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Reliability Study of Electric Circuit Breakers (A case study)

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A R T I C L E I N F O

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A B S T R A C T

Circuit breakers are crucial components for power systems 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 examined in Osogbo Power Holding Company of Nigeria (PHCN) equipment centre. Three dominant types were considered: SF6 (Sulphur hexafluoride Circuit Breaker), VCB (Vacuum Circuit Breaker) and OCB (Oil Circuit Breaker). Based on the results and analysis carried out, the SF6 breaker has the highest performance rate in terms of number of operations with a minimum failure rate. SF6 however, has the highest reliability and availability compared to the others.

1. Introduction

Reliability is an important factor in Engineering Systems designs. Its history goes back to the 1930s when probability concepts were applied to problems of electric power generation. However, during the World War II, the Germans applied basic reliability concepts to improve the reliability of their V_1 and V_2 missiles which was marked as the real beginning of the reliability application in engineering (Dhillon, 1996.).

Since the 1950s, the reliability field has developed into many specialized areas such as mechanical reliability, software reliability, human reliability and

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power systems reliability. In 1951, Professor W. Weibull of the Royal Institute of Technology, Stockholm published a statistical distribution to represent the breaking strength of materials. And in 1952, D.J. Davis presented failure data and the results of several goodness-of-fit, for competing failure probability distributions. This work provided the support for the assumption of exponential failure distribution which is widely used today to represent the failure behavior of various engineering items (Dhillon, 1996.) and (Elsayed, 1996).

Reliability assessment Techniques

Reliability is the ability to perform a required function under given condition for a given time or time interval, often expressed as probability. A term that is closely related to reliability is availability. Availability further includes the concepts of maintainability and the maintenance support-ability (SS-EN, 2001.) and is generally expressed as the ratio of available time (mean time to repair MTTR)) divided by total time (mean time to repair plus mean time to failure (MTTF)). One of the fundamentals of this research is to establish the reliability and availability of circuit breakers. Reliability calculation can be seen as a tool utilized to estimate the expected availability of systems or components.

One of the most basic measures of reliability performance is the average unavailability, here defined as:

$$U = \frac{r}{(\frac{1}{\lambda} + r)}$$

Since $\lambda r \ll 1$, the above equation is often approximate as

$$U = \lambda r$$

Where U is the unavailability, λ is the failure rate and r is the repair time.

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 breakers emerged when electric power distribution was developed on an industrial scale. This was in the late 19th century and in the early 20th century. Improvements in the first half of the 20th century centered on current handling capacity and reduced interruption time. Interruption time 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 (Madhu, 2003). Circuit breakers then were manually reset. In the case of electrical power distribution, this could mean hours before power was restored. Many of the breakers used today automatically reset in the event of lightning strikes, any form of short circuit and overload as the case may be. Household circuit breakers tend to be manually 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 of the grid and circuit breakers over the internet. Technicians at a central facility can monitor where breakers have tripped and attempt to re-route power through other segments of the grid. They can also reset the breakers remotely, significantly simplifying the task of restoring power.

The knowledge of circuit breakers 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 nearest to a zero current. Electric power transmission networks are protected and controlled by high voltage breakers. 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 and buses from various types of overhead or ground earth fault etc (Wikipedia, 2010.).

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. Their 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 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.

Types of circuit breakers

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:

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.

Low Oil Circuit Breakers: which operate with a minimum amount of oil, which are sometimes called minimum oil circuit breakers or small-oil circuit breakers. These circuit breakers are also 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.

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 (Madhu, 2003). 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 minimum losses. The gas uses sulphur hexa-fluoride (SF6) which under pressure has 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 3bar 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 change to liquid if its temperature drops below 10, (Charles, 1979.) so for outdoor switch gear, heaters must be provided.

Vacuum Circuit Breakers

High vacuum has two outstanding properties:

- 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.

- 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 increases.

Diagnostic Testing

The fact that some electrical equipment remains quiescent for much of its life is all the more reason for greater monitoring and testing to pinpoint any incipient faults.

Diagnostic testing of electrical equipment will give a ready indication of the condition of the equipment and provide a good guide to possible deterioration. The testing assists in the determination of permissible intervals between maintenance operations. Diagnostic test should be made wherever possible and the fullest use made of the information obtained there from.

Circuit breakers recommended diagnostic tests to be carried out on all types of circuit breakers are:

1. Timing test should be carried out using a reliable apparatus for: close operations, open operations, close/open operations and the time from initiation to operation of the contacts should be recorded. The apparatus should be arranged so that all the interrupters are timed at once, so that comparisons can be made of the timing between poles.
2. Timing test should be carried out to check the phase discrepancy and anti-pumping relays as stipulated by the manufacturer.
3. Voltage drop or resistance measurement should be carried out across each complete pole and across individual series components to detect any deterioration in contents or connections. Checks should be carried out on the circuit breaker operating mechanism to determine: running hours of operation motor, the automatic start up pressure, low pressure alarm and locked pressure

Additional diagnostic tests for:

1. A circuit breaker using SF6 gas for Insulation and arc quenching:- regular check should be carried out to determine:-

- The pressure setting of the “make up” gas alarm and the operation of the mirco-switch.
- “Alarm and block” pressure settings and the operation of micro-switch.
- The gas leakage rate.
- Dew point (condensation temperature) of the SF6
- The oxygen content of the SF6 gas

2. Circuit breakers using pressurized air for Insulation and arc quenching:- regular check should be carried out to determine:-

- The pressure setting of the “make up” control
- The pressure setting of the “low air” alarm
- The pressure setting of the “lock out” air control
- The loss of air

The “dew point” (condensation temperature) of the insulating air.

3. Circuit breakers using oil for Insulation and arc quenching:- regular check should be carried out to determine:-

- Oil level in the circuit breaker
- quality of oil in the breaker

The dielectric strength of the Insulating oil (Momoh, 2006.).

Maintenance of power system network.

Maintenance is crucial for transmission and distribution system operators both when acquiring new assets (apparatus) and when trying to utilize already existing assets in the best possible manner. The cost of maintenance and consequences of failures can be significantly higher than the cost of the equipment. Hence, it becomes important to study maintenance and its effects in all stages of the life-time of the asset. Maintenance actions are performed on the basis of components degradation and potential failure probabilities, consequences and characteristics.
The failures can be grouped into either of reoccurring failures (i.e. to some extent possible to predict) or random failures (WANG, 2005). Failures can further be divided into failures with incubation time (possible to detect before they happen) and instant failures (without incubation time).
These two pairs give us in total four types of component failures, which can be used in the identification of proper maintenance actions. Two important keywords will be predict and detect. Reoccurring failures and random failures can be addressed if it is possible to predict a failure, with statistics, e.g. the equipment may for example be close to worn-out after a number of cycles or time.

Failures with incubation time and instant failures can be addressed if it is possible to detect failures before they occur, this might be accomplished with thermograph, dielectric response measuring or vibration monitoring.

Random failures may be addressed with diagnostics. But diagnostics might not be suitable for failures that occur instantaneously (instant failures). However, instant component failure might be prevented by early replacement based on statistics. Components with random failures that go directly from functioning to failure, are hard to maintain before a failure occur and hence either has to be handled with corrective maintenance or system re-design. Important to note is that there is no dividing line between these four types of failures. A specific component can have failures within one or more of the groups. Furthermore, there might be methods to move a type of failure from one category to another, for example by improved failure statistics. It is, moreover, important to note that it is up to the maintenance organization to decide upon whether diagnosis or preventive maintenance actions shall be performed or not.

Corrective and preventive maintenance are briefly discussed below, followed by a brief overview of the strategies within power systems, concerning these two forms of maintenance.

Finally a number of problems regarding maintenance of power systems are outlined.

Common Maintenance Problems

Some common problems for power systems are identified by Hilber and Lindquist, (2003) (Hilber, 2005). Many of these problems have two sides, i.e. it is important to balance between the problem and its solution, which might be expensive and may include other drawbacks. Below are the problems presented:

Failures are often not analyzed to the extent that similar future failures can be prevented.

Effective maintenance actions are made but without structure and clear relevance to organization objectives.

Maintenance induced failures, maintenance is not failure free.

Periodical preventive maintenance is performed unnecessarily; maintenance is performed towards technical goals without economical considerations.

Non-existent reasons for maintenance actions: it is crucial to know why the maintenance action is performed (what will be improved?). Without this knowledge it is hard to estimate the value of the maintenance action.

Low visibility of maintenance strategy. If the effects of the maintenance activities not are clear for the organization it is hard to motivate the current strategy.

Accepting manufacturer's recommendations without consideration of specific circumstances of the usage. Does the manufacturer's maintenance goal coincide with that of the users?

Resistance towards new equipment for diagnostics that could improve the maintenance actions impact on system reliability (Hilber and Lindquist, 2003) and (Gillander, 1991).

It is worth admitting that there may be risk associated with installing new equipment in already existing system. The introduced equipment might introduce new failures and will probably need maintenance itself.

Corrective Maintenance

Corrective maintenance is performed after fault recognition and is intended to put the component in a state in which it can perform a required function (Elforsk, 1997). The component is used until it fails. Corrective maintenance might be considered as a last resort and might intuitively be considered as a failure of the organization performing the maintenance but, that is not necessarily the case. Corrective maintenance is part of the maintenance strategy during the planning stage. For equipment with random occurring instant failures corrective maintenance might be the only option. As mentioned above one might consider re-designing the system for these kinds of failures. It is quite likely that these failures might be worth "living with" while focusing on other areas with a better goal fulfillment per monetary unit.

Preventive Maintenance

The concept of preventive maintenance is to reduce failure probabilities by maintenance before failure or significant degradation has occurred (Elforsk, 1997). This often translates into trying to avoid costs of corrective maintenance and other costs that belong to unexpected failures.

Preventive maintenance can be divided into the following groups:

Periodical maintenance

Condition based maintenance

Periodical maintenance is as the name inclines performed at regular intervals (not limited to time). This is a good strategy in the case of a well identified ageing process of the component. The time intervals between the maintenance should be based on the expected time to failure with shorter intervals for the maintenance, than for the expected time to failure.

Usually the periodic maintenance is based on time intervals from the manufacturer's specifications or company policies. By generalizing, it can be stated that the manufacturer is more interested in the product not failing during the warranty time than in the organization maintenance costs (This can however be addressed with techniques such as Life Cycle Cost analysis in the procurement phase of equipment). The company policies seldom consider different make, usage and environment. A potential risk lies within the periodical maintenance if it is performed at these generalized time intervals. To maintain a component unnecessarily often introduces higher maintenance costs and risks for faults introduced by the maintenance activity (SS-EN, 2001.).

2. Materials and Methods

The research was carried out at Power Holding Company of Nigeria Osogbo Equipment works centre. The study involves measurement of numbers of performance and frequency of repair.

Measure of performance in terms of number of operations

The number of operation of a breaker is usually taken by the operating cycle counter. These counts the number of switching operations which includes all operations that have to do with opening and closing of breaker in either normal or abnormal conditions, (normal in the absence of fault and abnormal in presence of fault).

The study will focus on three types of breakers which are currently dominant in Osogbo PHCN equipment centre.

The oil and vacuum breakers are on medium voltage level and the SF6 gas on high voltage level.

Table 1 – 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 data is to compare the reliability assessment of the breakers in Osogbo equipment centre office at 33KV FEEDER.

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

Table 1: Number of Operation in PHCN Osogbo Works Centre, 2005

Breaker	Number of Operations in 2005											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SF6 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 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	Dec
SF6 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: 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
SF6 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 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
SF6 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 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
SF6 Gas	20	28	38	40	50	60	27	48	65	60	50	40
VCB	10	13	14	Contact	12	13	16	12	10	9	10	10
OCB Type	2	10	Contact	0	1	3	2	0	0	8	4	5

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

Table 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

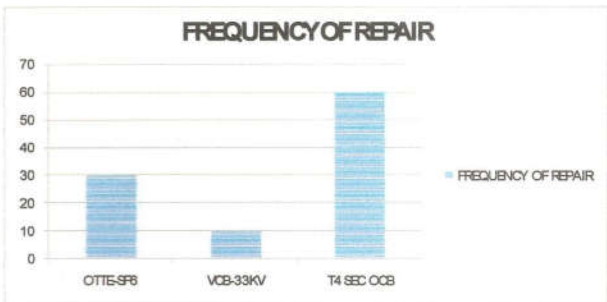

FIG. 1: Frequency of Repair

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.

Mean time to repair

This depends on product configuration. It measures the elapsed time required to perform a given maintenance activities and is subsequently used to calculate system availability and downtime.

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 performance. Thus it includes active corrective and preventive maintenance time.

3. Results and discussion

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

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 equipment centre at 33KV feeder.

Numbers of operations

The performance of SF_6 circuit breaker as shown in the year 2005 (fig .1) is more stable compare to the other two breakers.

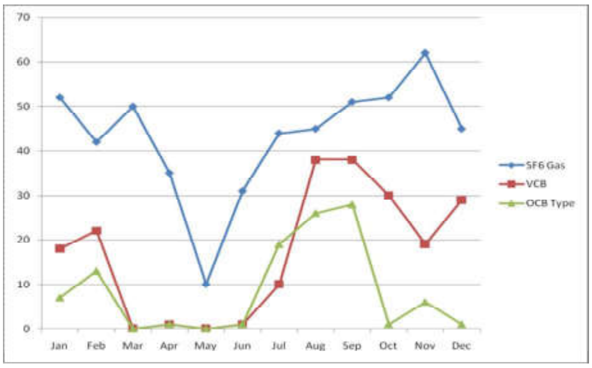

Fig. 2: Number of Operation in PHCN Osogbo Works Centre, 2005

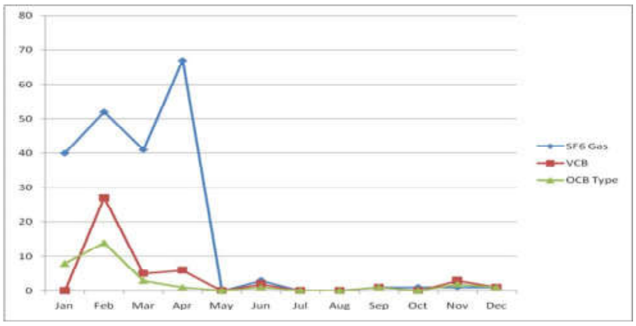

Fig. 3: Number of Operation in PHCN Osogbo Works Centre, 2006

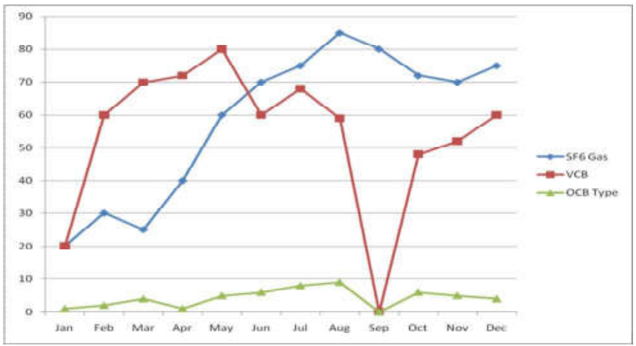

Fig. 4: Number of Operation in PHCN Osogbo Works Centre, 2007

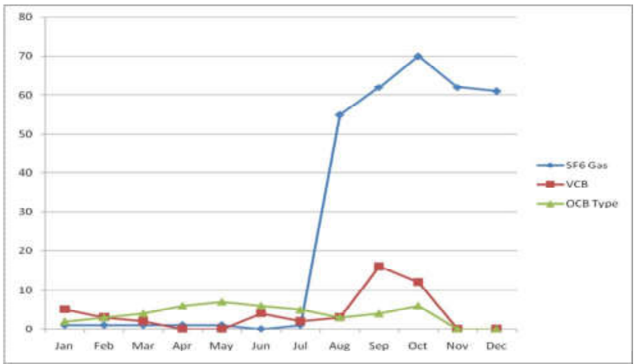

Fig.5: Number of Operation in PHCN Osogbo Works Centre, 2008

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.

Performance of circuit breakers statistics as surveyed for a period of five year

The performance of the various circuit breakers in table 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.

Mean time between failures calculation

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

Table 7: Maintenance period of Breakers.

Types of Circuit Breakers	Repairs	Period Per Year
SF6	Stable	One
VCB	Outright replacement of breaker	One
OCB	Contacts replacement four times	One

Table 8: number of faults and MBTF of CBs from 2005 to 2009.

YEARS	NO. OF FAULTS OF CB 2005-			T (HRS)	MBTF OF CB 2005-2009 (HRS/		
	SF6	VCB	OCB		SF6	VCB	OCB
2005	519	206	103	8760	16.88	42.52	85.04
2006	207	45	31		42.32	194.67	282.58
2007	702	649	51		12.48	13.5	171.76
2008	316	47	46		27.72	186.38	190.43
2009	526	129	35		16.65	67.91	250.29

Total time from January to December in hours is given as

$$T = \sum_{n=1}^{12} T_n$$

T_n = days of a month × 24hrs.

T= 8760 hours.

MTBF: mean time between failure = $1/\lambda$

Where: λ , is the failure rate of the device.

This can be calculated from 2005 to 2009 and is presented in table 8. Below

From the result obtained above from the year 2005 -2009 the mean time between failures in SF6 is minimal compare to the other two breakers. (VCB and OCB). This indicate higher rate of performance and reliability. 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 SF6 and high in VCB but low in OCB breakers.

As a result, for a device to have higher reliability, it means the cost of maintainability will be low: SF6 circuit breaker is more reliable than the other two breakers.

Data Analysis

Reliability

To calculate the reliability of each breaker in the year 2005 for example; Let R_1 denote Reliability of SF6 breaker, R_2 denote Reliability of VCB breaker and 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 =16.88+ 42.52 +85.04 = 144.44
Where: MTBF is the mean time between failures.
$F_1(t)$: denote the probability that SF6 will fail
$F_2(t)$: denote the probability that VCB will fail
$F_3(t)$: denote the probability that OCB will fail

$$F_1(t) = \frac{16.88}{144.44} = 0.12$$

$$F_2(t) = \frac{48.52}{144.44} = 0.29$$

$$F_3(t) = \frac{84.04}{144.44} = 0.59$$

Therefore $R_1 = 1 - F_1(t)$

$= 1 - 0.12 = 0.88$

$R_2 = 1 - F_2(t) = 1 - 0.29 = 0.71$

$R_3 = 1 - F_3(t) = 1 - 0.59 = 0.41$

The summary on table below shows the reliability of the three CBs.

Table 9: CBs reliability

CB	SF6	VCB	OCB
Reliability	0.88	0.71	0.41

The reliability value of SF6 is highest compare to the other two breakers and has the highest rate of performance. This shows that SF6 is more reliable compared to the other two breakers.

5. Conclusions

In the present utility environment, financial and market forces are, and will continue to, demand an efficient and a profitable operation of the power system with respect to power systems protection. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. The PHCN is determined to achieve both operational reliability and financial profitability; it has become clear that more efficient utilization and control of the existing generating, transmission and distribution systems infrastructures are required. 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 was dealt with. Statistically, it has been proven that most medium and high voltage circuit breaker failure can be traced to the operating mechanism. While there may be a wide range of operating principles for circuit breakers, they all share a common basis of being high mechanically design and essentially all performing the core function of closing and opening the breaker.

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 SF6 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 SF6 circuit breaker has been attributed to evolution of interrupter technology and the insulating mediums employed. This substantial progress has brought an increasing reliability and reduced maintenance requirement of SF6 circuit breakers.

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