuit breakers are also sometimes called the live tank circuit breakers because the oil tank is insulated from the ground.

When the breakers open, an arc is formed; the heat of the arc evaporates the surrounding oil and dissociates it into a substantial volume of gaseous hydrogen (hydrogen gas along with a small percentage of methane, ethylene and acetylene) at high pressure.

2.7.2 Gas Blast Circuit Breaker

The first high voltage SF_6 circuit breaker built in 1956 by Westinghouse could interrupt 5kA under 115kV, but it had 6 interrupting chambers in series per pole. [1]. The principle is similar to that of the air blast type, and auxiliary equipment is required to keep the gas under pressure. As the gas is expensive, leakage must be avoided and during maintenance, the gas must be pumped into shortage tanks with the minimum loss. The gas used is sulphur hexa fluoride (SF_6) which under pressure as better insulating properties than either insulating oil or compressed air. The gas is also inert and stable, non-flammable and non-toxic. The gas is at a pressure of about 3 bar from the insulating medium round the contacts. As the contacts are open, a jet of gas from a gas reservoir at a pressure of 15 – 16 bars is directed across the contacts. The gas at this pressure will liquefy if its temperature drops below 10^{o}C, [6] so for outdoor switch gear, heaters must be provided.

2.7.3 Vacuum Circuit Breakers

High vacuum has two outstanding properties:

1. Highest insulating strength-in comparison to various other insulating media in use in circuit breakers vacuum is a superior dielectric medium. It is better than all other media except air and SF6 gas which are generally employed at high pressure.
2. When an ac circuit is opened by separating the contacts in a vacuum, interruption occurs at the first current zero with the dielectric strength across the contacts building up at a rate thousands of times higher than that obtained with other circuit breakers. This is because with the increase in gap due to separation of contacts and movement of breaker contacts, the breakdown kv peak increase.

2.8.1. Primary functions of a circuit breaker

A circuit breaker must perform three (3) primary functions:

1. Carry rated current at rated voltage and power frequency when in closed position

2. Interrupt rated currents at rated voltage and power frequency on command

3. Maintain rated dielectric (power frequency and impulse) withstand levels when in open position

Item 2 above is the most complex of the three primary functions, since the circuit breaker must satisfactorily cope with a wide range of possible switching conditions, ranging from small load currents which might be either highly inductive or highly capacitive to switching of rated asymmetrical fault current. The dielectric, thermal and even mechanical stresses placed on the circuit breaker under these different switching conditions vary widely from case to case. The result of having a single device having to cope with this wide range of application stresses is that all circuit breakers are ultimately constrained in their designs to try and reach the best compromise solution in terms of performance, reliability and cost while fulfilling their primary rated functions.

2.8.2 Basic alternating current interruption principles

All circuit breakers used for interruption of alternating currents operate on the basis of utilizing an arc formed between a set of contacts and naturally occurring current zero crossings to achieve interruption. When interrupting a current, a circuit breaker is effectively required to transform its state from being a conductor to an insulator in the shortest possible time. Detailed descriptions of the AC interruption process can be found in many power systems and circuit breaker theory texts [12]

It is not the intent to reprise or review these descriptions in detail in this report.

The following is a generic description of the interruption process with respect to a non-specific (SF6) circuit breaker. The intent is to summarize the dominant factors determining successful interruption at a current zero and indicate their relevance to possible implementation of controlled fault interruption. Among the more important factors pertaining to controlled fault interruption are the arcing time behaviour and the operating time consistency of the circuit breaker. Ultimately, in the absence of any control over when the circuit breaker arcing contacts part with respect to a current zero, circuit breakers must be designed to cope with a range of arcing times within the constraint of their total contact stroke and contact speed. If the contact parting instant can be controlled with respect to a targeted current zero time, then the circuit breaker design could be further optimized.

Two main stresses are applied to a circuit breaker during interruption; thermal and dielectric. For successful interruption the circuit breaker must:

• Sufficiently “cool” the arc plasma at current zero i.e. achieve thermal interruption

• maintain a minimum rate of rise of dielectric strength exceeding the rate of rise of the recovery voltage across its contact gap(s)

The thermal stress is primarily governed by the magnitude of the arcing current and will vary from being very low to very high depending on the switching case. The initial period of transient recovery voltage across the open circuit breaker after current zero interruption may also affect the thermal interruption process.

The dielectric stress (or “transient recovery voltage”; TRV) begins to develop immediately after the current is interrupted. The rate of rise of and characteristic shape of the TRV is determined by the reactive state(s) of the power system connected to either side of the breaker. The magnitude of the stress is largely determined by the rated voltage and the type of earthling used on the power system. [10][11]

2.9 FAILURE RATE

Failure rate is the frequency with which an engineered system or component fails, expressed for example in failures per hour. It is often denoted by the Greek letter λ (lambda) and is important in reliability engineering.

The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system Far example, an automobile's failure rate in its fifth year of service may be many times greater than its failure rate during its first year of service. One does not expect to replace an exhaust pipe, overhaul the brakes, or have major transmission problems in a new vehicle.

In practice, the mean time between failures (MTBF. $1/\lambda$) is often used instead of the failure rate. The MTBF is an important system parameter in systems where failure rate needs to be managed, in particular for safety systems. The MTBF appears frequently in the engineering design requirements, and governs frequency of required system maintenance and inspections. In special processes called renewal processes, where the time to recover from failure can be neglected and the likelihood of failure remains constant with respect to time, the failure rate is simply the multiplicative inverse of the MTBF $1/\lambda$ [13].

2.9.1 Bathtub Rate Curve

The bathtub curve displays the different stages during the life time of a component or a device. The first region corresponds to burn in or early failure which is the same for all the breakers and the second region corresponds to constant and low failure rate (useful life time of operation for the component) which is the same for SF_6 and vacuum circuit breaker but shorter for oil circuit breaker due to frequent replacement of contacts. The third region corresponds to wear out that is, where the failure rate is increasing with time and it is short for SF_6 and oil circuit breaker but very sharp for vacuum circuit breaker due to the fact that it is fit and forget in the sense the interrupter unit· cannot be replaced.

The summary of the analysis are:

- The high performance of SF_6 indicates its reliability.
- The high performance on fault operations shows its efficiency.
- The stable operation is an indication of its maintainability feature.

High reliability and maintainability feature points to its availability.

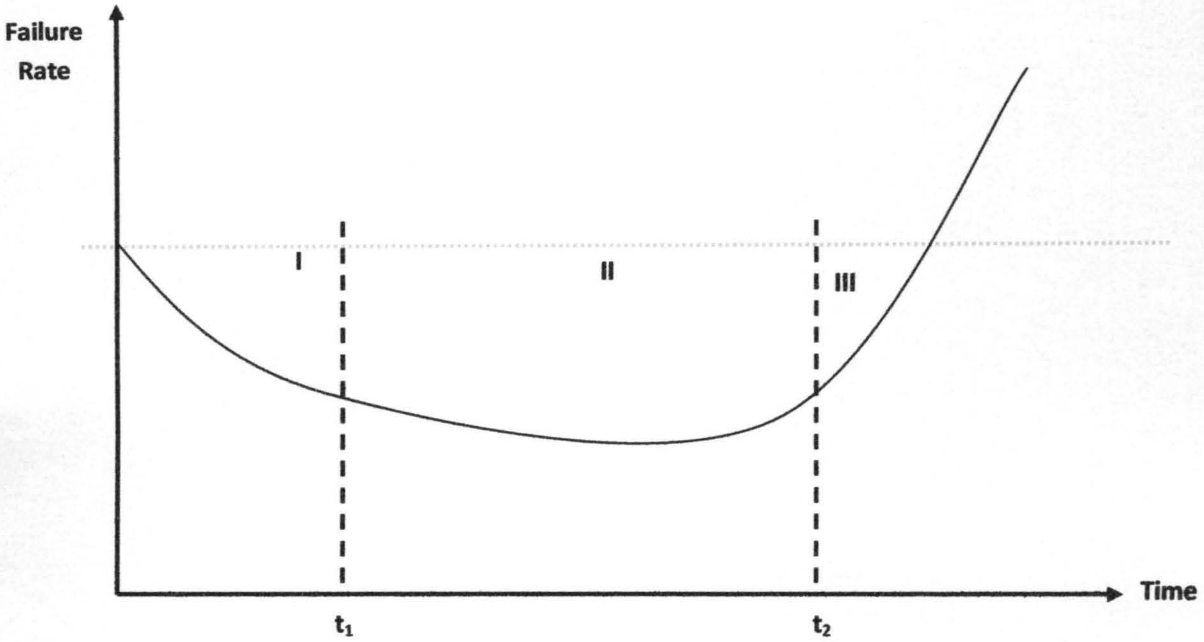

Fig. 2.6a: Variation of Failure Rate with Time for Oil Circuit Breaker

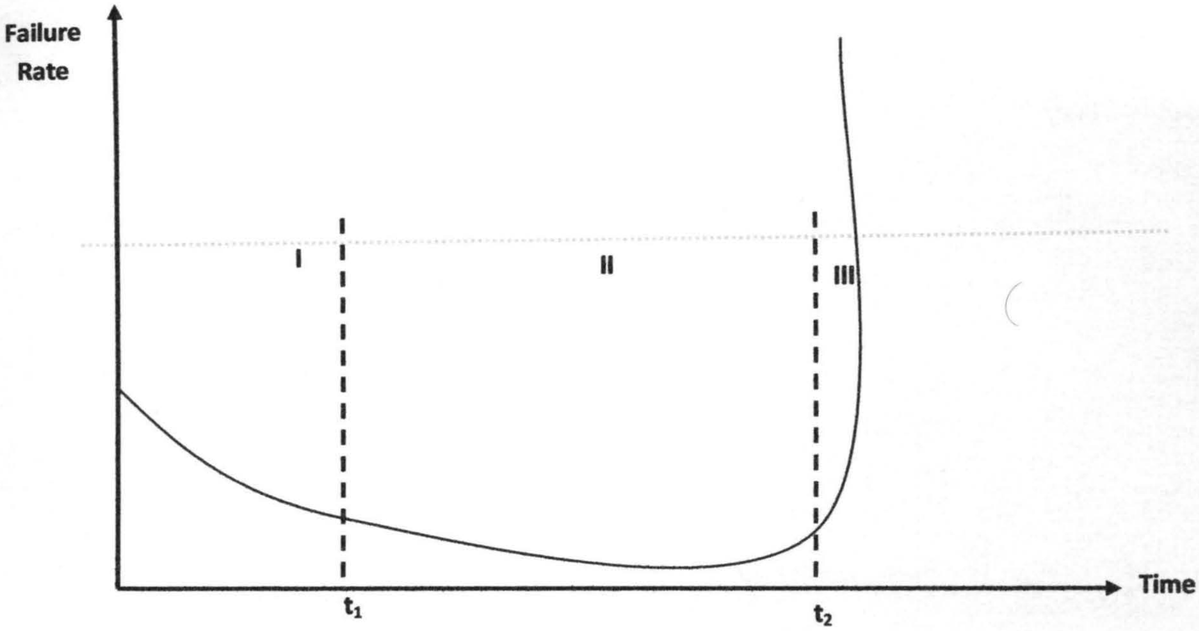

Fig. 2.6b: Variation of Failure Rate with Time for vacuum Circuit Breaker

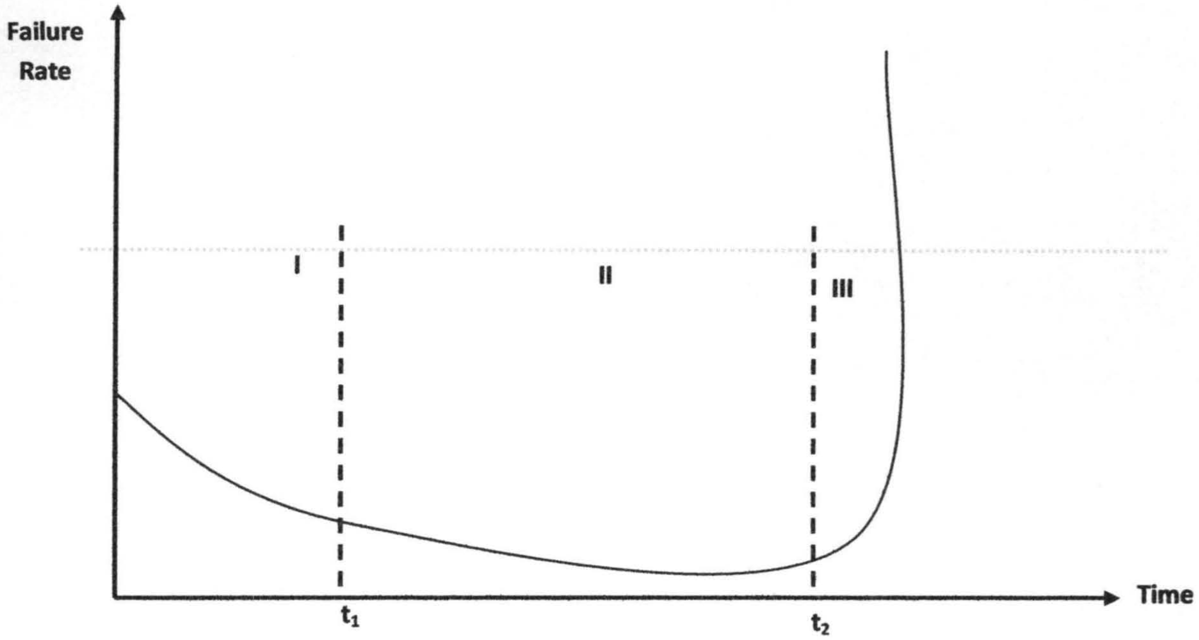

Fig. 2.6c: Variation of Failure Rate with Time for SF6 Gas Circuit Breaker

Legend

I - Burn in

II - Useful Life

III - Wear Out

CHAPTER THREE

DESIGN AND IMPLEMENTATION

3.0 THE MEASURE OF PERFORMANCE OF CIRCUIT BREAKER

The most important and mechanically most advanced substation apparatus the circuit – breaker has undergone significant improvements over the years. The two reasons for these are that, SF_6 replaced expressed air and oil as interrupting medium; and the operating mechanism technology has been refined and these has brought improved technical performance.

3.1 THE MEASURE OF PERFORMANCE IN TERMS OF NUMBER OF OPERATIONS

The above mention improved technology may not be the only evidence to conclude the high rate of performance of SF_6. Hence, there is need for other toots to validate these assumptions. A survey of various types of breakers at medium and high voltage levels that only 10 are vacuum and oil type. The number of operation of a breaker is been taken by the operating cycle counter. This counts the number of switching operations include all operations that have to do with opening and closing of breaker in either normal or abnormal condition, normal in the absence of fault and abnormal in presence of fault.

Also, the study will focus on three types of breakers which are currently dominant in Osogbo transmission station.

The oil and vacuum breakers are on medium voltage level and the SF_6 gas on high voltage level.

Table 3.1 – 3.6 show the statistics from the field in terms of number of operation carried out from the year 2005 to 2009.

The purpose of this result (Data) is to compare the reliability values of the breakers dominant in Osogbo equipment centre office, Osun state at 33kv FEEDER.

This is to measure their performances in terms of number of operation.

Table 3.1: Number of Operation in PHCN Osogbo Works Centre, 2005

Breaker Type	**Number of Operations in 2005**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	52	42	50	35	10	31	44	45	51	52	62	45
VCB	18	22	Replaced	1	0	1	10	38	38	30	19	29
OCB Type	7	13	Contact replaced	1	0	1	19	26	28	1	6	1

Sources: PHCN Osogbo Work Centre Equipment Office, 2005 at 33kv FEEDER

Table 3.2: Number of Operation in PHCN Osogbo Works Centre, 2006

Breaker Type	**Number of Operations in 2006**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	De
SF_6 Gas	40	52	41	67	0	3	0	0	1	1	1	1
VCB	Replaced	27	5	6	0	2	0	0	1	0	3	1
OCB Type	8	14	3	1	0	1	0	0	1	0	2	1

Sources: PHCN Osogbo Work Centre Equipment Office, 2006 at 33kv FEEDER

Table 3.3: Number of Operation in PHCN Osogbo Works Centre, 2007

Breaker Type	Number of Operations in 2007											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	20	30	25	40	60	70	75	85	80	72	70	75
VCB	20	60	70	72	80	60	68	59	Replaced	48	52	60
OCB Type	1	2	4	1	5	6	8	9	Contact replaced	6	5	4

Sources: PHCN Osogbo Work Centre Equipment Office, 2007 at 33kv FEEDER

Table 3.4: Number of Operation in PHCN Osogbo Works Centre, 2008

Breaker Type	Number of Operations in 2008											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	1	1	1	1	1	0	1	55	62	70	62	61
VCB	5	3	2	0	0	4	2	3	16	12	0	0
OCB Type	2	3	4	6	7	6	5	3	4	6	0	0

Sources: PHCN Osogbo Work Centre Equipment Office, 2008 at 33kv FEEDER

Table 3.5: Number of Operation in PHCN Osogbo Works Centre, 2009

Breaker Type	Number of Operations in 2009											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	20	28	38	40	50	60	27	48	65	60	50	40
VCB	10	13	14	Contact replaced	12	13	16	12	10	9	10	10
OCB Type	2	10	Contact replaced	0	1	3	2	0	0	8	4	5

Sources: PHCN Osogbo Work Centre Equipment Office, 2009 at 33kv FEEDER

Table 3.6: Frequency of maintenance

TYPES	FREQUENCY OF MAINTENANCE %	COMMON FAULT
VACUUM CIRCUIT BREAKER VCB	10	TOTAL REPLACEMENT
GAS CIRCUIT BREAKER	30	CHANGE OF TRANSMISSION ROD.
OIL CIRCUIT BREAKER	60	FREQUENT CHANGE OF CONTACT

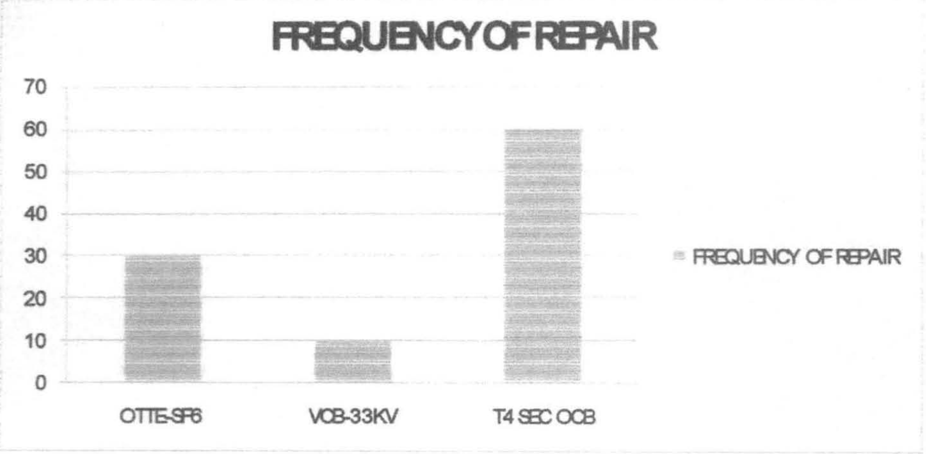

FIG. 3.1: Frequency of Repair

3.2 FREQUENCY OF REPAIR

The percentage of repair on SF6 gas is normal and that of the oil is very high while that of the vacuum is very low. This implies that the cost of maintenance of SF_6 is moderate and that of oil is very high while that of vacuum is very low but a failure of vacuum at the long run means total replacement of vacuum circuit breaker.

3.3 MEAN TIME TO REPAIR

Thiis depends on product configuration. It measures the elapse times requre to perform a given maintenance activities and is subsequently used to calculate system availability and downtime.

3.4 RESTORE TIME

This is the total time needed to restore equipment or device to a specified performance level or to maintain it at that level of perfomance. Thus it include active corrective and preventive maintainance times.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 PRESENTATION OF DATA

The data collected for this study over the period of 5 years (2005 – 2009) were analyzed and presented in this chapter.

Tables, graphics and charts were used in this discussion. Each table contains information on a survey carried out based on the performance of circuit breakers in Osogbo PHCN transmission station.

Table 4.1: Number of Operation in PHCN Osogbo Works Centre, 2005

	Number of Operations in 2005											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	52	42	50	35	10	31	44	45	51	52	62	45
VCB	18	22	Replaced	1	0	1	10	38	38	30	19	29
OCB Type	7	13	Contact replaced	1	0	1	19	26	28	1	6	1

Sources: PHCN Osogbo Work Centre Equipment Office, 2005 at 33kv FEEDER

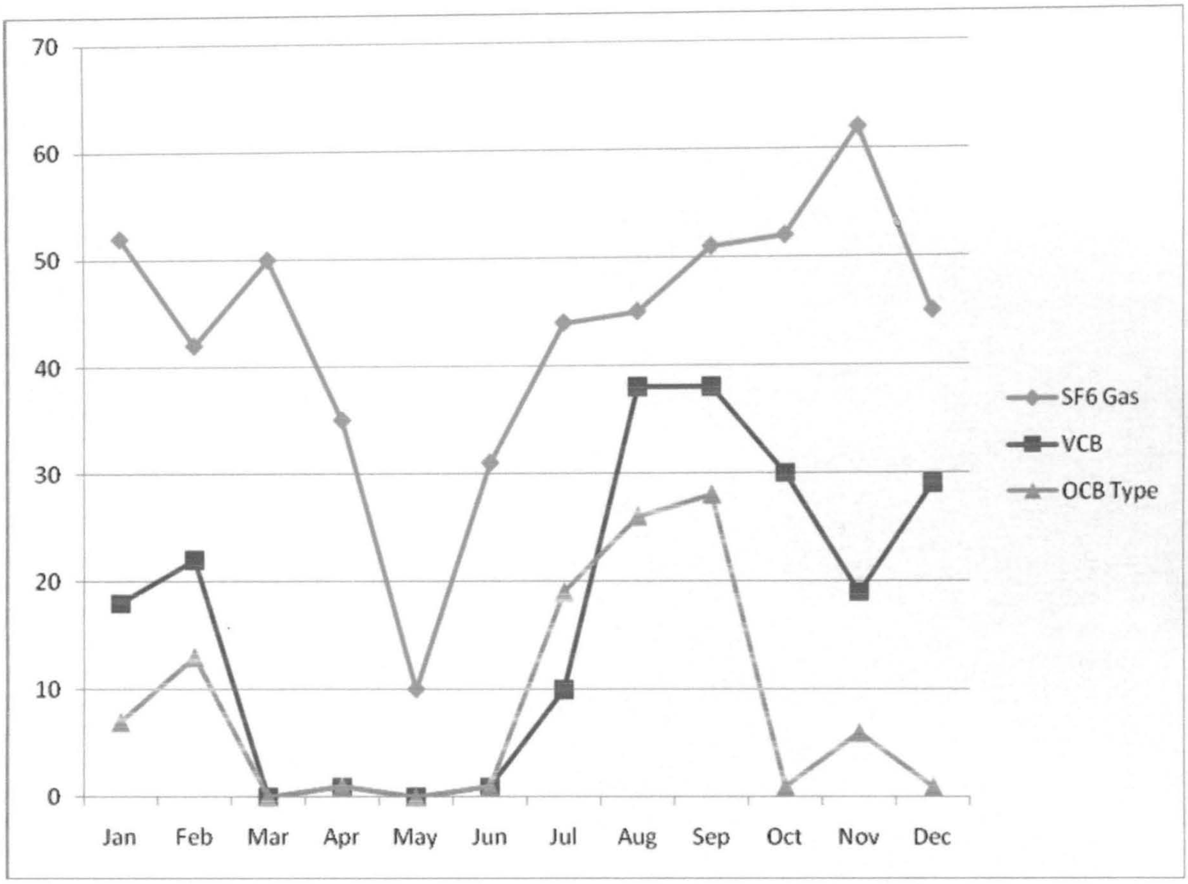

Fig. 4.1: Number of Operation in PHCN Osogbo Works Centre, 2005

Table 4.2: Number of Operation in PHCN Osogbo Works Centre, 2006

Breaker Type	Number of Operations in 2006											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	D
SF_6 Gas	40	52	41	67	0	3	0	0	1	1	1	1
VCB	Replaced	27	5	6	0	2	0	0	1	0	3	1
OCB Type	8	14	3	1	0	1	0	0	1	0	2	1

Sources: PHCN Osogbo Work Centre Equipment Office, 2006 at 33kv FEEDER

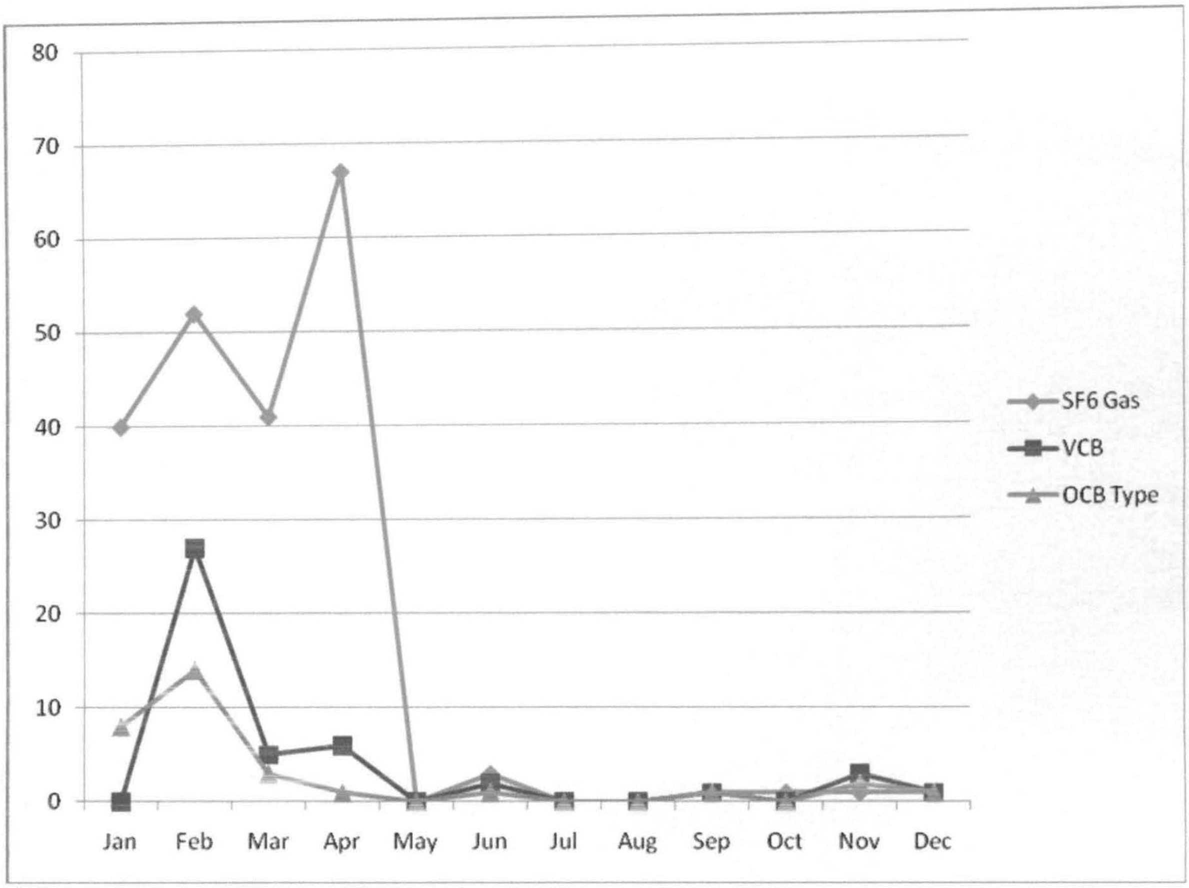

Fig. 4.2: Number of Operation in PHCN Osogbo Works Centre, 2006

Table 4.3: Number of Operation in PHCN Osogbo Works Centre, 2007

Breaker Type	**Number of Operations in 2007**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	De
SF_6 Gas	20	30	25	40	60	70	75	85	80	72	70	75
VCB	20	60	70	72	80	60	68	59	Replaced	48	52	60
OCB Type	1	2	4	1	5	6	8	9	Contact replaced	6	5	4

Sources: PHCN Osogbo Work Centre Equipment Office, 2007 at 33kv FEEDER

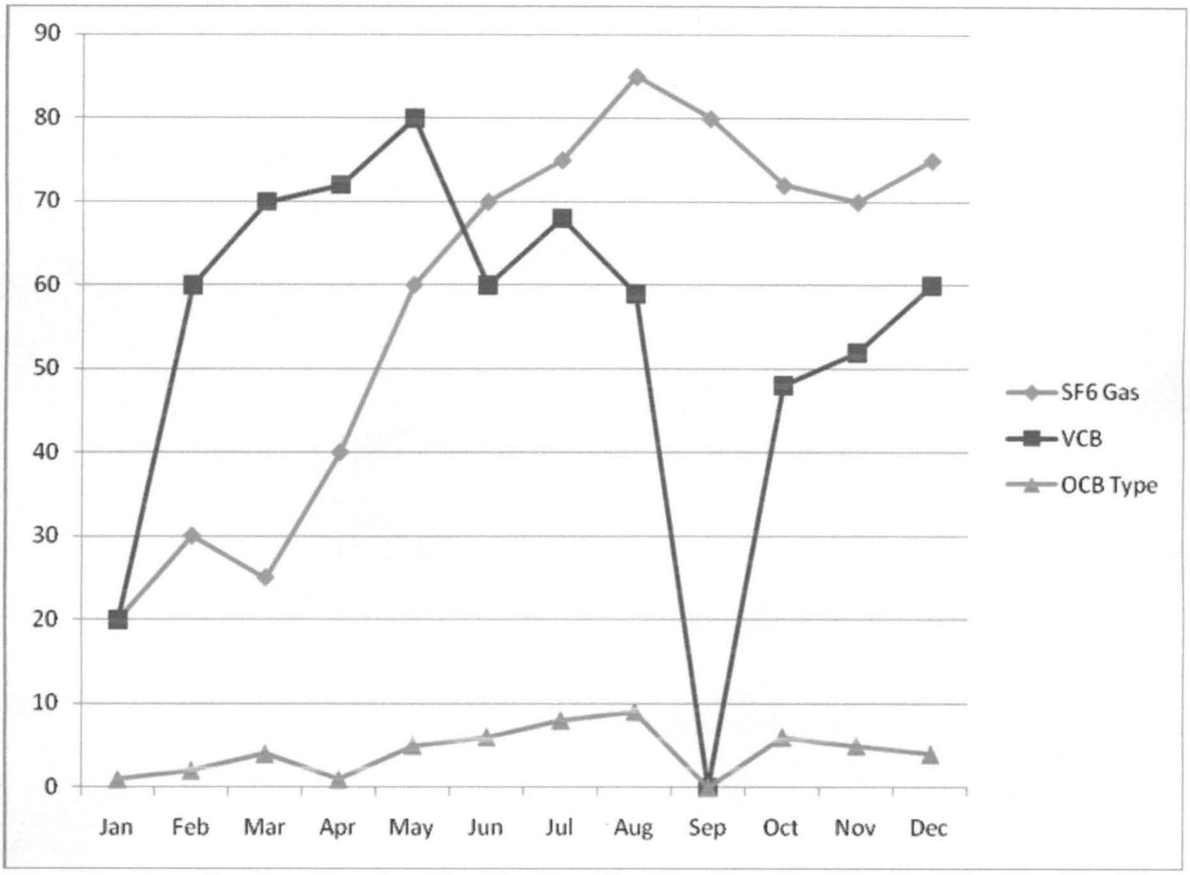

Fig. 4.3: Number of Operation in PHCN Osogbo Works Centre, 2007

Table 4.4: Number of Operation in PHCN Osogbo Works Centre, 2008

Breaker Type	**Number of Operations in 2008**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	1	1	1	1	1	0	1	55	62	70	62	61
VCB	5	3	2	0	0	4	2	3	16	12	0	0
OCB Type	2	3	4	6	7	6	5	3	4	6	0	0

Sources: PHCN Osogbo Work Centre Equipment Office, 2008 at 33kv FEEDER

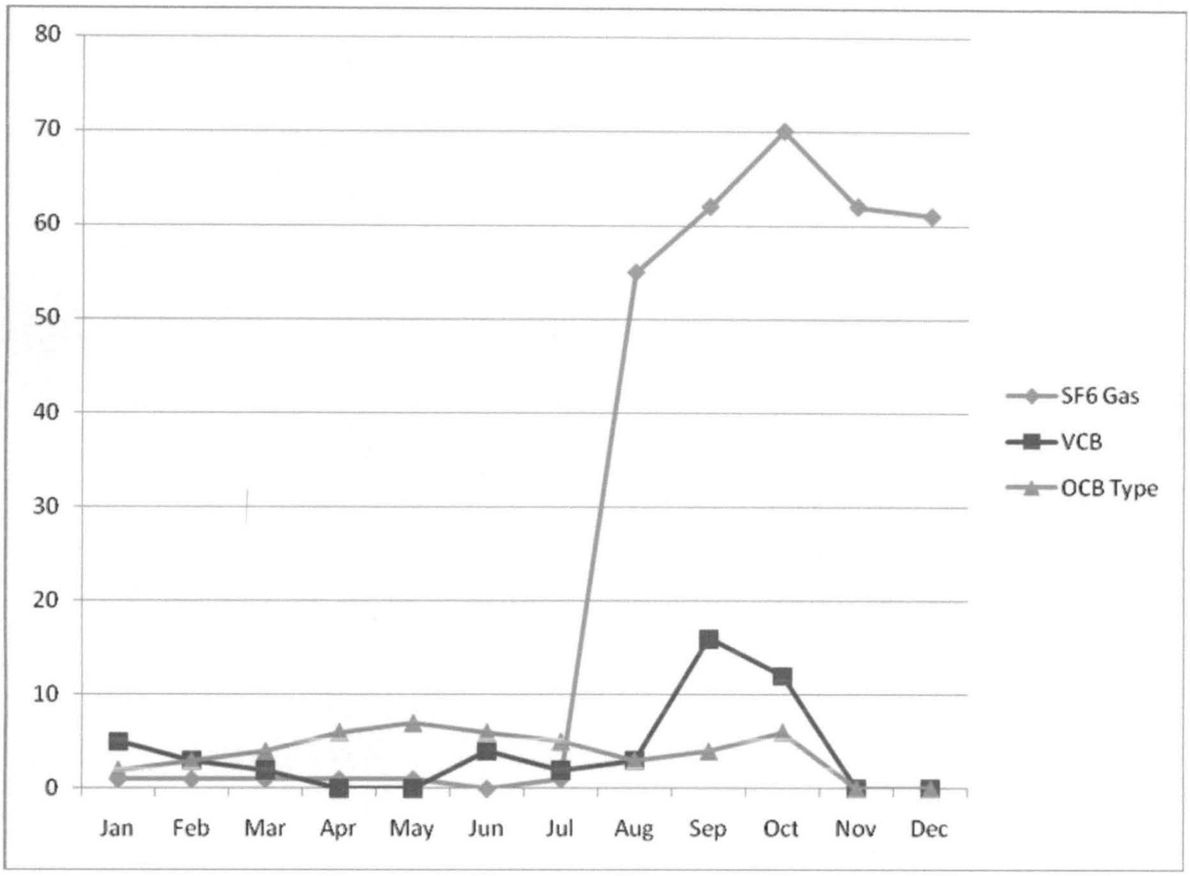

Fig.4.4: Number of Operation in PHCN Osogbo Works Centre, 2008

Table 4.5: Number of Operation in PHCN Osogbo Works Centre, 2009

Breaker Type	**Number of Operations in 2009**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF_6 Gas	20	28	38	40	50	60	27	48	65	60	50	40
VCB	10	13	14	Contact replaced	12	13	16	12	10	9	10	10
OCB Type	2	10	Contact replaced	0	1	3	2	0	0	8	4	5

Sources: PHCN Osogbo Work Centre Equipment Office, 2009 at 33kv FEEDER

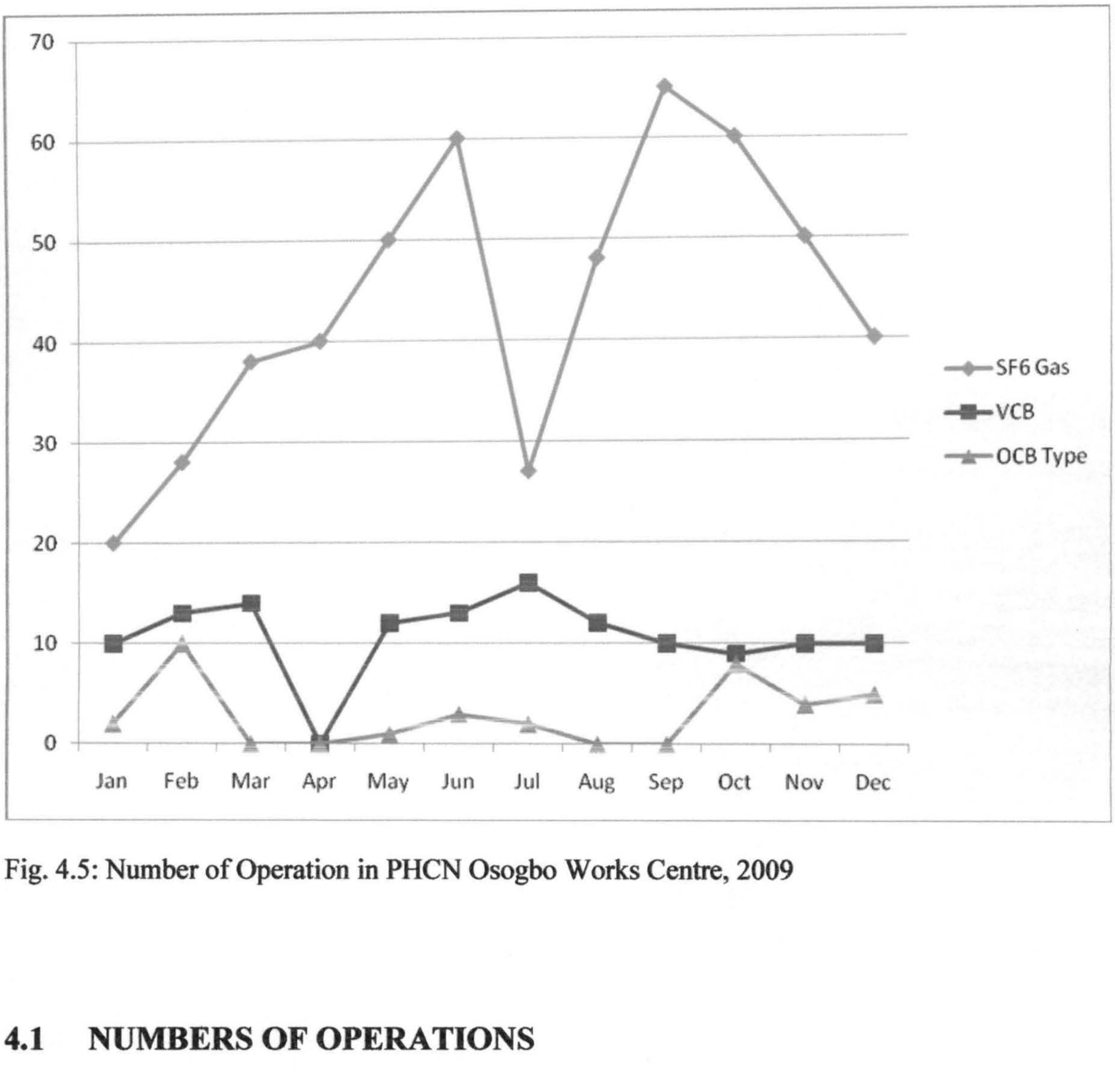

Fig. 4.5: Number of Operation in PHCN Osogbo Works Centre, 2009

4.1 NUMBERS OF OPERATIONS

The performance of SF_6 circuit breaker as shown in the year 2005 (fig 4.1.0) is more stable compare to the other two breakers.

The reasons for low outages for example in VCB (VCB was opened for safe working space and to rectify air leakage on the phase of VCB).

The performance of circuit breakers as surveyed for a period of five year, it shows that SF6 perform an average of 450 operations on fault without the breaker itself encountering any problem shows a high efficiency.

4.2 THE PERFORMANCE OF CIRCUIT BREAKERS STATISTICS AS SURVEYED FOR A PERIOD OF FIVE YEAR

Table 4.6

Types of Circuit Breakers	Repairs	Period Per Year
Oil	Contacts replacement four times	One
VCB	Outright replacement of breaker	One
SF_6	Stable	One

The performance of the various circuit breakers in table 4.1 shows that SF6 is stable compared to other type of breakers. Also, it was gathered that over a period of 5 years that SF6 perform an average of 450 operations on fault without the breaker encountering any problem shows a high efficiency.

4.3 MEAN TIME BETWEEN FAILURE CALCULATIONS

From the result or datas collected from the table above, the mean time between failure (MTBF) can be calculated, from the year 2005 – 2009.

Total time from January to December in hours is given as

$(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10} + T_{11} + T_{12})$

$= 31 \times 24 + 28 \times 24 + 31 \times 24 + 30 \times 24 + 31 \times 24 + 30 \times 24 + 31 \times 24 + 31 \times 24 + 30 \times 24 + 31 \times 24 + 30 \times 24 + 31 \times 24 = 8760$ hours.

T_1 - T_{12} represent the time from January to December.

MT BF – mean time between failure given as $1/\lambda$

Where λ is the failure rate of the device.

This can be calculated from 2005 – 2009

(i). 2005

For SF_6.

No of fault at the end the year = 519

Total time at the end of the year = 8760 hours, MTBF = $1/\lambda$ = 16.89Hertz^{-1}hours

For VCB

Total time = 8760 hours

No of fault at the end of the year = 144

MTBF = $1/\lambda$ = 61.00 hertz^{-1} hours

OCB

$1/\lambda$ = 84.7 hertz^{-1} hour

(ii). 2006

For SF_6 breaker

Total time = 8760 hours

No of faults at the end of the year 2006.

$= 207$

MTBF = $1/\lambda$ = 42.3 Hetz^{-1} hours

For VCB

Total time = 8760 hours

No of faults at the end of year 2006

$= 45$

MTBF = $1/\lambda = \frac{8760}{45}$ = 195 Hertz^{-1} / hours

For OCB

Total time = 8760 hours

No of fault at the end of the year = 31

MTBF = $1/\lambda = \frac{8760}{31}$ = 282.6 Hertz^{-1} hours

(iii). For 2007

Total time = 8760 hours

For SF_6 breaker

Total no of faults at the end of the year

$= 702$

MTBF = $1/\lambda = \frac{8760}{702}$ = 12.48 Hertz^{-1} hours

For VCB. Total no of faults at the end of the year = 649

MTBF = $1/\lambda$ = $\frac{8760}{649}$ = 13.50 Hertz^{-1} hours

For OCB.

Total no of faults at the end

The year = 51

MTBF = $\frac{8760}{51}$ = 171.8 Hertz^{-1} hours

(iv). For 2008

For SF_6 gas breaker

Total no of faults = 316.

MTBF = $1/\lambda$ = $\frac{8760}{316}$ = 27.72 Hertz^{-1} hours

For VCB

Total no of faults = 47

MTBF = $1/\lambda$ = $\frac{8760}{47}$ = 186.4 Hertz^{-1} hours

For OCB

Total no of faults = 46

MTBF = $1/\lambda$ = $\frac{8760}{46}$ = 190.4 Hertz^{-1} hours

(v). For 2009

For SF_6

Total fault at the end of the year

= 526

Total time = 8760 hours

$$MTBF = {}^{l}/_{\lambda} = \frac{8760}{523} = 16.56 \text{ Hertz}^{-1} \text{ hours}$$

For VCB

Total faults at the end of the year

= 129

$$MTBF = {}^{l}/_{\lambda} = \frac{8760}{29} \; 67.90 \text{ Hertz}^{-1} \text{ hours}$$

For OCB

Total fault at the end of the

Year = 35

$$MTBF = {}^{l}/_{\lambda} = \frac{8760}{35} = 250.3 \text{ Hertz}^{-1} \text{ hour}$$

From the result obtained above from the year 2005 -2009 the mean time between failure in SF_6 is minimal compare to the other two breakers. (VCB and OCB). This indicate higher rate of performance and reliability.

As a result, for a device to have higher reliability, it means the cost of maintainability will be low: SF_6 circuit breaker is more reliable than the other two breakers.

4.4 ANALYSIS OF DATA

4.4.1 Reliability

To calculate the reliability of each breaker in the year 2005 for example,

Let R_1 denote Reliability of SF_6 breaker

Let R_2 denote Reliability of VCB breaker

Let R_3 denote Reliability of OCB breaker

$R_T = 1 - F(t)$, where F(t) denote probability that the breaker will fail

R_T denote reliability of the breaker

Total MTBF = 16.89 + 61.00 +84.70 = 162.59

Where MTBF is the mean time between failures.

$F_1(t)$ denote the probability that SF_6 will fail

$F_2(t)$ denote the probability that VCB will fail

$F_3(t)$ denote the probability that OCB will fail

$F_1(t) = \frac{16.89}{162.59} = 0.10$

$F_2(t) = \frac{61}{162.59} = 0.38$

$F_3(t) = \frac{84.7}{162.59} = 0.52$

Therefore $R_1 = 1 - F_1(t)$

$= 1 - 0.10 = 0.9$

$R_2 = 1 - F_2(t) = 1 - 0.38 = 0.62$

$R_3 = 1 - F_3(t) = 1 - 0.52 = 0.48$

The summary of the shows that the reliability of SF_6 = 0.9

VCB = 0.62

$$OCB = 0.48$$

The reliability value of SF_6 is higher compare to the other two breakers, which shows it high rate of performance.

In terms of number of operations, the probability of performing an operation over the period of 5 years without failure within a specified time is very high in SF_6 and high in VCB but low in OCB breakers.

This shows that SF_6 is more reliable compare to the other two breakers.

4.4.2 Maintainability

In general, maintenance is any action that restores failed units to an operational condition or retains non-failed units in an operational state. The SF_6 circuit breaker from the graph shown, it can retain an operational state for a bug time, that of VCB is not continuous while that of oil circuit breaker has just short period of stable operation.

4.4.3 Operational Availability

This is the percentage of a calendar time to which one can expect a system to work properly when it is required. SF6 as show from the analysis of the graph it has a high operational availability with continuous operation; vacuum also has a long period of operation while that of oil circuit breaker has low operational availability due to frequent replacement of contacts.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0 Conclusion:

The PHCN is currently focusing on increasing the functionality of power system apparatus to improve electrical power quality and facilitate better system asset management. Nevertheless, ever increasing demands for power system availability require that equipment reliability and availability be continually improved.

In this work a review of various types of circuit breaker has been carried out and their performance in terms of number of operation has been dealt with. Statistically seen, most medium and high voltage circuit breaker failure can be traced to the operating mechanism. While there may appear to be a wide range of operating principles for circuit breakers, they all share a common basis in being highly mechanical designs and essentially all performing the core function of closing and opening the breaker.

Also, one of the objectives of this work is to consider the inevitability of circuit breakers and for a device to be inevitable shows that it plays a vital role in the protection of power system switch year. Hence, several maintenance practices has been discussed but the automated circuit breaker monitoring has been discussed where by a mobile agent techniques can be applied in circuit breaker maintenance. Utilizing mobile agent techniques, the convenience and speed of accessing and generating maintenance data will be improved.

Since the objectives of this study were to determine the performance of circuit breakers and its applications. The result of the study reveals that of all the breakers used on medium and high voltage level, the SF_6 type of circuit breaker has shown a high performance in terms of operation while that of vacuum also has a good performance as seen from the field experience. This high performance of SF_6 circuit breaker has been attributed to evolution of interrupter technologies and the insulating mediums they employ. This substantial progress has brought an increasing reliability and reducing maintenance requirement of SF_6 circuit breakers.

5.1 Recommendations:

1. The generally regarded as a sound quality indication for assessing circuit breaker are dielectric medium, operation and maintenance history, contact resistance and number of operation.

   The performance of circuit breakers operation carried out in the course of this work has shown SF_6 circuit breaker to possess a high quality indicator and this type of breaker offer many advantages when used in power switch gear.

These advantages include:

- Size reduction
- Weight reduction
- Simplified design
- Reliable operation
- Ease of handling
- Quiet operation
- Easy of maintenance

Based on this numerous advantages, I recommend SF_6 circuit breaker to be applied in all the PHCN power switch gear in other to increase their performance

2. Electric utilities are pressured to reduce their overhaul and maintenance costs and improve power system operation. One way to accomplish first goal is to extend the interval between maintenance cycles and doing less maintenance, or performing maintenance based on equipment condition (predictive) rather than time. To sustain the confidence level on this critical piece of equipment different maintenance programs such as mobile agent software have been established. These programs follow established standards, guidelines and the recommendations of the manufacturer. Usually all maintenance recommendations are based on experience with particular circuit breaker being used in a given system. Performing the same maintenance approach on all breakers can be inefficient especially in the cases when utility company owns large number of units. This is also very costly because of the down time required to perform these procedures. A more logical approach· may be to continually evaluate the condition of circuit breaker that through experience have been identified as being the most likely to fail, which could provoke a severe damage that would disrupt the service. By equipping the crew with new information access methods to replace the old paper-based information exchange and logging method, the efficiency may be improved since less time will be spent on preparation, reporting and logging. If the inevitability of circuit breakers are to be maintained hence automated Circuit Breaker Monitoring remains the best option.

REFERENCES

[1] Madhu,S.''Re; who invented the circuit breaker?" MadSci Network:Science history, April 2003

[2] Circuit breaker. From wikipedia the free encyclopedia,2008

[3] QIU Shi-Yi. The reliability of electrical equipment maintenance [M]. Beijing: China Electric Power Press, 2007.

[4] WU Bo, dawn hair. Mechanical system reliability, maintenance and decision-making model [M]. Beijing: Chemical Industry Press, 2006.

[5] Entrepreneurs Association of China's power supply branch. Substation maintenance [M]. Beijing: China Electric Power Press, 2006.

[6] WANG Yong-hua. Vacuum circuit breaker condition monitoring and fault diagnosis of Analysis [J]. Electrical Test, 2005,

[7] Fan Ting-wei, Li R, Huo Fengming. SB6 new type of circuit breaker maintenance of [J]. Hebei Electric Power Technology, 2006, (2). Reposted elsewhere in the paper for free download http://www.hi138.com.

[8] Alvan, S. *"Electrical Power Equipment and Measurement with Heavy Current Electrical Applications"*, McGraw-Hill Book Company (UK) Limited, England, 1980.

[9] Charles, A. G. *"Power Systems Analysis"*, John Wiley & Sons, New York 1979.

[10] Garzon R. D., *High Voltage Circuit Breakers : Design and Applications*, Marcel Dekker[1]

[11] Inc, New York, 1997] and van der Sluis, pp63-66, [van der Sluis, L., *Transients in Power Systems*, John Wiley & Sons Ltd, Chichester, 2001.]).

[12] (Greenwood [Greenwood, Allan, Electrical Transients in Power Systems, 2nd edition, John Wiley & Sons

[13] Failure Rate, the wikipedia (free encyclopedia)